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Prediction of Anemia Using Naïve-Bayes Classification Algorithm in Machine Learning

Pearl D'Souza and Ritu Bhargava

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Prediction of Anemia Using Naïve-Bayes Classification Algorithm in Machine Learning

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Abstract To make accurate forecasts, machine learning algorithms rely on past data. It makes use of statistical methods and algorithms that are trained to make classifications or predictions. Consider anemia prediction in the medical machine learning domain, which is the most common hematological disease. When there aren't enough good red blood cells in the body, oxygen can't go where it needs to go. This paper aims to use a machine learning algorithm to develop an early detection of anemia in patients with low hemoglobin (HGB) counts, as well as to determine which parameters have the greatest impact. The Naïve Bayes algorithm using the multiple instance learning method is the main algorithm used in the research, and the analysis is carried out using the WEKA utility tool. This research uses a training dataset of 500 instances along with 7 fields (RBC, MCV, MCHC, TLC, PLT, HGB, and DECISION) to conduct the prediction. The real data constructed from the HGB test results collected from patients in the range set (11.6–16.6) is trained and tested by using the Naïve Bayes algorithm, which performs best with 90% accuracy in the percentage split of 66%. The WEKA experimenter proves that the Naïve Bayes algorithm gives the best performance with F-measure, sensitivity, the true positive rate (TP Rate), precision, and the lowest value in the false positive rate (FP Rate), respectively. Based on the performance chart curve for predicting anemia, it shows the highest weight, as visualized further.

Keywords WEKA · Anemia · Kaggle · HGB · LD

P. D'Souza
Principal, Sophia Girls' College (Autonomous) Ajmer, Ajmer, India

R. Bhargava (✉)
Associate Professor, Department of Computer Science, Sophia Girls' College (Autonomous) Ajmer, Ajmer, India
e-mail: ritu@sophiacollegeajmer.in

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1 Introduction

The basic tenet of machine learning is the systematic examination of data for the purpose of discovering previously unsuspected connections and patterns [1]. The machine learning process consists of three key components. Combining classification (clustering), analytical rules, and process modelling a set of output decision rules is developed through a classification analysis [2] for a certain dataset. Extracting data from a training set and transforming it into full structures enables machine learning systems or database machine learning processes to accurately identify trends in new data sets. Naïve Bayes classification algorithms are used in medical healthcare to improve the processing of medical data. Anemia is a medical condition that describes the reduction in hemoglobin or red blood cells in human blood [3]. Considering a CBC (complete blood count) test is conducted for patients in a laboratory, Anemia is affected by various features and attribute values that impact it the most. HGB (hemoglobin) count is one of them, which indicates that the low HGB (lack of enough red blood cells in the body) causes symptoms such as fatigue, headaches, dizziness, and shortness of breath [4].

In this work, the machine learning tool is used as an analysis of medical data. The machine learning tool is used for the analysis of the data and the framework that efficiently employs a number of different categorization techniques [5]. This tool processes the datasets by filtering out the irrelevant data that is not in use, and the remaining data is passed into the training and testing sets. Data mining in the medical domain, particularly in databases, involves analysing massive amounts of data to predict specific patterns of information [6].

This paper contains a set of 500 instances associated with HGB (hemoglobin) tests of patients, and the results predict anemic patients in the normal range taken (11.6–16.6), assisting doctors in providing immediate treatment [7]. The accuracy estimated using the Naïve Bayes Classification algorithm in predicting Anemia in patients turned out to be 90%, which is accurate [8]. The evaluation of data using the Naïve Bayes classifier takes 66% of the classified data as a training set and uses it to train algorithms [9]. Then it classifies the test data (34% of it) based on the decision rules found in the training set for predicting Anemia. Using 7 predictive features and the Naïve Bayes Classification algorithm computes the best prediction of Anemia using hemoglobin count (HGB) data [10].

2 Literature Work and Related Study

Pouria et al. [2]. presented the work on the Naïve Bayes Algorithm and its applications: Naïve Bayes text classification, spam filtration, and sentiment analysis with zero conditional probability estimation.

Green et al. [3] discussed an improved accuracy of 92% that was achieved in predicting whether a patient had chronic kidney disease using the Naïve Bayes. At first, eGFR was used to forecast whether or not a patient would be sick, and the resulting information helped those who were sick by suggesting which foods they should eat and which they should avoid.

Aidaroos et al. [9] used the Naïve Bayes approach to mine medical datasets from various perspectives, highlighting the main features of the dataset based on the requirements. Based on the experimental results compared to those of other approaches, it is determined that NB (Naïve Bayes) is the best approach for the majority of the used medical datasets.

Manal et al. [11] discussed Anemia type prediction based on algorithms under the data mining concept on a sample of 41 patients, with the CBC that is used to construct the results using the WEKA experimenter. The algorithms undertaken are the J48 decision tree algorithm, which further gives the best performance with an accuracy score of 93.75% and a percentage split of 60%, respectively.

Ninad et al. [12] presented work on the pre-detection of heart diseases and diabetes by providing health-related report values. In their proposed work, in order to classify the dataset, the Naïve Bayes algorithm is used to provide accurate results. With the result generated, heart diseases among the patients are predicted, leading to a successful evaluation of the ailment.

3 Objective of Work

Data Pre-Processing step.

To analyse medical data using Naïve Bayes algorithm.

To analyse and predict the accuracy of the result by forming Confusion Matrix.

Visualization of the test result obtained through the threshold curve.

3.1 Naïve Bayes Classification Algorithm

The Bayes theorem-based supervised learning technique is primarily employed in the context of classification issues. In text classification, when a high-dimensional training dataset is required, this approach is particularly popular because it is a probabilistic classifier, making predictions solely based on the object's probability [11]. The name Bayes Theorem has been shortened to "Bayes Rule" or "Bayes Law." Here, the conditional probability is what ultimately decides the likelihood.

The formula of Bayes' Theorem is presented as:-

$$P\ (A|B) = P\ (B|A).P\ (A)/P\ (B)$$

In this case, P (A|B) stands for the posterior probability, or the likelihood of confirming hypothesis A in light of evidence for event B.

Likelihood, denoted by P (B|A), is the probability that a hypothesis is supported by the available evidence.

Prior probability, or P (A), is the likelihood of a hypothesis before any evidence is observed.

Marginal probability, denoted by P (B), stands for evidence probability.

In this paper we have a dataset of Medical conditions and corresponding target variable as "Anemia". So using this dataset we have to decide that whether or not an individual is suffering from Anemia [12].

Naïve Bayes algorithm is one of fastest and the easiest Machine Learning Algorithms for predicting a class of a dataset [11]. It can be easily used for both Binary as well as Multi-class Classifications. For Text-classification problems it has become the most preferable choice [13].

Evaluation Metric.

3.2 *Means of Judgment*

An accurate set is one in which the values are relatively close to one another. The accuracy of a measurement set is determined by whether or not its mean is close to the actual value of the quantity being measured. Data points from repeated measurements of the same quantity are required if one wishes to measure more than two terms [13].

Accuracy = (TP + TN)/(TP + FP + TN + FN).

Precision = TP/(TP + FP).

TP = True positive,

TN = True Negative.

False positives (FP) and false negatives (FN) are the opposite of true positives and true negatives, respectively.

Where TP (True Positive) is returned if both the estimated and real values are positive, FP (False Positive) is returned if the predicted value is positive when the true value is negative, and FN (False Negative) is returned if the predicted value is negative when the true value is positive [13].

3.3 *The Matrix of Confusion*

The Naïve Bayes classifier will now be further evaluated using a confusion matrix.

It's similar to a table based on a classifier's performance in test data, also known as the "true value." It will help identify comparisons between classes (Table 1).

Table 1 Shows the confusion matrix generated based on the classifier's performance in test data, which includes the feature vectors from which classification of the data is possible

Feature vector	Target vector	<– Classified as
70	11	YES
5	84	NO

3.4 Dataset

This part will use the Kaggle dataset as an experimental material. The purpose of using this dataset is to compare the accuracy of the developed model. There are seven features in this dataset that are closely related to Anemia itself. Following are the features that are used as reference:-

- The number of erythrocytes, often known as red blood cells, is what an RBC (Red Blood Cell) count determines.
- "MCV" (Mean Corpuscular Volume) is a standard for determining the typical size of a person's red blood cells.
- To diagnose anemia, clinicians assess hemoglobin levels in the blood and utilise the mean cell hemoglobin concentration (MCHC) test.
- TLC (Total Leucocyte Count also known as White Blood Cells) measures the total number of all the leukocytes in the blood.
- PLT (Platelets) fragments of very large cells in the bone marrow called megakaryocytes which create blood clots to slow or halt bleeding and heal wound.
- HGB (Hemoglobin) test measures how much HGB the RBC contains, a protein in red blood cells that carries oxygen. Range taken for HGB is 13.1–15.5 as a standard limit for predicting the Anemia count in patients.
- DECISION/Outcome predicts the patient's condition, whether it is detected Anemia or healthy (Tables 2, 3, 4, 5, 6, 7 and 8).

Table 2 Represents the RBC (Red Blood Cell) statistical data by calculating its mean, standard deviation, weighted sum and precision value respectively using Naïve Bayes Classifier

RBC		
Mean	3.7261	4.6429
Std. dev.	0.7583	0.6303
Weight sum	218	281
Precision	0.0286	0.0286

Table 3 Represents the MCV (Mean Corpuscular Volume) statistical data by calculating its mean, standard deviation, weighted sum and precision value respectively

MCV		
Mean	86.1835	88.7075
Std. dev.	11.7825	7.0078
Weight sum	218	281
Precision	0.3437	0.3437

Table 4 Represents the MCHC (the average amount of hemoglobin in a group of red blood cells) statistical data by predicting its mean, standard deviation, weighted sum and precision value respectively

MCHC		
Mean	31.308	32.3791
Std. dev.	2.921	2.5003
Weight sum	218	281
Precision	0.2634	0.2634

Table 5 Represents the TLC (Total Leucocyte Count/ White Blood Cells) statistical data by predicting its mean, standard deviation, weighted sum and precision value respectively

TLC		
Mean	9.3814	8.5111
Std. dev.	6.4148	3.768
Weight sum	218	281
Precision	0.1713	0.1713

Table 6 Represents the PLT (Platelets) statistical data by predicting its mean, standard deviation, weighted sum and precision value respectively

PLT		
Mean	231.5893	215.8174
Std. dev.	107.9867	92.0536
Weight sum	218	281
Precision	3.1401	3.1401

Table 7 Represents the HGB (Hemoglobin) statistical data by predicting its mean, standard deviation, weighted sum and precision value in the range from (13.1–15.5) respectively

HGB		
Mean	9.8422	13.2785
Std. dev.	1.4945	1.193
Weight sum	218	281
Precision	0.1855	0.1855

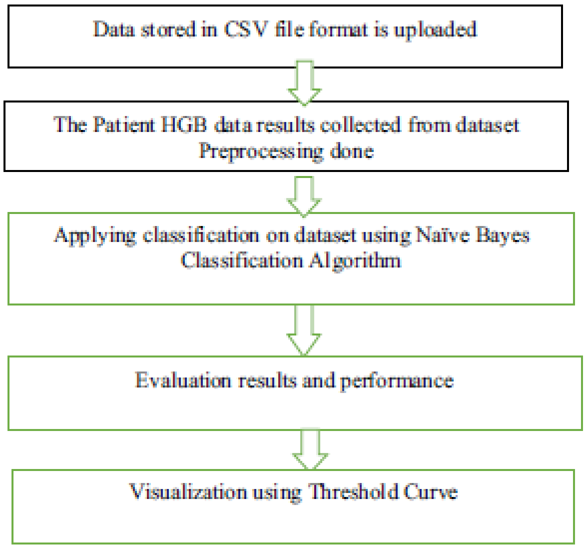
4 Methodology

In this section 7 features are considered to predict anemic patient categorized as an input. The data is analysed completely from Hemoglobin (HGB) count test results, which are conducted by collecting blood samples from 500 (instances). The data is then transformed into a standard file format CSV, which supports WEKA tool to build

Table 8 Represents the total count of Anemia patients and healthy patients in (YES/NO)

Attribute	YES	NO
	0.44	0.56

Fig. 1 Represents the flowchart of proposed model



the ANEMIA dataset filtering out irrelevant data. The HGB data contain statistical data as mean count for positive(YES) anemic patients is 9.842 on the other hand mean count for non-anemic patients is 13.278 respectively. The algorithm Naïve Bayes classifier is applied for predicting Anemia using WEKA tool in the split percentage of 66%. The implementation process involves the collection of HGB results and pre-process data to extract the values out of it. After the classification process data is visualized using the threshold curve for both (YES/NO) criteria (Fig. 1).

5 Results and Observations

The data has been analyzed and presented in the form of Graphs by using 500 instances in the dataset using Naïve Bayes, in WEKA tool with test option split (66%) data (Figs. 2, 3, 4, 5, 6, 7, 8 and 9).

Findings

See Table 9.

Recall (sensitivity) = True Positive rate/(True Positive rate + False Negative rate).

Precision = True Positive rate/(True Positive rate + False Positive rate).

F-measure = (2 * recall * precision)/(recall + precision).

In other words, the True Positive rate is the proportion of positive cases that have been accurately labelled.

Number of true positives wrongly labelled as false negatives is the False Negative Rate.

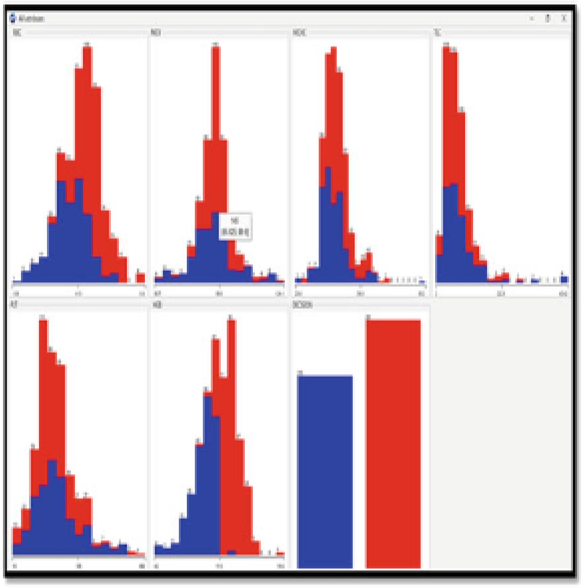


Fig. 2 Graphs generated above for each feature taken (RBC, MCV, MCHC, TLC, PLT, HGB, DECISION) represents the color code blue (probability of NO non-anemic patients) and color code red implies the probability of anemic patient (YES). Final Decision/ Outcome is plotted in histogram above (total of 281 anemic patients) and 218 non-anemic patients respectively

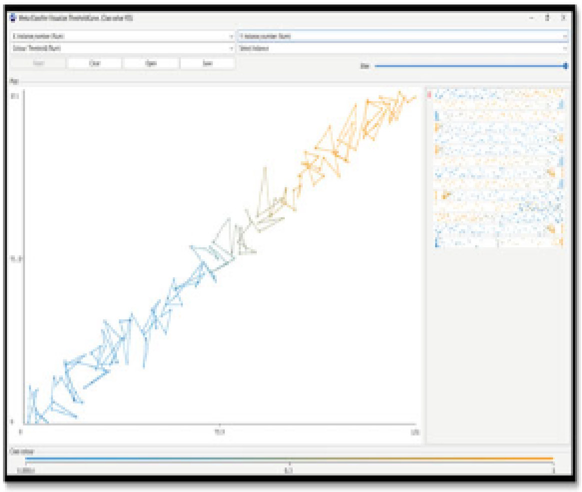


Fig. 3 Performance chart of ROC, graph shows the X-axis (Instance Num) and Y-axis (Instance Num) is represented by blue colour code for non-anemic patients and yellow colour code for anemic disease. Initially it is shown on anemic patients and after that the anemic value is shown

The number of false-positive results existing so far is known as the False Positive rate (Table 10).

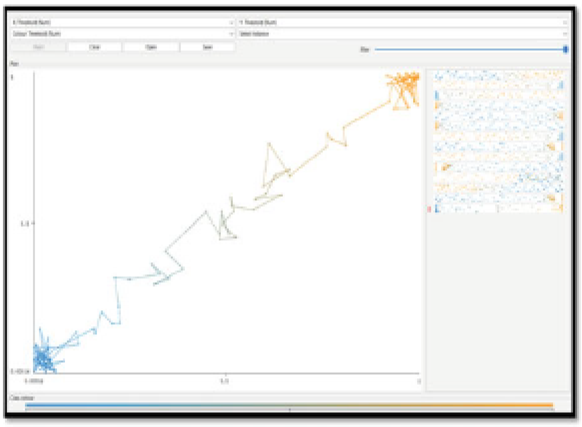


Fig. 4 Shows performance chart in the graph plotted along X-axis and Y-axis representing the threshold curve. Blue color code indicates the non-anemic patients and yellow code indicates the anemic patient. Here the threshold value is given after that both x-axis and y-axis increased sequentially which is shown in the above graph

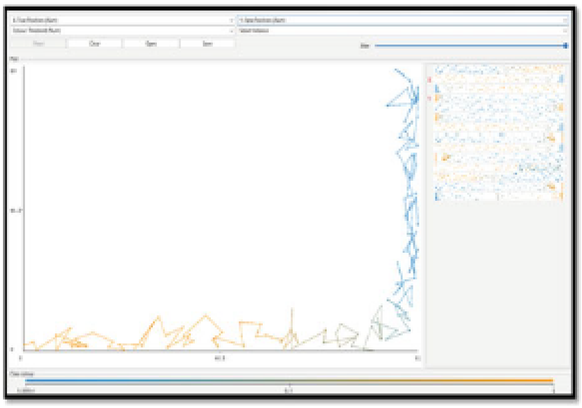


Fig. 5 Shows the graph plotted along X-axis (True Positive) value and Y-axis (False Positive) value as represented. Here TP positive rate has a similar value in the initial phase and after that value of the false positive rate it goes exponentially which is shown in the above graph

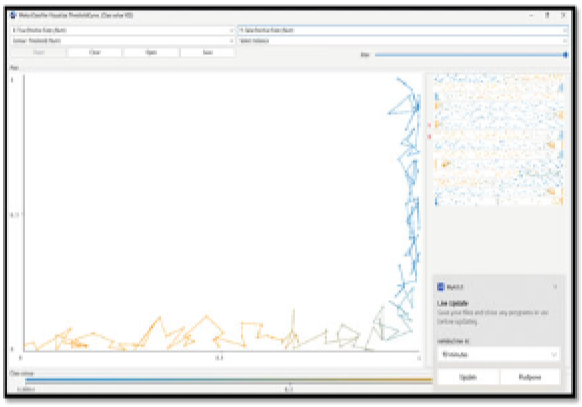


Fig. 6 Shows the graph plotted along X-axis (True Positive Rate) value and Y-axis (False Positive Rate) value represented. Here TP true positive rate go similar value in the initial phase and after that value of false positive rate is go exponentially which is shown in the above graph

Fig. 7 Shows the graph plotted along X-axis (False Negative) value and Y-axis (True Negative) value as represented. Here in the graph the True negative value is increased initially and after that the false negative value goes sequentially which is shown in the above graph

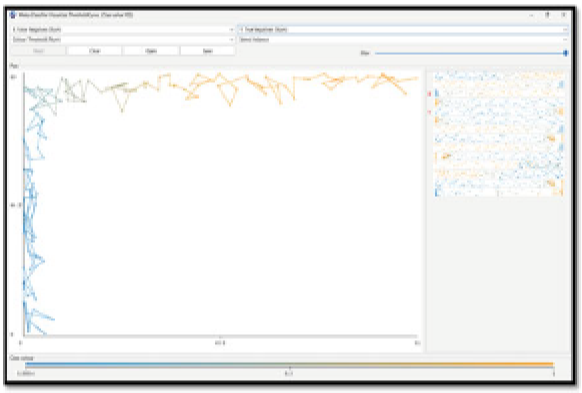


Fig. 8 Shows the graph plotted along X-axis (TP True Positive Rate) and Y-axis (False Positive Rate FP value represented. Here TP true positive rate has a similar value in the initial phase and after that value of false positive rate goes exponentially which is shown in the above graph

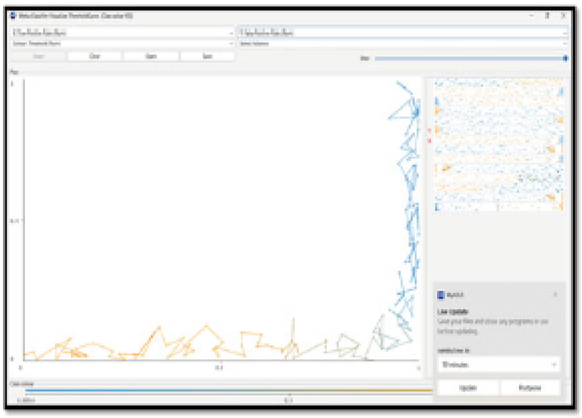


Fig. 9 Shows the Class Decision outcome obtained while taking 7 features (RBC, MCV, TLC, PLT, HGB, MCHC, DECISION) color code blue represents non-anemic patients whereas color code red represents anemic patients

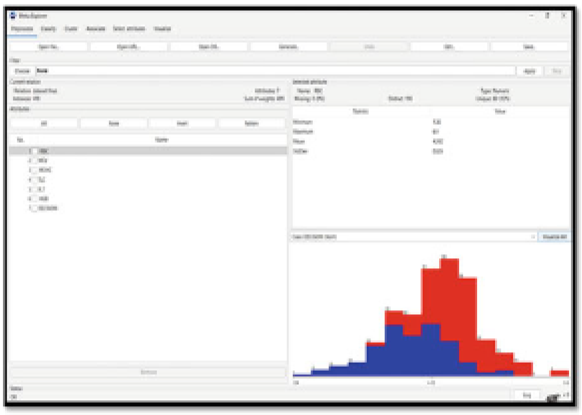


Table 9 Includes the result through accuracy (correctly classified instances) by simulating the result of the algorithm using 66% training set data. Evaluation of algorithm performance recall (sensitivity), precision, F-measures, true positive rate and false positive rate

Detailed accuracy by class									
Algorithm	TP rate	FP rate	Precision	Recall	F-Measure	MCC	ROC area	PRC area	Class
Naïve Bayes	0.864	0.056	0.933	0.864	0.897	0.813	0.971	0.961	YES
	0.944	0.136	0.884	0.944	0.913	0.813	0.971	0.979	NO
Weighted Avg	0.906	0.098	0.908	0.906	0.906	0.813	0.971	0.970	

Table 10 Represents Naïve Bayes algorithm output using 66% training set data accuracy score of 90%

Correctly classified instances	154	90.5882%
Incorrectly classified instances	16	9.4118%

6 Conclusion

This paper focuses on the Methodology approach of classification algorithms in order to get the best prediction of Anemia, based on a training dataset of 500 instances with 7 fields (RBC, MCV, MCHC, TLC, PLT, HGB, DECISION) considered. The dataset is constructed from the result of complete blood count HGB. The experiment is conducted on a training dataset by using Naïve Bayes Algorithm performs best with 90% accuracy in the percentage split of 66%. When using the WEKA utility tool it predicts that Naïve Bayes Algorithm gives the best performance with F-Measure, Sensitivity, The True Positive Rate (TP Rate), Precisions and the lowest value in the false positive rate (FP Rate). Based on the performance chart curve for predicting Anemia he highest weight is shown.

In Future, using more of the machine learning algorithms in order to classify all types of Anemic diseases on multiple datasets must be performed so as to find the accuracy score and interpreting the results respectively.

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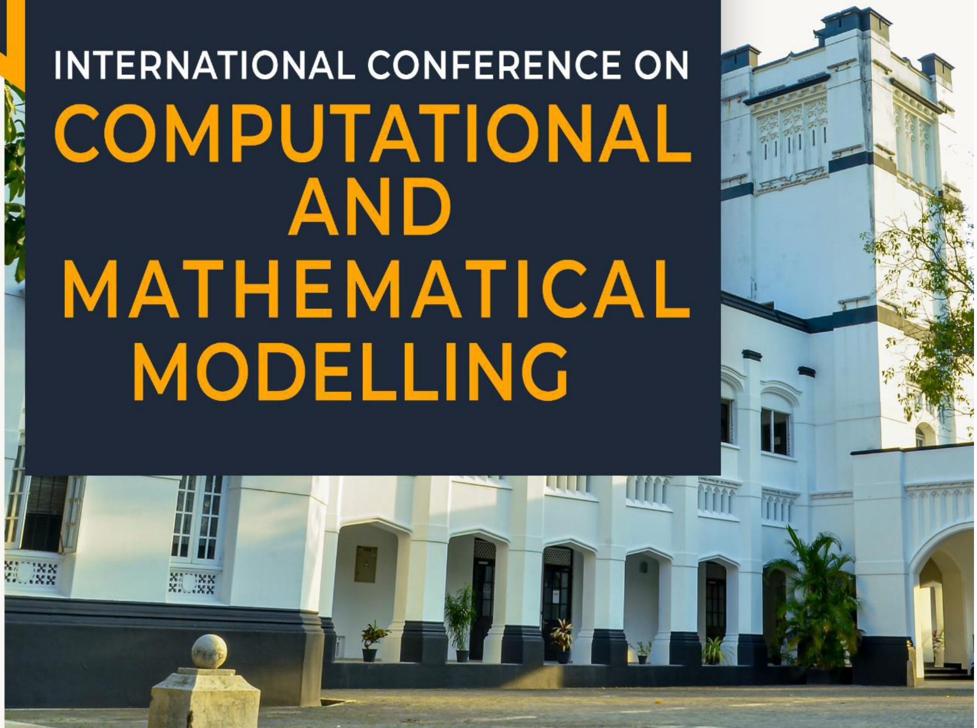

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Multiple instances learning boosting diagnostically prediction of diabetes based on measurements

Ritu Bhargava [1], Sister Pearl D'Souza [2], Pramod Singh Rathore [3*], Avinash Panwar [4] and Megha Raghav [5]

[1] Department of Computer Science, Sophia Girls' College (Autonomous), Ajmer, India
[2] Principal, Sophia Girls' College (Autonomous) Ajmer
[3] Department of Computer and Communication Engineering, Manipal University Jaipur,Jaipur, India
[4] Department of Computer Science ,Mohanlal Sukhadia University - Udaipur, India
[5] Research Scholar, MDS University, Ajmer, India
* pramodrathore188@gmail.com

Abstract
This research addresses the urgent need for early diabetes detection by harnessing advanced Machine Learning techniques, specifically Linear Regression within a Multiple Instance Learning framework. Utilizing the PIMA Indian Diabetes dataset, which includes 768 cases and 8 distinct features, this study aims to robustly predict diabetes risk. The analysis, conducted using Python, focuses on key variables such as Pregnancies, Glucose, and Blood Pressure against diabetes outcomes. By enhancing predictive accuracy, this study contributes significantly to timely diabetes intervention, potentially reducing the global health burden posed by this escalating condition.

Keywords: *Multiple Instance, Boosting, XGBoost, classifiers*

1 Introduction

Diabetes is a fatal disease [1].This disease caused by damaged cause in the pancreas. The pancreas of people with diabetes cannot produce enough insulin i.e. a hormone that regulates blood sugar or glucose that the body needs [2]. Some of the consequences of diabetes include heart attacks, strokes, wounds that are difficult to heal, sexual dysfunction and many more [3]. The medical world has not found a cure for the sufferer until now. One thing that can be done is to make an early diagnosis to prevent complications in diabetes [4]. One solution to prevent someone from getting diabetes is to create an early detection system that can predict whether someone has the potential to suffer from diabetes or not, quickly, and accurately. To create diabetes detection system, the combination of MIL (Multiple Instance Learning) methods can be used [5]. Diabetic retinopathy (DR) is one of the diabetes-derived diseases and is the main cause of blindness in both developed and developing countries [6]. PIMA Indians are a Native American group that lives in Mexico and Arizona, USA [2]. By using machine learning methods, the intent is to predict the relationship of dependent factor with every other variable found from the dataset used. An unified network, namely Multiple Instance Learning with Boosting mechanism for grading the level of disease, is discussed in the paper. Multiple-Instance Learning is a type of weak supervision [7]. MIL is particularly well suited for medical data analysis. In the standard assumption, negative data are said to contain only negative instances, while positive data contain at least one positive instance. The implementation consist of independent variables plotted along the Y –axis and dependent variable (Target Variable) plotted along the X-axis [6].

2 Related work

Abiyev et. al demonstrates a novel approach to automate the detection of chest diseases using deep convolutional neural networks (CNNs). The objective of the study is to develop an accurate and efficient system that can assist medical professionals in diagnosing various chest diseases based on chest X-ray images.

Ruoxian Song proposed ADAMIL (Domain Adaptation Multi-Instance Learning) with attention mechanism for precise grading of Diabetic Retinopathy (DR) levels in retinal images. They framed weakly supervised DR grading as a multi-instance learning problem and implemented domain adaptation with attention mechanism. Labeled instances were generated through cross-domain methods to filter irrelevant instances in the target domain [8].

Ayse DOGRU and Selim BUYRUKOGLU [12] conducted a comparative study on ensemble learning (bagging and boosting) versus single-based machine learning algorithms for predicting type-2 diabetes. They used the early-stage diabetes risk prediction dataset from the UCI Machine Learning Repository, consisting of 520 instances with 17 features [9].

Rani, A. S. & Jyothi applied Machine Learning, including K-Nearest Neighbor, Logistic Regression, Decision Tree, SVM, Gradient Boosting, and Random Forest, to predict diabetes using a dataset. Random Forest demonstrated the highest accuracy among the models analyzed [9].

Kamanasish Bhattacharjee, Millie Pant & Shilpa Srivastava presented work on Evolutionary multiple instance boosting framework for weakly supervised learning .The focus is on enhancing the Multiple Instance Learning Boost framework through DE, a population-based evolutionary meta-heuristic method by optimizing mainly the weights assigned to weak classifiers [10].

Kalyankar, Gauri D., Shivananda R. Poojara, and Nagaraj V. Dharwadkar [15] explores the application of machine learning and Hadoop for analyzing diabetic patient data to make predictions related to diabetes management and outcomes. It was published by IEEE [10].

3 Terms Used

3.1 Boosting Ensemble Machine Learning (MIL)

"Boosting" is a popular and powerful tool in statistical machine learning. The basic idea behind boosting is to take a simple learning algorithm, assign equal weight to each data points and train several simple classifiers, further combine them [11]. A subset is created from the original dataset. Initially, all data points are assigned equal weights, a base model is created on this subset. This model is used to make predictions on the whole dataset. Boosting does not train the model in parallel. It tries to learn sequentially. Equal weights are initially given to all data in the training dataset. Then the weights are increased where the misclassification is made. It tries to correct the error in the previous step by creating a new model again Gradient Boosting and XGBoost (extreme Gradient Boosting) algorithms were used as boosting ensemble machine learning model [12].

3.2 Gradient Boosting

3.3 Multiple Instance Learning (MIL) Algorithm

Multiple Instance Learning [14] is a type of weakly supervised learning algorithm where training data is arranged in bags, where each bag contains a set of instances $X = \{x1, x2, \ldots\ldots\ldots\ldots Xm\}$ and there is one single label Y per bag, Y belongs to $\{0, 1\}$ in the case of a binary classification problem. It is assumed that individual labels exist for the instances within a bag, but they are unknown during training [15]. In the standard Multiple Instance assumption, a bag is considered negative if all its instances are negative. On the other hand, a bag is positive, if at least one instance in the bag is positive.$X = \{x1, x2, \ldots\ldots\ldots\ldots Xm\}$ And there is only single label Y per Bag. Y belongs to $\{0, 1\}$ Labels $y1, y2, \ldots\ldots\ldots yM$ exist for the instances within a bag, but they are unknown during training. Suppose a binary classification data $(X1, Y1)$,$(X2, Y2)$, ..., (Xn, Yn) where $Xi = \{xi1, xi2, ..., xim\}, i \in 1, 2, \ldots, n, n$ is the number of bags, m is the dimension of Xi and $Yi \in [0, 1]$.$Yi = 1$ indicates that the positive bag Xi contains at least one positive instance $xij(j = \{1, 2, \ldots, m\})$. $Yi = 0$ means that there are no positive instances in the bag Xi. The task is to identify a real-valued function $h(xij)$ to infer the instance label yij corresponding to an instance xij. This function is estimated through a weak classifier [16]. Then, through boosting, weak classifiers are combined to form a strong classifier with low error. Multiple instance learning is classified into positive instances(represented by binary value (1) and negative instances by binary value (0).

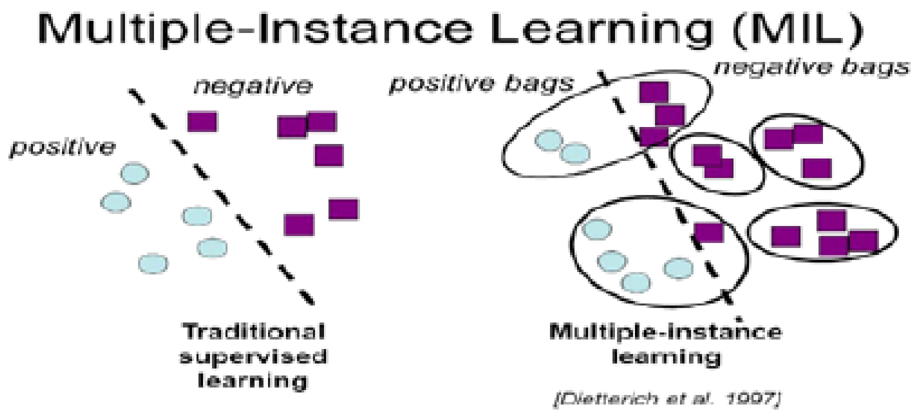

Figure 1: shows Bag Level Classification

Mulitple instance learning is classified into positive instances(represented by binary value [1] and negative instances by binary value[0] .

4 Linear Regression

Categorized further into :-

4.1 Simple Linear Regression

In which one dependent variable and one independent variable (Linear Regression

4.2 Multiple Linear Regression

In which one dependent variable and multiple independent variables (Linear Regression machine learning)

$$DerivativeEquation : Y = a + bX \tag{1}$$

Where

- Y signifies the Dependent variable
- X is an explanatory variable .
- b represents the slope of the
- line, a is the intercept(the value of y when x = 0)

4.3 Evaluation Metrics

The following evaluation metrics were used in the comparison of single base, bagging and boosting ensemble methods [8].

- Accuracy = (TP + TN)/(TP + FP + TN + FN)
- Recall = TP/(TP + FN)
- Precision =TP/(TP+FP)
- Specificity = TN/(TN+FP)
- F1 - Score = (2* Precison * Recall)/(Precision + Recall)

  where
- TP (True Positive) if the estimated value with the actual values is positive;
- FP (False Positive) if the predicted value is positive while the true value is negative;
- FN (False Negative) if the predicted value is negative while the true value is positive;
- TN (True Negative) if the estimated value with the actual value is negative [25].

4.4 Confusion Matrix

It is like table based on the performance of classifier in a test data generally known as true value. It will help for identifying comparison between classes [26].
print(confusion_matrix(Y_test, logreg_predict)

$$\begin{bmatrix} 87 & 9 \\ 23 & 35 \end{bmatrix}$$

5 Dataset

This section will use the PIMA Indian Diabetes Dataset as experimental material. This dataset is open and published by the National Institute of Diabetes and Digestive and Kidney Diseases [27]. The purpose of using this dataset is to compare the accuracy of the developed model. There are nine features in this dataset that are closely related to diabetes itself. Following are the features that are used as reference: -

1. The number of times of pregnancy
2. The amount of glucose in the blood
3. The measurement of blood pressure
4. The thickness of the skin folds on the triceps,
5. The level of insulin in the blood after 2 hours of administration of serum insulin,
6. Weight for each woman
7. Diabetes pedigree function
8. Age for each subject
9. The patient's condition, whether it is detected diabetes or healthy.

6 Tables

Table represents the first 5 rows of the dataset in which we have calculated the outcome value(0/1) in order to find out the difference between positive and negative instances of first five rows from the dataset .

Table 1: difference between positive and negative

class 'pandas.core.frame.DataFrame'
RangeIndex: 768 entries, 0 to 767
Data columns (total 9 columns):

Number	Column	Non-Null Count	Data-type
0	Pregnancies	768 non-null	int64
1	Glucose	768 non-null	int64
2	BloodPressure	768 non-null	int64
3	Skin Thickness	768 non-null	int64
4	Insulin	768 non-null	int64
5	BMI	768 non-null	float64
6	DiabetesPedigreeFunction	768 non-null	float64
7	Age	768 non-null	int64
8	Outcome	768 non-null	int64

7 Methodology

This section presents the relationship between the dependent variable (Outcome) and the independent variables which are seven in count . It consists of five process

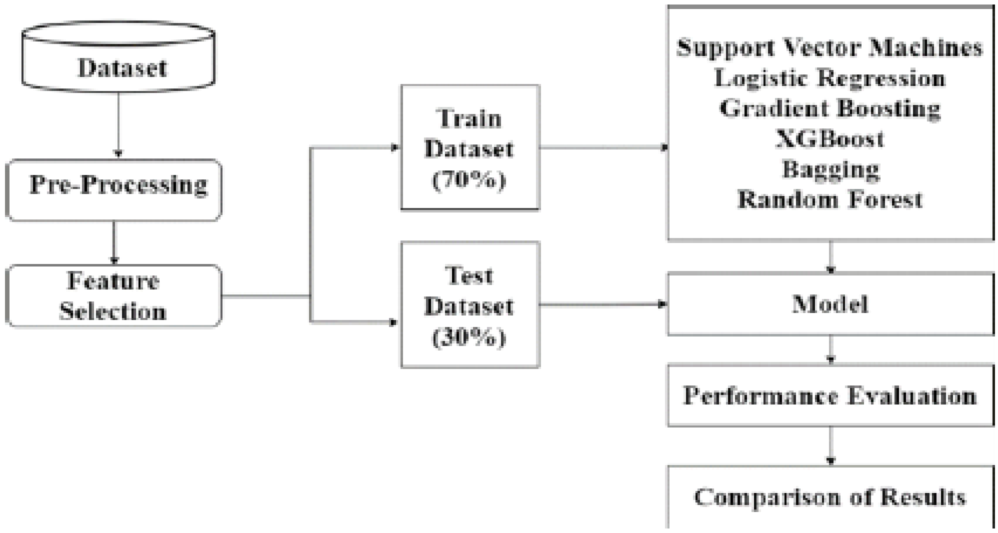

Figure 2: shows structure of diabetes prediction approach model[8]which elaborates the dataset uploaded named Diabetes dataset and then fields are selected which are passed through Train and Test dataset .Further performance analysis is done

steps: dataset, data pre-processing, feature selection, machine learning algorithms and evaluation metrics

Here , Test Size = 0.3 is taken which implies that 30% variables will go under Test Dataset(X_test, Y_test) and remaining 70% will go in Train DATASET(X_train ,Y_train).

8 Results and observations

The data has been analysed and presented in the form of Graphs Based on the results of test that have been carried out , it was found that one main Feature that is more important in diabetes data is 'Glucose'.

A number between 0 and 1 for each feature is taken, where 0 means "not used at all" and 1 means "perfectly predicts the target"so here "Glucose" is by far the most important feature. accuracy_score(Y_test, logreg_predict) 0.792207792207792

print(confusion$_{m}atrix(Y_{t}est, logreg_{p}redict)$ $\begin{bmatrix} 87 & 9 \\ 23 & 35 \end{bmatrix}$

Table 2: represent classification report predicting the precision ,Recall,f1-score and support

	Precision	Recall	F1-Score	Support
0	0.79	0.91	0.84	96
1	0.8	0.6	0.69	58
$Accuracy$			0.79	154
$macro - avg$	0.79	0.75	0.77	154
$Weighted - avg$	0.79	0.79	0.79	154

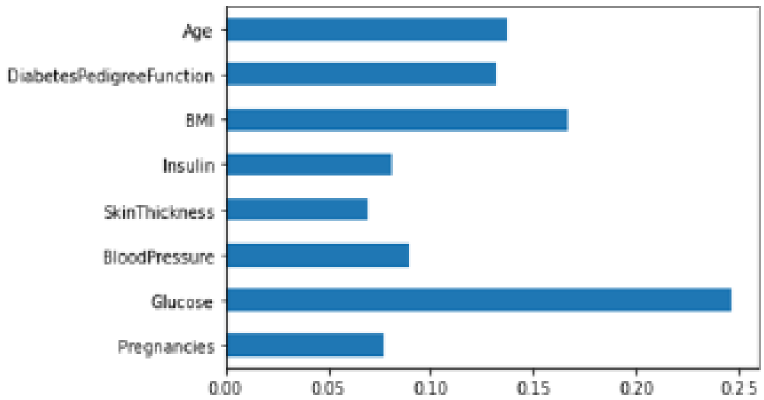

Figure 3: shows 'Feature importance rates' which depicts the feature which is highly used for predicting diabetes in an individual compared with age factor as well

9 Finding

The above graph (Figure 4) shows that the data is biased towards data points having outcome value as 0 where it means that diabetes was not present actually. The number of non-diabetics is almost twice the number of diabetic patients which concludes that Prediction values are more influenced since patient diagnosed diabetic are half in size to that of patient not.

Table 3: Tells the count of diabetic patients and non diabetic from the Diabetes Dataset.

Variable	**Estimated value**
1	non diabetic count is 500
1	Diabetic count is 268

To calculate the percentage of data

Table 4: Tells the percentage count of patient diagnosed with diabetes and patient not

Outcome	**Prediction**	**value_count**	**%**
0	Non Diabetic	0.651042	65%
1	Diabetic	0.348958	34%

It is easy to see that there is no single feature that has a very high correlation with our outcome value.Some of the features have a negative correlation with the outcome value and some have positive.

10 Conclusion

This paper focuses on the methodology of multiple-instance learning to detect diabetes accurately and precisely. Apart from this, the X variable and Y variable Relationship

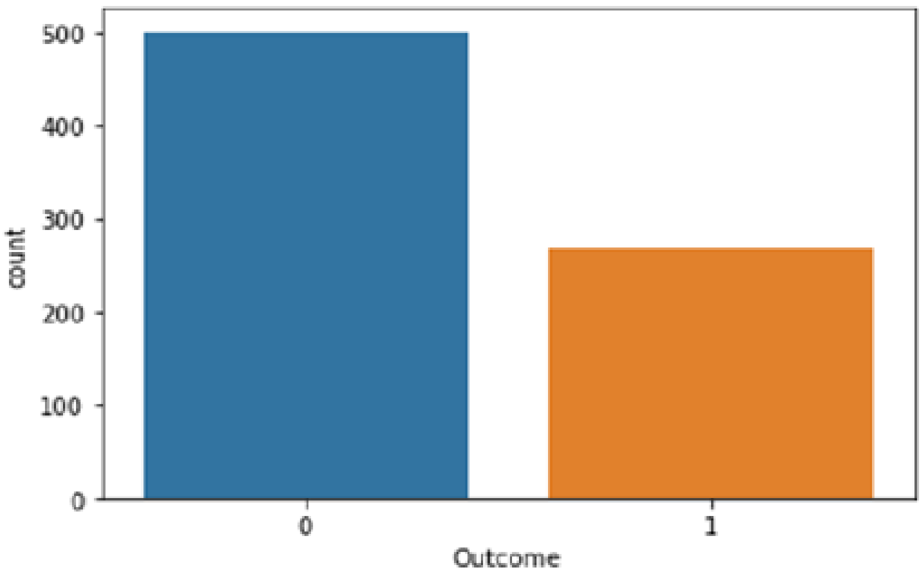

Figure 4: Visualization Graph(using Seaborn library) shows the Target Variable –'Outcome' where the number of diabetes patient are almost half of the non – diabetic ones

(x = diabetes_dataset[['Pregnancies', 'Glucose', 'Blood_Pressure', 'Skin_Thickness' 'Insulin', 'BMI', 'Diabetes_PedigreeFunction', 'Age']] y = diabetes_ dataset [['Outcome']]) has been used.Multiple Instance Learning & Boosting Algorithms have been successfully used as an early detection system for diabetes disease using PIMA Indian Diabetes dataset. Implementation results determine the adequacy of the designed system with an achieved accuracy of 79%. Early-stage diabetes risk prediction dataset was used, including a count of 768 (268 with diabetes and 500 without diabetes). Visualization Graph shows the Target Variable in which the data is biased towards data points having outcome value as 0 where it means that diabetes was not present. It shows that there are there is one main feature that can be used for prediction further that is 'Glucose' for the PIMA Indian Diabetes Dataset

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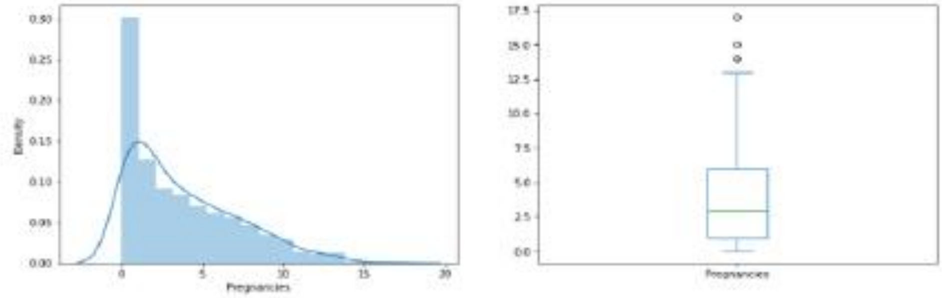

Figure 5: The Graph shows the Histogram (a) and Box plot(b) has many outliers and long lag where many values are present and a median =2.5

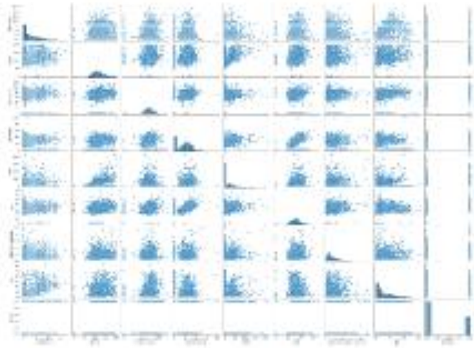

Figure 6: represent the pair plot for each Variable showing a relationship metric .Doctors uses this analysis for medical diagnosis based on slopes measured for all 7 features undertaken.

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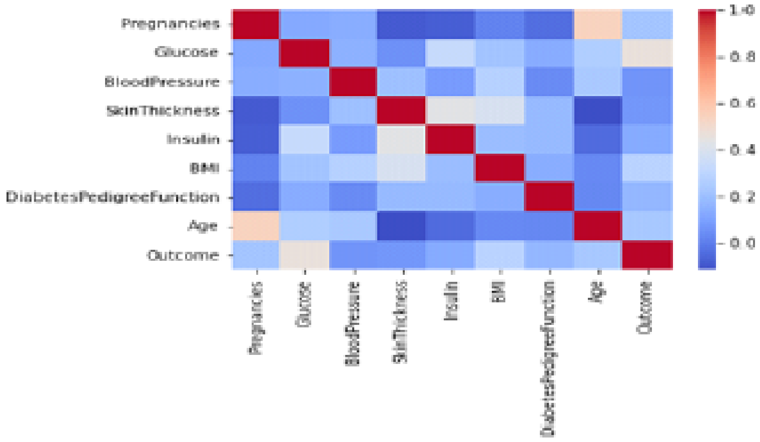

Figure 7: shows the correlation matrix where skin_thickness , insulin has positive correlation with pregnancies whereas Age has negative correlation with pregnancies

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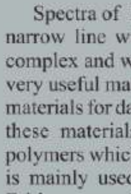
Absorption Spectra of Neodymium and Erbium Complexes

Spectra of Rare earth complexes are highly significant because of narrow line width of these elements, its internal structure is quite complex and weak crystal field interactions makes the rare-earth ion, very useful materials in laser action. Their Laser properties are useful materials for data storage, amplifiers and in solid-state lasers. Recently these materials are replacement of new photonics materials like polymers which have low cost and are better than others. Neodymium is mainly used in lasers, ceramic glasses and ceramic capacitors. Erbium, an element from heavy rare-earth plays an important application in biological sciences.

This book is a useful document for the researchers, students and policy makers who are involving in the field of rare-earth.



Dr. Deep Mala
(M.Sc., M.Phil, Ph.D & CSIR NET)

She is presently working as Associate Professor and Head in the Department of Physics, Sophia Girls' College (Autonomous), Ajmer since last 19 years. She has published many research papers in national and international journals. She has participated and presented research papers in many national and international seminar and conferences. She has delivered lectures in refresher courses. She is life member of IAPT.

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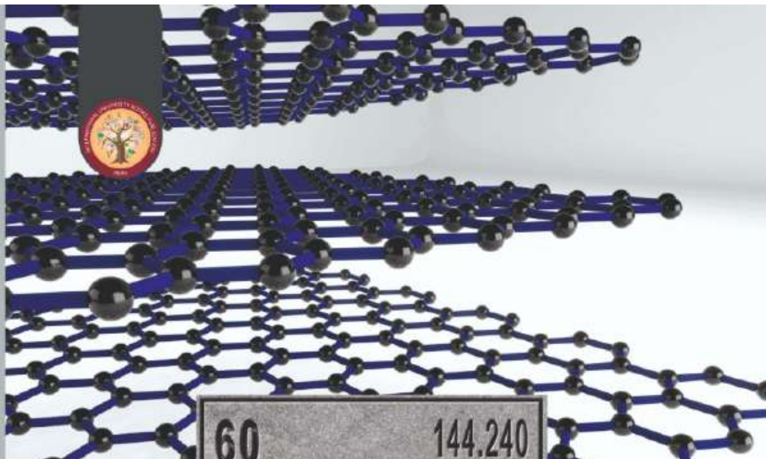
Absorption Spectra of Neodymium and Erbium Complexes

Dr. Deep Mala



Absorption Spectra of Neodymium and Erbium Complexes

Dr. Deep Mala

Birds are vital indicators of environmental health, encapsulated by Birdlife International's motto: "Save the Birds; if birds die, we all die." Their widespread presence makes them key measures of ecological well-being. The Indian subcontinent, particularly Rajasthan's arid wetlands, offers a unique opportunity to monitor habitat health. These wetlands, including those in the Thar Desert and Aravalli mountains, attract tourists but lack detailed data on bird abundance and habitat relationships. A study in Ajmer's central Aravalli foothills documented 76 bird species across five wetlands, highlighting their importance for resident, migratory, and passage birds. The study found that seasonal water level changes create dynamic habitats, supporting diverse bird populations year-round. However, threats from agriculture and urbanization jeopardize these ecosystems. Sustainable management and community involvement are essential to conserving avifaunal diversity and maintaining ecological integrity in these vital wetlands.

Mriganka Upadhyay
Vivek Sharma

Avifauna of Satellite Wetlands of Central Aravalli, Ajmer, Rajasthan

Mriganka Upadhyay
Associate Professor and Head, Department of Zoology, Sophia Girls' College (Autonomous), Ajmer, Rajasthan

Vivek Sharma
Guest Faculty, Department of Zoology, Maharshi Dayanand Saraswati University, Ajmer

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Prediction of Anemia Using Naïve-Bayes Classification Algorithm in Machine Learning

Pearl D'Souza and Ritu Bhargava

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Prediction of Anemia Using Naïve-Bayes Classification Algorithm in Machine Learning

Pearl D'Souza and Ritu Bhargava

Abstract To make accurate forecasts, machine learning algorithms rely on past data. It makes use of statistical methods and algorithms that are trained to make classifications or predictions. Consider anemia prediction in the medical machine learning domain, which is the most common hematological disease. When there aren't enough good red blood cells in the body, oxygen can't go where it needs to go. This paper aims to use a machine learning algorithm to develop an early detection of anemia in patients with low hemoglobin (HGB) counts, as well as to determine which parameters have the greatest impact. The Naïve Bayes algorithm using the multiple instance learning method is the main algorithm used in the research, and the analysis is carried out using the WEKA utility tool. This research uses a training dataset of 500 instances along with 7 fields (RBC, MCV, MCHC, TLC, PLT, HGB, and DECISION) to conduct the prediction. The real data constructed from the HGB test results collected from patients in the range set (11.6–16.6) is trained and tested by using the Naïve Bayes algorithm, which performs best with 90% accuracy in the percentage split of 66%. The WEKA experimenter proves that the Naïve Bayes algorithm gives the best performance with F-measure, sensitivity, the true positive rate (TP Rate), precision, and the lowest value in the false positive rate (FP Rate), respectively. Based on the performance chart curve for predicting anemia, it shows the highest weight, as visualized further.

Keywords WEKA · Anemia · Kaggle · HGB · LD

P. D'Souza
Principal, Sophia Girls' College (Autonomous) Ajmer, Ajmer, India

R. Bhargava (✉)
Associate Professor, Department of Computer Science, Sophia Girls' College (Autonomous) Ajmer, Ajmer, India
e-mail: ritu@sophiacollegeajmer.in

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1 Introduction

The basic tenet of machine learning is the systematic examination of data for the purpose of discovering previously unsuspected connections and patterns [1]. The machine learning process consists of three key components. Combining classification (clustering), analytical rules, and process modelling a set of output decision rules is developed through a classification analysis [2] for a certain dataset. Extracting data from a training set and transforming it into full structures enables machine learning systems or database machine learning processes to accurately identify trends in new data sets. Naïve Bayes classification algorithms are used in medical healthcare to improve the processing of medical data. Anemia is a medical condition that describes the reduction in hemoglobin or red blood cells in human blood [3]. Considering a CBC (complete blood count) test is conducted for patients in a laboratory, Anemia is affected by various features and attribute values that impact it the most. HGB (hemoglobin) count is one of them, which indicates that the low HGB (lack of enough red blood cells in the body) causes symptoms such as fatigue, headaches, dizziness, and shortness of breath [4].

In this work, the machine learning tool is used as an analysis of medical data. The machine learning tool is used for the analysis of the data and the framework that efficiently employs a number of different categorization techniques [5]. This tool processes the datasets by filtering out the irrelevant data that is not in use, and the remaining data is passed into the training and testing sets. Data mining in the medical domain, particularly in databases, involves analysing massive amounts of data to predict specific patterns of information [6].

This paper contains a set of 500 instances associated with HGB (hemoglobin) tests of patients, and the results predict anemic patients in the normal range taken (11.6–16.6), assisting doctors in providing immediate treatment [7]. The accuracy estimated using the Naïve Bayes Classification algorithm in predicting Anemia in patients turned out to be 90%, which is accurate [8]. The evaluation of data using the Naïve Bayes classifier takes 66% of the classified data as a training set and uses it to train algorithms [9]. Then it classifies the test data (34% of it) based on the decision rules found in the training set for predicting Anemia. Using 7 predictive features and the Naïve Bayes Classification algorithm computes the best prediction of Anemia using hemoglobin count (HGB) data [10].

2 Literature Work and Related Study

Pouria et al. [2]. presented the work on the Naïve Bayes Algorithm and its applications: Naïve Bayes text classification, spam filtration, and sentiment analysis with zero conditional probability estimation.

Green et al. [3] discussed an improved accuracy of 92% that was achieved in predicting whether a patient had chronic kidney disease using the Naïve Bayes. At first, eGFR was used to forecast whether or not a patient would be sick, and the resulting information helped those who were sick by suggesting which foods they should eat and which they should avoid.

Aidaroos et al. [9] used the Naïve Bayes approach to mine medical datasets from various perspectives, highlighting the main features of the dataset based on the requirements. Based on the experimental results compared to those of other approaches, it is determined that NB (Naïve Bayes) is the best approach for the majority of the used medical datasets.

Manal et al. [11] discussed Anemia type prediction based on algorithms under the data mining concept on a sample of 41 patients, with the CBC that is used to construct the results using the WEKA experimenter. The algorithms undertaken are the J48 decision tree algorithm, which further gives the best performance with an accuracy score of 93.75% and a percentage split of 60%, respectively.

Ninad et al. [12] presented work on the pre-detection of heart diseases and diabetes by providing health-related report values. In their proposed work, in order to classify the dataset, the Naïve Bayes algorithm is used to provide accurate results. With the result generated, heart diseases among the patients are predicted, leading to a successful evaluation of the ailment.

3 Objective of Work

Data Pre-Processing step.

To analyse medical data using Naïve Bayes algorithm.

To analyse and predict the accuracy of the result by forming Confusion Matrix.

Visualization of the test result obtained through the threshold curve.

3.1 *Naïve Bayes Classification Algorithm*

The Bayes theorem-based supervised learning technique is primarily employed in the context of classification issues. In text classification, when a high-dimensional training dataset is required, this approach is particularly popular because it is a probabilistic classifier, making predictions solely based on the object's probability [11]. The name Bayes Theorem has been shortened to "Bayes Rule" or "Bayes Law." Here, the conditional probability is what ultimately decides the likelihood.

The formula of Bayes' Theorem is presented as:-

$$P\ (A|B) = P\ (B|A).P\ (A)/P\ (B)$$

In this case, P (A|B) stands for the posterior probability, or the likelihood of confirming hypothesis A in light of evidence for event B.

Likelihood, denoted by P (B|A), is the probability that a hypothesis is supported by the available evidence.

Prior probability, or P (A), is the likelihood of a hypothesis before any evidence is observed.

Marginal probability, denoted by P (B), stands for evidence probability.

In this paper we have a dataset of Medical conditions and corresponding target variable as "Anemia". So using this dataset we have to decide that whether or not an individual is suffering from Anemia [12].

Naïve Bayes algorithm is one of fastest and the easiest Machine Learning Algorithms for predicting a class of a dataset [11]. It can be easily used for both Binary as well as Multi-class Classifications. For Text-classification problems it has become the most preferable choice [13].

Evaluation Metric.

3.2 *Means of Judgment*

An accurate set is one in which the values are relatively close to one another. The accuracy of a measurement set is determined by whether or not its mean is close to the actual value of the quantity being measured. Data points from repeated measurements of the same quantity are required if one wishes to measure more than two terms [13].

Accuracy = (TP + TN)/(TP + FP + TN + FN).

Precision = TP/(TP + FP).

TP = True positive,

TN = True Negative.

False positives (FP) and false negatives (FN) are the opposite of true positives and true negatives, respectively.

Where TP (True Positive) is returned if both the estimated and real values are positive, FP (False Positive) is returned if the predicted value is positive when the true value is negative, and FN (False Negative) is returned if the predicted value is negative when the true value is positive [13].

3.3 *The Matrix of Confusion*

The Naïve Bayes classifier will now be further evaluated using a confusion matrix.

It's similar to a table based on a classifier's performance in test data, also known as the "true value." It will help identify comparisons between classes (Table 1).

Table 1 Shows the confusion matrix generated based on the classifier's performance in test data, which includes the feature vectors from which classification of the data is possible

Feature vector	Target vector	<– Classified as
70	11	YES
5	84	NO

3.4 Dataset

This part will use the Kaggle dataset as an experimental material. The purpose of using this dataset is to compare the accuracy of the developed model. There are seven features in this dataset that are closely related to Anemia itself. Following are the features that are used as reference:-

- The number of erythrocytes, often known as red blood cells, is what an RBC (Red Blood Cell) count determines.
- "MCV" (Mean Corpuscular Volume) is a standard for determining the typical size of a person's red blood cells.
- To diagnose anemia, clinicians assess hemoglobin levels in the blood and utilise the mean cell hemoglobin concentration (MCHC) test.
- TLC (Total Leucocyte Count also known as White Blood Cells) measures the total number of all the leukocytes in the blood.
- PLT (Platelets) fragments of very large cells in the bone marrow called megakaryocytes which create blood clots to slow or halt bleeding and heal wound.
- HGB (Hemoglobin) test measures how much HGB the RBC contains, a protein in red blood cells that carries oxygen. Range taken for HGB is 13.1–15.5 as a standard limit for predicting the Anemia count in patients.
- DECISION/Outcome predicts the patient's condition, whether it is detected Anemia or healthy (Tables 2, 3, 4, 5, 6, 7 and 8).

Table 2 Represents the RBC (Red Blood Cell) statistical data by calculating its mean, standard deviation, weighted sum and precision value respectively using Naïve Bayes Classifier

RBC		
Mean	3.7261	4.6429
Std. dev.	0.7583	0.6303
Weight sum	218	281
Precision	0.0286	0.0286

Table 3 Represents the MCV (Mean Corpuscular Volume) statistical data by calculating its mean, standard deviation, weighted sum and precision value respectively

MCV		
Mean	86.1835	88.7075
Std. dev.	11.7825	7.0078
Weight sum	218	281
Precision	0.3437	0.3437

Table 4 Represents the MCHC (the average amount of hemoglobin in a group of red blood cells) statistical data by predicting its mean, standard deviation, weighted sum and precision value respectively

MCHC		
Mean	31.308	32.3791
Std. dev.	2.921	2.5003
Weight sum	218	281
Precision	0.2634	0.2634

Table 5 Represents the TLC (Total Leucocyte Count/ White Blood Cells) statistical data by predicting its mean, standard deviation, weighted sum and precision value respectively

TLC		
Mean	9.3814	8.5111
Std. dev.	6.4148	3.768
Weight sum	218	281
Precision	0.1713	0.1713

Table 6 Represents the PLT (Platelets) statistical data by predicting its mean, standard deviation, weighted sum and precision value respectively

PLT		
Mean	231.5893	215.8174
Std. dev.	107.9867	92.0536
Weight sum	218	281
Precision	3.1401	3.1401

Table 7 Represents the HGB (Hemoglobin) statistical data by predicting its mean, standard deviation, weighted sum and precision value in the range from (13.1–15.5) respectively

HGB		
Mean	9.8422	13.2785
Std. dev.	1.4945	1.193
Weight sum	218	281
Precision	0.1855	0.1855

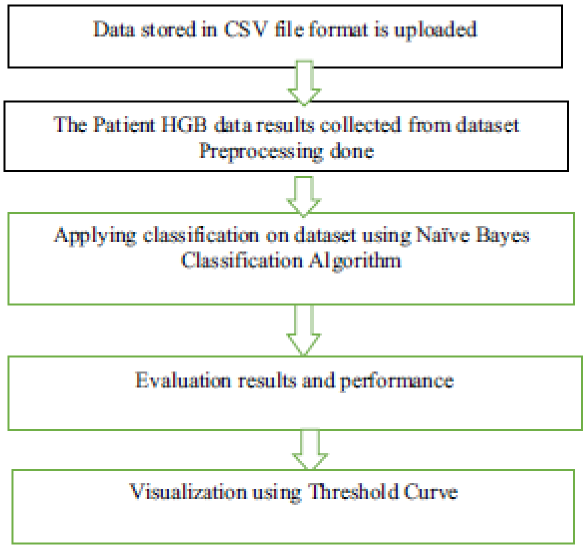
4 Methodology

In this section 7 features are considered to predict anemic patient categorized as an input. The data is analysed completely from Hemoglobin (HGB) count test results, which are conducted by collecting blood samples from 500 (instances). The data is then transformed into a standard file format CSV, which supports WEKA tool to build

Table 8 Represents the total count of Anemia patients and healthy patients in (YES/NO)

Attribute	YES	NO
	0.44	0.56

Fig. 1 Represents the flowchart of proposed model



the ANEMIA dataset filtering out irrelevant data. The HGB data contain statistical data as mean count for positive(YES) anemic patients is 9.842 on the other hand mean count for non-anemic patients is 13.278 respectively. The algorithm Naïve Bayes classifier is applied for predicting Anemia using WEKA tool in the split percentage of 66%. The implementation process involves the collection of HGB results and pre-process data to extract the values out of it. After the classification process data is visualized using the threshold curve for both (YES/NO) criteria (Fig. 1).

5 Results and Observations

The data has been analyzed and presented in the form of Graphs by using 500 instances in the dataset using Naïve Bayes, in WEKA tool with test option split (66%) data (Figs. 2, 3, 4, 5, 6, 7, 8 and 9).

Findings

See Table 9.

Recall (sensitivity) = True Positive rate/(True Positive rate + False Negative rate).

Precision = True Positive rate/(True Positive rate + False Positive rate).

F-measure = (2 * recall * precision)/(recall + precision).

In other words, the True Positive rate is the proportion of positive cases that have been accurately labelled.

Number of true positives wrongly labelled as false negatives is the False Negative Rate.

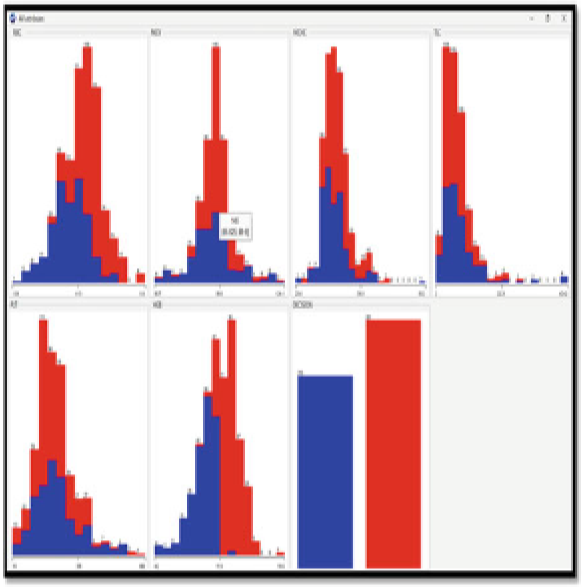


Fig. 2 Graphs generated above for each feature taken (RBC, MCV, MCHC, TLC, PLT, HGB, DECISION) represents the color code blue (probability of NO non-anemic patients) and color code red implies the probability of anemic patient (YES). Final Decision/ Outcome is plotted in histogram above (total of 281 anemic patients) and 218 non-anemic patients respectively

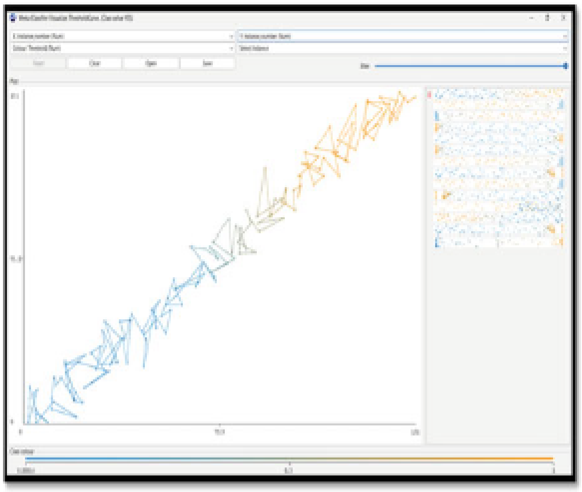


Fig. 3 Performance chart of ROC, graph shows the X-axis (Instance Num) and Y-axis (Instance Num) is represented by blue colour code for non-anemic patients and yellow colour code for anemic disease. Initially it is shown on anemic patients and after that the anemic value is shown

The number of false-positive results existing so far is known as the False Positive rate (Table 10).

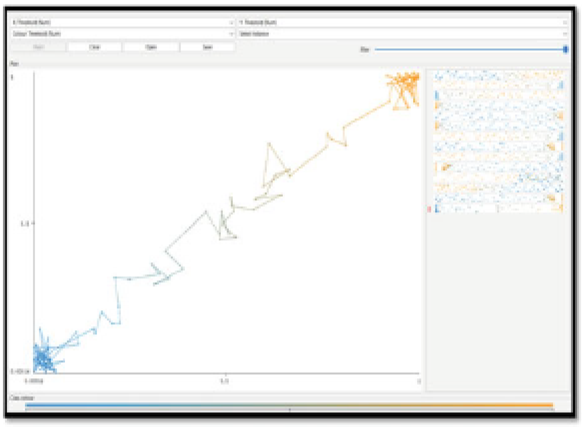


Fig. 4 Shows performance chart in the graph plotted along X-axis and Y-axis representing the threshold curve. Blue color code indicates the non-anemic patients and yellow code indicates the anemic patient. Here the threshold value is given after that both x-axis and y-axis increased sequentially which is shown in the above graph

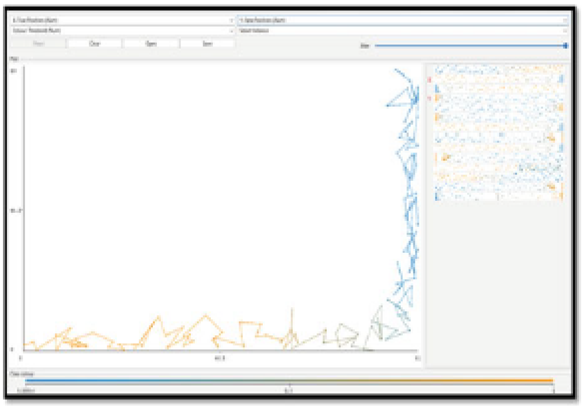


Fig. 5 Shows the graph plotted along X-axis (True Positive) value and Y-axis (False Positive) value as represented. Here TP positive rate has a similar value in the initial phase and after that value of the false positive rate it goes exponentially which is shown in the above graph

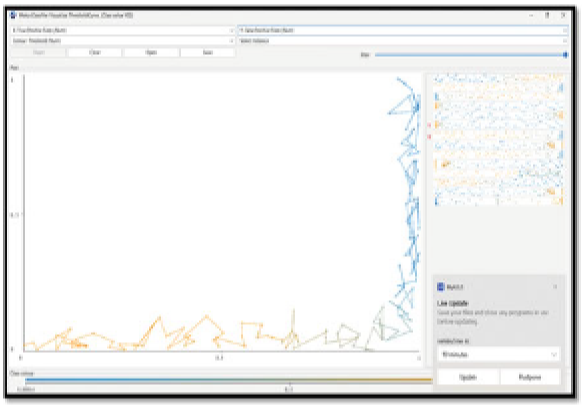


Fig. 6 Shows the graph plotted along X-axis (True Positive Rate) value and Y-axis (False Positive Rate) value represented. Here TP true positive rate go similar value in the initial phase and after that value of false positive rate is go exponentially which is shown in the above graph

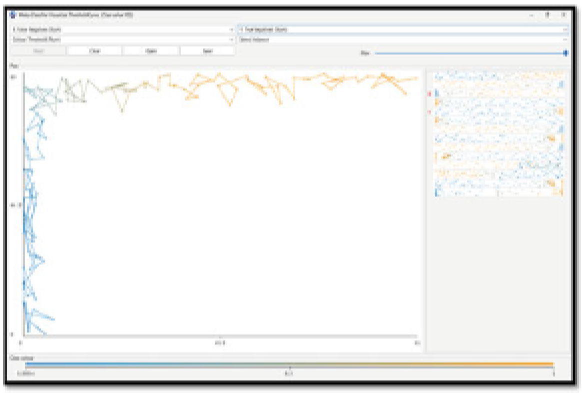


Fig. 7 Shows the graph plotted along X-axis (False Negative) value and Y-axis (True Negative) value as represented. Here in the graph the True negative value is increased initially and after that the false negative value goes sequentially which is shown in the above graph

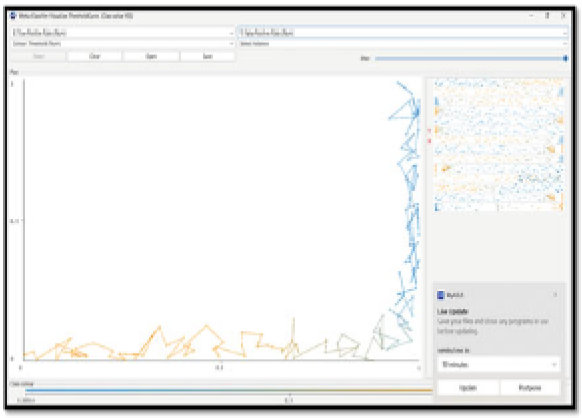


Fig. 8 Shows the graph plotted along X-axis (TP True Positive Rate) and Y-axis (False Positive Rate FP value represented. Here TP true positive rate has a similar value in the initial phase and after that value of false positive rate goes exponentially which is shown in the above graph

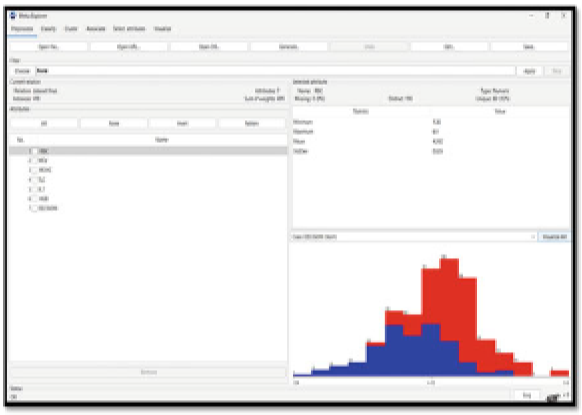


Fig. 9 Shows the Class Decision outcome obtained while taking 7 features (RBC, MCV, TLC, PLT, HGB, MCHC, DECISION) color code blue represents non-anemic patients whereas color code red represents anemic patients

Table 9 Includes the result through accuracy (correctly classified instances) by simulating the result of the algorithm using 66% training set data. Evaluation of algorithm performance recall (sensitivity), precision, F-measures, true positive rate and false positive rate

Detailed accuracy by class									
Algorithm	TP rate	FP rate	Precis ion	Recall	F-Measure e	MCC	ROC area	PRC area	Class
Naïve Bayes	0.864	0.056	0.933	0.864	0.897	0.813	0.971	0.961	YES
	0.944	0.136	0.884	0.944	0.913	0.813	0.971	0.979	NO
Weighted Avg	0.906	0.098	0.908	0.906	0.906	0.813	0.971	0.970	

Table 10 Represents Naïve Bayes algorithm output using 66% training set data accuracy score of 90%

Correctly classified instances	154	90.5882%
Incorrectly classified instances	16	9.4118%

6 Conclusion

This paper focuses on the Methodology approach of classification algorithms in order to get the best prediction of Anemia, based on a training dataset of 500 instances with 7 fields (RBC, MCV, MCHC, TLC, PLT, HGB, DECISION) considered. The dataset is constructed from the result of complete blood count HGB. The experiment is conducted on a training dataset by using Naïve Bayes Algorithm performs best with 90% accuracy in the percentage split of 66%. When using the WEKA utility tool it predicts that Naïve Bayes Algorithm gives the best performance with F-Measure, Sensitivity, The True Positive Rate (TP Rate), Precisions and the lowest value in the false positive rate (FP Rate). Based on the performance chart curve for predicting Anemia he highest weight is shown.

In Future, using more of the machine learning algorithms in order to classify all types of Anemic diseases on multiple datasets must be performed so as to find the accuracy score and interpreting the results respectively.

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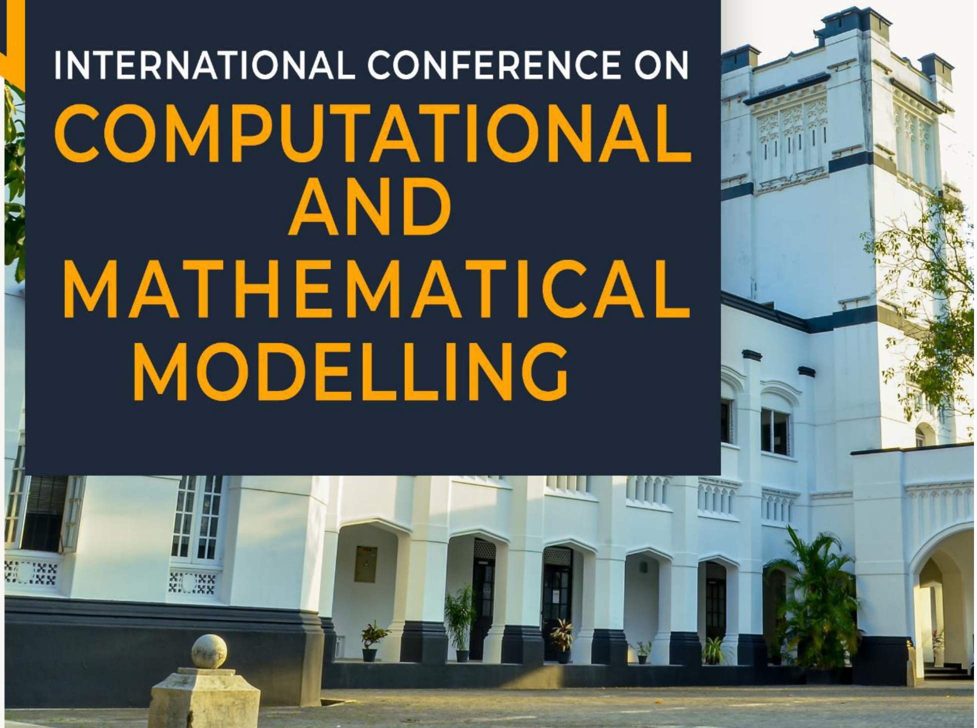

CENTRE FOR MATHEMATICAL MODELLING
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Multiple instances learning boosting diagnostically prediction of diabetes based on measurements

Ritu Bhargava [1], Sister Pearl D'Souza [2], Pramod Singh Rathore [3*], Avinash Panwar [4] and Megha Raghav [5]

[1] Department of Computer Science, Sophia Girls' College (Autonomous), Ajmer, India
[2] Principal, Sophia Girls' College (Autonomous) Ajmer
[3] Department of Computer and Communication Engineering, Manipal University Jaipur,Jaipur, India
[4] Department of Computer Science ,Mohanlal Sukhadia University - Udaipur, India
[5] Research Scholar, MDS University, Ajmer, India
* pramodrathore188@gmail.com

Abstract
This research addresses the urgent need for early diabetes detection by harnessing advanced Machine Learning techniques, specifically Linear Regression within a Multiple Instance Learning framework. Utilizing the PIMA Indian Diabetes dataset, which includes 768 cases and 8 distinct features, this study aims to robustly predict diabetes risk. The analysis, conducted using Python, focuses on key variables such as Pregnancies, Glucose, and Blood Pressure against diabetes outcomes. By enhancing predictive accuracy, this study contributes significantly to timely diabetes intervention, potentially reducing the global health burden posed by this escalating condition.

Keywords: *Multiple Instance, Boosting, XGBoost, classifiers*

1 Introduction

Diabetes is a fatal disease [1].This disease caused by damaged cause in the pancreas. The pancreas of people with diabetes cannot produce enough insulin i.e. a hormone that regulates blood sugar or glucose that the body needs [2]. Some of the consequences of diabetes include heart attacks, strokes, wounds that are difficult to heal, sexual dysfunction and many more [3]. The medical world has not found a cure for the sufferer until now. One thing that can be done is to make an early diagnosis to prevent complications in diabetes [4]. One solution to prevent someone from getting diabetes is to create an early detection system that can predict whether someone has the potential to suffer from diabetes or not, quickly, and accurately. To create diabetes detection system, the combination of MIL (Multiple Instance Learning) methods can be used [5]. Diabetic retinopathy (DR) is one of the diabetes-derived diseases and is the main cause of blindness in both developed and developing countries [6]. PIMA Indians are a Native American group that lives in Mexico and Arizona, USA [2]. By using machine learning methods, the intent is to predict the relationship of dependent factor with every other variable found from the dataset used. An unified network, namely Multiple Instance Learning with Boosting mechanism for grading the level of disease, is discussed in the paper. Multiple-Instance Learning is a type of weak supervision [7]. MIL is particularly well suited for medical data analysis. In the standard assumption, negative data are said to contain only negative instances, while positive data contain at least one positive instance. The implementation consist of independent variables plotted along the Y –axis and dependent variable (Target Variable) plotted along the X-axis [6].

2 Related work

Abiyev et. al demonstrates a novel approach to automate the detection of chest diseases using deep convolutional neural networks (CNNs). The objective of the study is to develop an accurate and efficient system that can assist medical professionals in diagnosing various chest diseases based on chest X-ray images.

Ruoxian Song proposed ADAMIL (Domain Adaptation Multi-Instance Learning) with attention mechanism for precise grading of Diabetic Retinopathy (DR) levels in retinal images. They framed weakly supervised DR grading as a multi-instance learning problem and implemented domain adaptation with attention mechanism. Labeled instances were generated through cross-domain methods to filter irrelevant instances in the target domain [8].

Ayse DOGRU and Selim BUYRUKOGLU [12] conducted a comparative study on ensemble learning (bagging and boosting) versus single-based machine learning algorithms for predicting type-2 diabetes. They used the early-stage diabetes risk prediction dataset from the UCI Machine Learning Repository, consisting of 520 instances with 17 features [9].

Rani, A. S. & Jyothi applied Machine Learning, including K-Nearest Neighbor, Logistic Regression, Decision Tree, SVM, Gradient Boosting, and Random Forest, to predict diabetes using a dataset. Random Forest demonstrated the highest accuracy among the models analyzed [9].

Kamanasish Bhattacharjee, Millie Pant & Shilpa Srivastava presented work on Evolutionary multiple instance boosting framework for weakly supervised learning .The focus is on enhancing the Multiple Instance Learning Boost framework through DE, a population-based evolutionary meta-heuristic method by optimizing mainly the weights assigned to weak classifiers [10].

Kalyankar, Gauri D., Shivananda R. Poojara, and Nagaraj V. Dharwadkar [15] explores the application of machine learning and Hadoop for analyzing diabetic patient data to make predictions related to diabetes management and outcomes. It was published by IEEE [10].

3 Terms Used

3.1 Boosting Ensemble Machine Learning (MIL)

"Boosting" is a popular and powerful tool in statistical machine learning. The basic idea behind boosting is to take a simple learning algorithm, assign equal weight to each data points and train several simple classifiers, further combine them [11]. A subset is created from the original dataset. Initially, all data points are assigned equal weights, a base model is created on this subset. This model is used to make predictions on the whole dataset. Boosting does not train the model in parallel. It tries to learn sequentially. Equal weights are initially given to all data in the training dataset. Then the weights are increased where the misclassification is made. It tries to correct the error in the previous step by creating a new model again Gradient Boosting and XGBoost (extreme Gradient Boosting) algorithms were used as boosting ensemble machine learning model [12].

3.2 Gradient Boosting

3.3 Multiple Instance Learning (MIL) Algorithm

Multiple Instance Learning [14] is a type of weakly supervised learning algorithm where training data is arranged in bags, where each bag contains a set of instances $X = \{x1, x2, \ldots\ldots\ldots\ldots Xm\}$ and there is one single label Y per bag, Y belongs to $\{0, 1\}$ in the case of a binary classification problem. It is assumed that individual labels exist for the instances within a bag, but they are unknown during training [15]. In the standard Multiple Instance assumption, a bag is considered negative if all its instances are negative. On the other hand, a bag is positive, if at least one instance in the bag is positive.$X = \{x1, x2, \ldots\ldots\ldots\ldots Xm\}$ And there is only single label Y per Bag. Y belongs to $\{0, 1\}$ Labels $y1, y2, \ldots\ldots\ldots yM$ exist for the instances within a bag, but they are unknown during training. Suppose a binary classification data $(X1, Y1)$,$(X2, Y2)$, ..., (Xn, Yn) where $Xi = \{xi1, xi2, ..., xim\}, i \in 1, 2, \ldots, n, n$ is the number of bags, m is the dimension of Xi and $Yi \in [0, 1]$.$Yi = 1$ indicates that the positive bag Xi contains at least one positive instance $xij(j = \{1, 2, \ldots, m\})$. $Yi = 0$ means that there are no positive instances in the bag Xi. The task is to identify a real-valued function $h(xij)$ to infer the instance label yij corresponding to an instance xij. This function is estimated through a weak classifier [16]. Then, through boosting, weak classifiers are combined to form a strong classifier with low error. Multiple instance learning is classified into positive instances(represented by binary value (1) and negative instances by binary value (0).

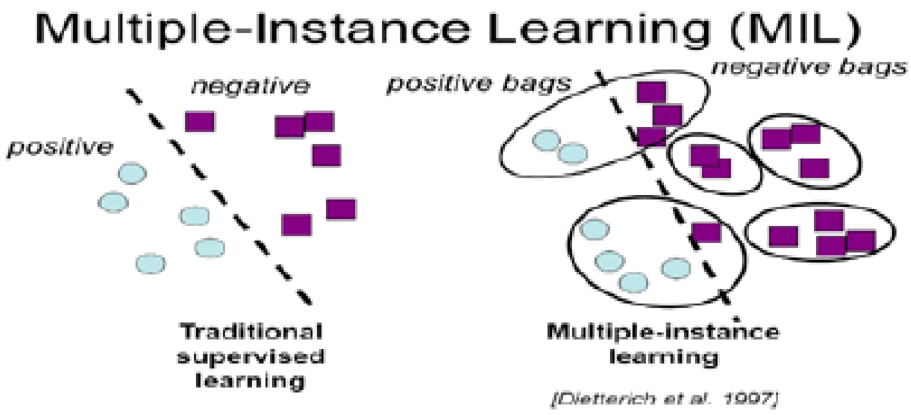

Figure 1: shows Bag Level Classification

Mulitple instance learning is classified into positive instances(represented by binary value [1] and negative instances by binary value[0] .

4 Linear Regression

Categorized further into :-

4.1 Simple Linear Regression

In which one dependent variable and one independent variable (Linear Regression

4.2 Multiple Linear Regression

In which one dependent variable and multiple independent variables (Linear Regression machine learning)

$$DerivativeEquation : Y = a + bX \tag{1}$$

Where

- Y signifies the Dependent variable
- X is an explanatory variable .
- b represents the slope of the
- line, a is the intercept(the value of y when x = 0)

4.3 Evaluation Metrics

The following evaluation metrics were used in the comparison of single base, bagging and boosting ensemble methods [8].

- Accuracy = (TP + TN)/(TP + FP + TN + FN)
- Recall = TP/(TP + FN)
- Precision =TP/(TP+FP)
- Specificity = TN/(TN+FP)
- F1 - Score = (2* Precison * Recall)/(Precision + Recall)

  where
- TP (True Positive) if the estimated value with the actual values is positive;
- FP (False Positive) if the predicted value is positive while the true value is negative;
- FN (False Negative) if the predicted value is negative while the true value is positive;
- TN (True Negative) if the estimated value with the actual value is negative [25].

4.4 Confusion Matrix

It is like table based on the performance of classifier in a test data generally known as true value. It will help for identifying comparison between classes [26].
print(confusion_matrix(Y_test, logreg_predict)

$$\begin{bmatrix} 87 & 9 \\ 23 & 35 \end{bmatrix}$$

5 Dataset

This section will use the PIMA Indian Diabetes Dataset as experimental material. This dataset is open and published by the National Institute of Diabetes and Digestive and Kidney Diseases [27]. The purpose of using this dataset is to compare the accuracy of the developed model. There are nine features in this dataset that are closely related to diabetes itself. Following are the features that are used as reference: -

1. The number of times of pregnancy
2. The amount of glucose in the blood
3. The measurement of blood pressure
4. The thickness of the skin folds on the triceps,
5. The level of insulin in the blood after 2 hours of administration of serum insulin,
6. Weight for each woman
7. Diabetes pedigree function
8. Age for each subject
9. The patient's condition, whether it is detected diabetes or healthy.

6 Tables

Table represents the first 5 rows of the dataset in which we have calculated the outcome value(0/1) in order to find out the difference between positive and negative instances of first five rows from the dataset .

Table 1: difference between positive and negative

class 'pandas.core.frame.DataFrame'
RangeIndex: 768 entries, 0 to 767
Data columns (total 9 columns):

Number	Column	Non-Null Count	Data-type
0	Pregnancies	768 non-null	int64
1	Glucose	768 non-null	int64
2	BloodPressure	768 non-null	int64
3	Skin Thickness	768 non-null	int64
4	Insulin	768 non-null	int64
5	BMI	768 non-null	float64
6	DiabetesPedigreeFunction	768 non-null	float64
7	Age	768 non-null	int64
8	Outcome	768 non-null	int64

7 Methodology

This section presents the relationship between the dependent variable (Outcome) and the independent variables which are seven in count . It consists of five process

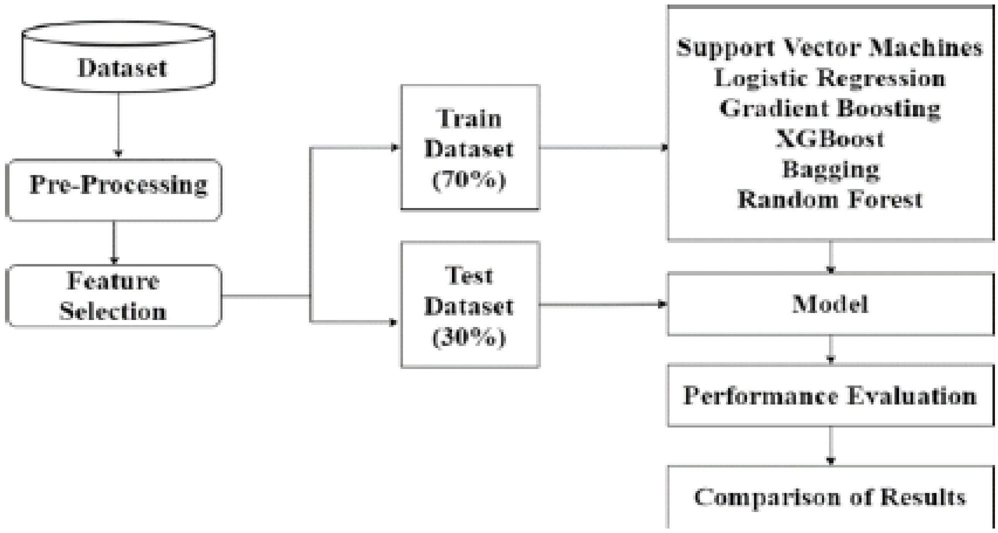

Figure 2: shows structure of diabetes prediction approach model[8]which elaborates the dataset uploaded named Diabetes dataset and then fields are selected which are passed through Train and Test dataset .Further performance analysis is done

steps: dataset, data pre-processing, feature selection, machine learning algorithms and evaluation metrics

Here , Test Size = 0.3 is taken which implies that 30% variables will go under Test Dataset(X_test, Y_test) and remaining 70% will go in Train DATASET(X_train ,Y_train).

8 Results and observations

The data has been analysed and presented in the form of Graphs Based on the results of test that have been carried out , it was found that one main Feature that is more important in diabetes data is 'Glucose'.

A number between 0 and 1 for each feature is taken, where 0 means "not used at all" and 1 means "perfectly predicts the target"so here "Glucose" is by far the most important feature. accuracy_score(Y_test, logreg_predict) 0.792207792207792

print(confusion$_{m}atrix(Y_{t}est, logreg_{p}redict)$ $\begin{bmatrix} 87 & 9 \\ 23 & 35 \end{bmatrix}$

Table 2: represent classification report predicting the precision ,Recall,f1-score and support

	Precision	Recall	F1-Score	Support
0	0.79	0.91	0.84	96
1	0.8	0.6	0.69	58
$Accuracy$			0.79	154
$macro-avg$	0.79	0.75	0.77	154
$Weighted-avg$	0.79	0.79	0.79	154

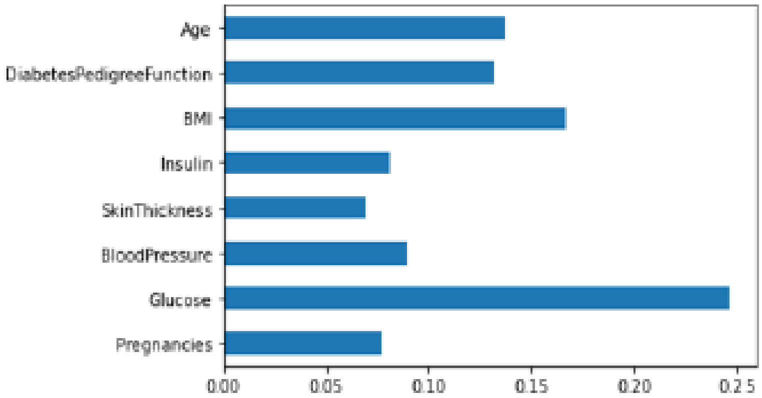

Figure 3: shows 'Feature importance rates' which depicts the feature which is highly used for predicting diabetes in an individual compared with age factor as well

9 Finding

The above graph (Figure 4) shows that the data is biased towards data points having outcome value as 0 where it means that diabetes was not present actually. The number of non-diabetics is almost twice the number of diabetic patients which concludes that Prediction values are more influenced since patient diagnosed diabetic are half in size to that of patient not.

Table 3: Tells the count of diabetic patients and non diabetic from the Diabetes Dataset.

Variable	Estimated value
1	non diabetic count is 500
1	Diabetic count is 268

To calculate the percentage of data

Table 4: Tells the percentage count of patient diagnosed with diabetes and patient not

Outcome	Prediction	value_count	%
0	Non Diabetic	0.651042	65%
1	Diabetic	0.348958	34%

It is easy to see that there is no single feature that has a very high correlation with our outcome value.Some of the features have a negative correlation with the outcome value and some have positive.

10 Conclusion

This paper focuses on the methodology of multiple-instance learning to detect diabetes accurately and precisely. Apart from this, the X variable and Y variable Relationship

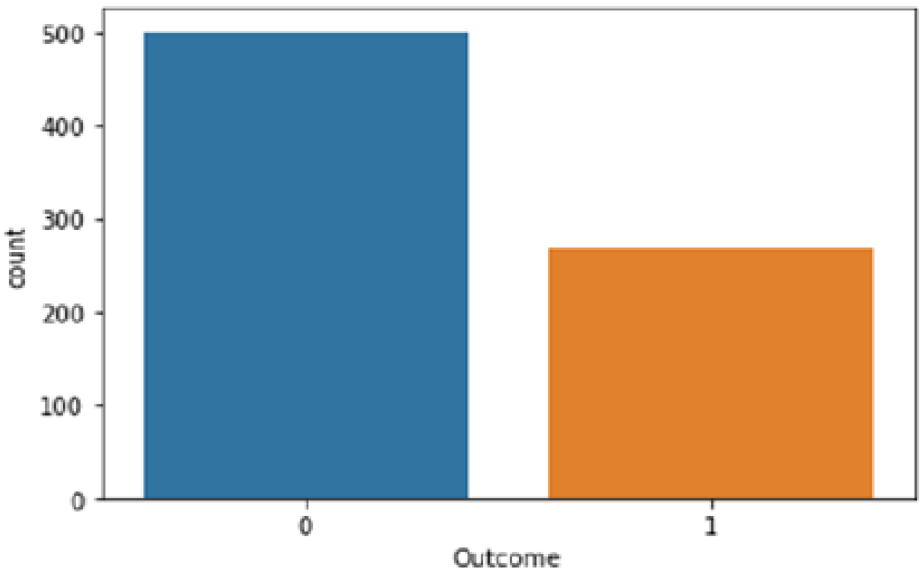

Figure 4: Visualization Graph(using Seaborn library) shows the Target Variable –'Outcome' where the number of diabetes patient are almost half of the non – diabetic ones

(x = diabetes_dataset[['Pregnancies', 'Glucose', 'Blood_Pressure', 'Skin_Thickness' 'Insulin', 'BMI', 'Diabetes_PedigreeFunction', 'Age']] y = diabetes_ dataset [['Outcome']]) has been used.Multiple Instance Learning & Boosting Algorithms have been successfully used as an early detection system for diabetes disease using PIMA Indian Diabetes dataset. Implementation results determine the adequacy of the designed system with an achieved accuracy of 79%. Early-stage diabetes risk prediction dataset was used, including a count of 768 (268 with diabetes and 500 without diabetes). Visualization Graph shows the Target Variable in which the data is biased towards data points having outcome value as 0 where it means that diabetes was not present. It shows that there are there is one main feature that can be used for prediction further that is 'Glucose' for the PIMA Indian Diabetes Dataset

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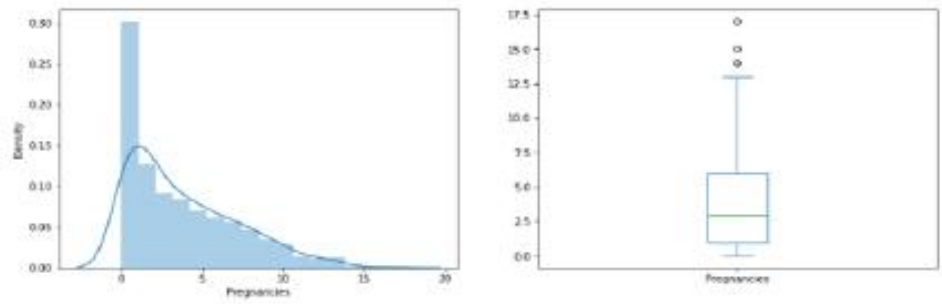

Figure 5: The Graph shows the Histogram (a) and Box plot(b) has many outliers and long lag where many values are present and a median =2.5

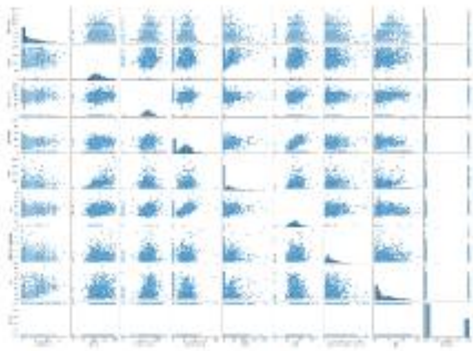

Figure 6: represent the pair plot for each Variable showing a relationship metric .Doctors uses this analysis for medical diagnosis based on slopes measured for all 7 features undertaken.

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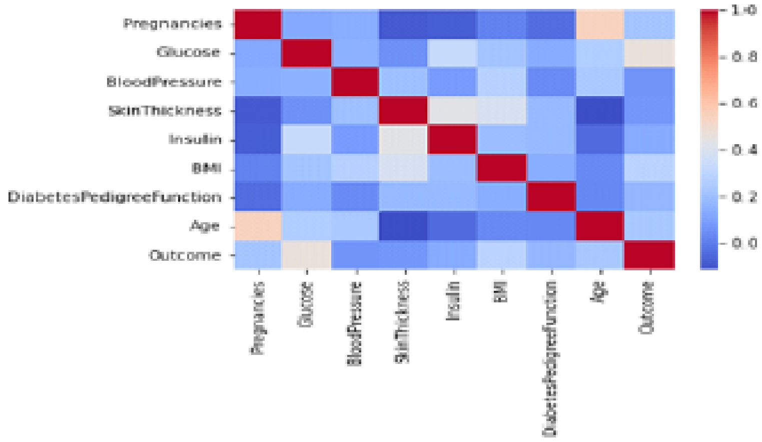

Figure 7: shows the correlation matrix where skin_thickness , insulin has positive correlation with pregnancies whereas Age has negative correlation with pregnancies

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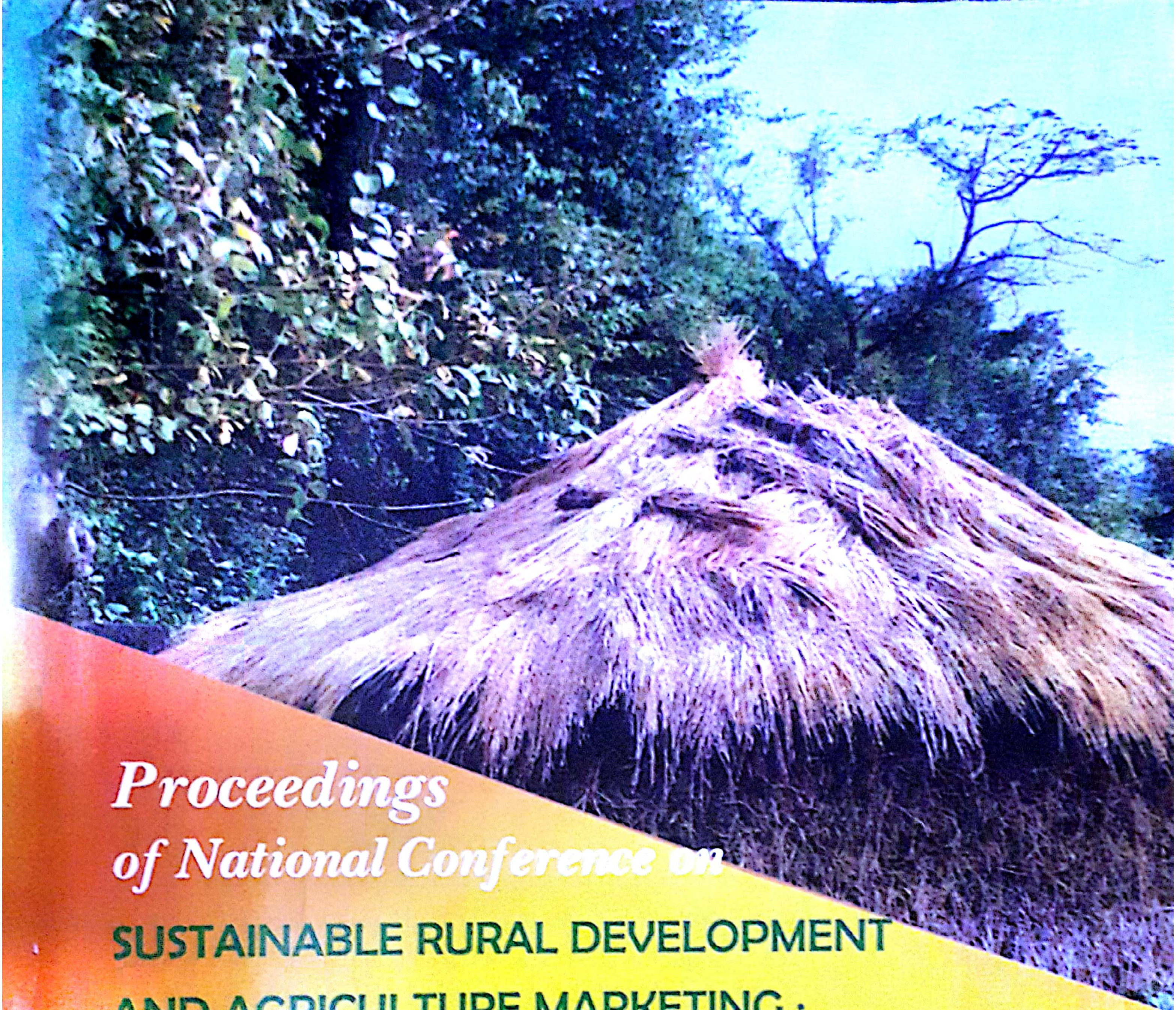

Proceedings of National Conference on

SUSTAINABLE RURAL DEVELOPMENT AND AGRICULTURE MARKETING : ISSUES AND CHALLENGES

Chief Editor
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INDEX

"Breaking Barriers: Kudumbhashree"
The Model for Rural Agricultural Development

Dr. Madhumita Hussain
Associate Professor
Sophia Girls' College, Ajmer

ABSTRACT

Exploring the pivotal role of Panchayati Raj Institutions (PRIs) in the transformation of agricultural marketing practices and its consequential impact on rural prosperity in India. As the backbone of the country's agrarian landscape, rural development holds paramount importance, and effective agricultural marketing is a cornerstone of rural economic growth. PRIs, established under the 73rd Amendment Act of the Indian Constitution, have emerged as instrumental catalysts in this process. PRIs facilitate rural development by empowering local communities to collectively address challenges related to agriculture, infrastructure, and governance.

In the context of agricultural marketing, PRIs have proven to be dynamic forces, actively involved in shaping market infrastructure, disseminating market information, and promoting innovative strategies for farmers' benefit. They promote the formation of Farmer Producer Organizations (FPOs) and encourage direct farmer-to-consumer sales, reducing dependency on middlemen and ensuring better returns for farmers.Drawing focus upon case study from Kerela state of India, This case studydemonstrates the impact of Kudumbhashree in fostering rural prosperity of Kerela.

Keywords

PRIs, Agricultural Marketing, Rural Economic Growth, Market Infrastructure, Kudumbhshree

Introduction

One of the special features of our constitution is the possibility of amendment of Act's according to the need of the hour. This feature of the constitution has led the country towards the direction of growth and prosperity, one can easily notice the change in the growth graph of the country since independence. Rural development has been a key focus of several amendments to the Indian Constitution. One the most prominent is the 73rd Amendment Act, 1992 introduced constitutional provisions for rural local self-government institutions, commonly known as Panchayati Raj institutions (PRIs). It granted constitutional status to Panchayats at the village, intermediate, and district levels and mandated reservations for Scheduled Castes (SCs), Scheduled Tribes (STs), and women in these institutions. It aimed to decentralize power and promote grassroots governance in rural areas.These amendments collectively aim to strengthen rural development and governance by promoting local self-governance, ensuring representation of marginalized groups, and facilitating the development of rural infrastructure and services. They reflect India's commitment to empowering rural communities and improving the overall quality of life in rural areas.

Rural growth is a multifaceted process encompassing economic, social, and infrastructural development in rural areas. Panchayati Raj Institutions (PRIs) serve as the cornerstone of rural development by providing a platform for decentralized governance and community participation. PRIs play a pivotal role in rural growth through their responsibilities in local governance, resource allocation, planning, and implementation of development projects. They ensure that development initiatives are tailored to local needs and priorities, empowering rural communities to actively participate in decision-making processes. PRIs also monitor project progress, promote accountability, and work towards the inclusive and sustainable development of rural regions. In essence, PRIs serve as vital catalysts for driving rural growth and enhancing the well-being of rural populations.Rural growth hinges on the transformation of rural communities into vibrant and self-sustaining entities. PRIs contribute significantly to this transformation by fostering not only economic development but also social progress. They facilitate the equitable distribution of resources, ensuring that essential services such as education, healthcare, and infrastructure reach even the remotest corners of rural areas. PRIs empower local leaders and residents to take charge of their own development, reducing dependency on centralized authorities. Through grassroots initiatives and community-driven projects, PRIs stimulate entrepreneurship, improve agricultural productivity, and enhance overall quality of life in rural settings. Thus, PRIs serve as linchpins in the pursuit of holistic rural growth, embodying the principle that sustainable development begins at the local level.

- **According to Gandhiji,** "Indian independence must begin at the bottom. Every village should be a republic or a Panchayat having full powers. The greater the power of Panchayats, the better it is for the people" (Dayal 1970, 15). To him "Swaraj" signified the vesting of the ultimate authority in the peasant and the labourer. True democracy cannot be worked from below by the people of every village.
- The Constitution 73rd (Amendment) Act, 1992 has provided a new dimension to the concept of Panchayati Raj. In other words, the concept of people's participation should be considered as an ideological commitment and, therefore, legislative and structural measures should be initiated to give legitimacy to people's participation(Vijaykumar 1999, 32-33).

GCF- Gross Capital Formation- Gross capital formation (formerly gross domestic investment) consists of outlays on additions to the fixed assets of the economy plus net changes in the level of inventories.

GCF is a crucial indicator because it reflects the level of investment in agriculture, which, in turn, can influence agricultural productivity, modernization, and overall sector growth. Higher GCF typically signifies greater potential for agricultural development and increased agriculturaloutput.

GVA – Gross Value Added- Gross Value Added is the value of goods and services produced by an industry, sector, manufacturer, area or region in an economy.

GVA is used to determine the economic contribution of agriculture to a country's Gross Domestic Product (GDP). It reflects the sector's efficiency, productivity, and profitability. Increases in GVA indicate growth and improved performance in the agricultural sector.

These are the indicators which are used in micro economics to understand the subtle level growth taking place in any field.

Below data is been taken from the National Agricultural Statistics: At a Glance 2022 to show the change in GCF and GVA.

Table:1.1 Population and Agricultural Workers

(In Million)

Year	Total Population	Average Annual Exponential Growth Rate (%)	Rural Population	Total Workers	Agricultural Workers: Cultivators	Agricultural Labourers	Total
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
1951	361.1	1.25	298.6 (82.7)	139.5	69.9 (71.9)	27.3 (28.1)	97.2 (69.7)
1961	439.2	1.96	360.3 (82.0)	188.7	99.6 (76.0)	31.5 (24.0)	131.1 (69.5)
1971	548.2	2.20	439.0 (80.1)	180.4	78.2 (62.2)	47.5 (37.8)	125.7 (69.7)
1981	683.3	2.22	525.5 (76.9)	244.6	92.5 (62.5)	55.5 (37.5)	148.0 (60.5)
1991	846.4	2.16	628.7 (74.5)	314.1	110.7 (59.7)	74.6 (40.3)	185.3 (59.0)
2001	1028.7	1.97	742.5 (72.2)	402.2	127.3 (54.4)	106.8 (45.6)	234.1 (58.2)
2011	1210.9	1.50	833.7 (68.9)	481.9	118.8 (45.1)	144.3 (54.9)	263.1 (54.6)

Source: Registrar General of India.

Notes:

1. For 2001, figures include estimated figures for those of the three sub-divisions viz. Mao Maram, Paomata and Purul of Senapati district of Manipur as census results of 2001 Census in these three sub- divisions were cancelled due to technical and administrative reasons.
2. The 1991 Census could not be held owing to disturbed conditions prevailing in Jammu & Kashmir. Hence the population figures for 1991 of Jammu & Kashmir have been worked out by 'interpolation'. The data on workers in Col. 5-7 exclude J&K.
3. The 1981 census could not be held in Assam. The figures for 1981 for Assam have been worked out by interpolation. The data on workers in Col. 5-7 exclude Assam.
4. Figures within parentheses in Col.-4 are percentages to the Total Population.
5. Figures within parentheses in Col.-6 and 7 are percentages to Col.-8.
6. Figures within parentheses in Col.-8 is percentage share of Agricultural Workers in Total Workers.

Table 1.2: Share of GCF in Agriculture and Allied Sector in GVA from Agriculture and Allied Sector

(Figures in Percentage)

Year	At Constant (2011-12) Prices: Public	Private	Total	At Current Prices: Public	Private	Total
(1)	(2)	(3)	(4)	(5)	(6)	(7)
2011-12	2.4	15.9	18.2	2.4	15.9	18.2
2012-13	2.4	14.1	16.5	2.4	14.0	16.3
2013-14	2.1	15.6	17.7	2.1	15.1	17.2
2014-15	2.3	14.7	17.0	2.3	13.6	15.9
2015-16	2.6	12.1	14.7	2.5	10.9	13.4
2016-17	2.8	12.7	15.5	2.7	11.2	13.8
2017-18	2.5	12.3	14.8	2.4	10.5	12.8
2018-19*	2.8	12.9	15.8	2.6	10.9	13.6
2019-20#	2.4	12.8	15.2	2.2	10.6	12.8
2020-21@	2.3	13.7	15.9	2.1	11.3	13.5

Source: National Statistics Office (NSO)
*:3rd Revised Estimates, #:2nd Revised Estimates, @:1st Revised Estimates

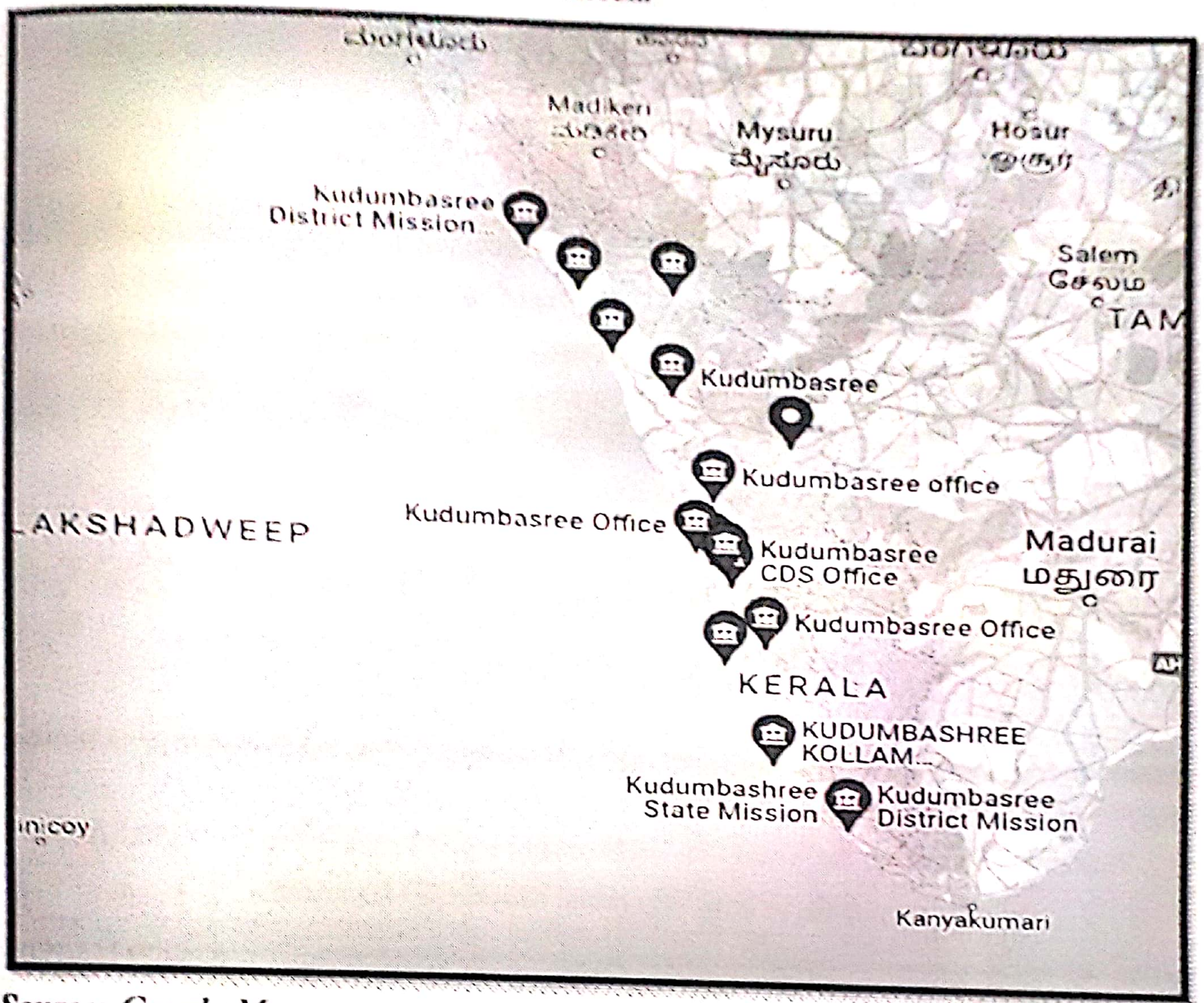
From the above tables we can notice the volume and percentage change in GCF and GVA respectively which indicates the agricultural progress in India. These achievements are not possible through central control and processings. This grassroot level change is only possible through Panchayati Raj Institutions which can act as catalysts for rural agricultural development by facilitating local decision-making, resource allocation, skill development, and market access. Local people involvement can empower rural communities to address their unique agricultural challenges and improve overall agricultural productivity and sustainability. Effective implementation and capacity-building at the PRI level are vital for the success of these initiatives.

The outstanding efforts can be seen in the state of Kerala where **KUDUMBSHREE** is an active body, came into existence in 1997.The Model was supported by the authority of Panchayat Raj Institutions (PRIs) in Kerala.

Kudumbashree's structure revolves around a three-tier network for women within the community. It starts with the Neighbourhood Groups (NHGs) at the grassroots level, followed by Area Development Societies (ADS) in the middle tier, and culminates with Community Development Societies (CDS) at the local government level. This community structure was born out of pioneering experiments conducted in Alappuzha Municipality and Malappuram during the early 1990s.The Kudumbashree community network was gradually expanded to encompass the entire state of Kerala over three phases spanning 2000 to 2002. Membership in Kudumbashree is warmly open to all adult women, with each family being entitled to one membership.

In 2011, the Ministry of Rural Development (MoRD), Government of India, embraced Kudumbashree, recognizing it as the State Rural Livelihoods Mission (SRLM) under the prestigious National Rural Livelihoods Mission (NRLM). This move marked a significant moment in the journey of Kudumbashree, emphasizing the vital role it plays in uplifting the lives of women and communities across the state. Working actively in 14 districts Thiruvananthapuram, Kollam, Pathanamthitta, Alappuzha, Kottayam, Idukki, Ernakulam, Thrissur, Palakkad, Malappuram, Kozhikode, Wayanad, Kannur, Kasarago.

Map: 1.1 Map showing the Locations of Kudumbashree Offices in 14 Districts of Kerela



Source: Google Map

Table: 1.3 Showing the JLGs, Area under Cultivation and No. of Women farmers in JLG till Oct. 2023

Data as on 20-07-2023

District	TVM	KLM	PTA	ALP	KTM	IDK	EKM	TSR	PKD	MLP	KKD	WYD	KNR	KSD	Total
Joint Liability Groups															
No. of JLGs	4667	3972	4074	5720	4069	7456	6297	7261	3518	4686	4210	8250	6783	4250	75353
Area under cultivation (Ha)	1194.3	901.67	1892.54	1684.5	1505.43	2245.27	2363.93	3049.07	1157.57	10253.8	1201.35	4025	2792.59	940	20348.94
No. of women farmers in JLG	24300	19860	20370	29452	18300	32455	26158	29627	15282	18816	18320	36250	30212	21360	375810

Table: 1.4 Showing the Medium Scale, Small Scale Value Addition Units, Agribusiness Ventures, Biopharmacy Units till oct. 2023

Medium scale Value Addition Unit															
No. of units functioning	18	7	11	1	15	2	10	52	4	15	14	7	3	5	164
No. of beneficiaries	90	38	55	5	71	8	50	260	16	65	54	35	15	25	811
Small scale Value Addition Unit															
No. of units functioning	30	42	15	64	43	29	62	106	16	31	14	17	43	23	533
No. of beneficiaries	93	108	52	255	65	58	134	194	54	76	38	32	103	83	1330
Agribusiness Ventures															
No. of units functioning	45	55	49	73	176	64	183	182	61	59	33	60	56	195	1235
No. of beneficiaries	97	156	153	3653	704	157	233	272	145	106	27	110	126	255	2322
Biopharmacy units															
No. of units functioning	9	18	8	11	12	3	18	20	7	23	10	5	15	3	142
No. of beneficiaries	17	21	12	55	15	33	33	23	35	31	24	10	26	6	296

Source: Kudumbashree | Data on Kudumbashree

Table: 1.5 Showing the Total No. of Markets Conducted, Product Sold, JLG engaged, Urban Vegetable Kiosk till Oct. 2023

Total No. of markets conducted 2022-23	907	372	2126	1336	2431	1234	1029	1738	352	1519	1183	405	767	356	6618
Kg of JLG product sold	323318	34018	316236	177334	321184	185774	192684	238063	211092.9	613180	173830	29510.75	63016	159370	1416969.3
No. of JLG engaged	3498	1739	5168	9214	2549	4529	5329	2279	1555	5711	5013	5259	6037	1281	29902
Urban Vegetable Kiosk															
No. of Unit functioning	10	0	1	4	1	2	4	6	0	10	6	4	14	4	85
No. of JLG engaged	159	0	4	1	64	0	4	235	0	48	41	113	217	0	901

Source: Kudumbashree | Data on Kudumbashree

Table: 1.6 Showing the Agribusiness Ventures, No of Units Functioning ans Beneficiaries till Oct. 2023

Agribusiness Ventures															
No. of units functioning	43	55	49	73	176	64	183	182	61	59	33	60	56	195	1235
No. of beneficiaries	97	156	153	3653	704	157	233	272	145	106	27	110	126	255	2322

Source: Kudumbashree | Data on Kudumbashree

Table: 1.7 Showing the Marketing Data and Statistics 2023-24

	Program	Number of events Establishments	Sales (in Cr)
1	Monthly Markets	352	1.27
2	Trade Fairs	73	2.36
3	Food fests	37	2.22
4	Vishu Market	905	4.32
5	Onam Markets	1085	23.09
6	Other State Saras Mela	8	0.3
7	Kudumbashree Saras Mela	1	14.95
8	Nano Markets	1115	0.44
9	Signature Store Calicut airport	1	0.13
10	Premium Basket -Metro	1	0.1
11	Marketing outlets	69	1.02
12	Pink Cafes	14	
13	Kiosks	120	0.69
14	E Commerce Portal	2017 products in Kudumbashree Portal/ 632 products in Amazon/ 42 Products in Flipkart. 135 Order in ONDC, Total 54,582 Orders	0.41
15	Kudumbashree Bazaar	11 Kudumbashree bazaar	0.54
16	Community Enterprises Fund	5 Cr disbursed to 456 Me units.	
17	Home Shops	Home shop functioning in 13 Districts. 2005 Home shop owners	6.4
19	Railway One station One Product	Kiosk Opened in 10 Stations	0.2
	Total		58.9

Source: Kudumbashree | Data on Kudumbashree

Through a multi-tiered structure, Kudumbashree has not only elevated the status of wom which has effectively contributed to bring Agribusiness from farms to markets and ultimately contributed to rural development and economic growth of Kerela state as sho in the above tables we can notice.Kudumbashree goes beyond traditional farming practic and encourages women to explore diverse agribusiness ventures. **Mahila Kis Sashakthikaran Pariyojana (MKSP)** a sub component of the National Rural Liveliho Mission (NRLM) aims at increasing the visibility of women in agriculture, reducing drudge and providing a livelihood opportunity by adopting sustainable and eco-friend agriculture.Kudumbashree, the programme implementing agency (PIA) for Kerala, h undertaken the project through the institution of Joint Liability Group (JLG) of wom farmers. The project target was kept at promoting 30,000 JLG with 1,50,000 women farme undertaking cultivation in 24,000 Ha.MKSP project focuses on capacity building of t farming community through the identification of best practices among the communit Resource persons are selected from the community and act as the grass root workers this programme. Trainings form an integral part of project aiming at providing scientif practices and solution to the door step of the farmers.It provides them with the resource training, and financial support needed to establish and manage businesses related t agriculture. These ventures encompass activities like organic farming, vegetable cultivation poultry farming, fish farming, and agro-processing units. Through these enterprises, wome not only gain economic independence but also drive rural economic development.One c the notable features of Kudumbashree is its three-tier structure, comprising Neighbourhoo Groups (NHGs), Area Development Societies (ADS), and Community Development Societie (CDS). This network enables women to collaborate, share knowledge, and access a wide market for their agricultural produce. The CDS acts as a bridge between NHGs and markets coordinating the marketing of products, ensuring fair prices, and promoting collectiv bargaining, which is crucial for small-scale farmers.

Market Linkages and Financial Inclusion

Kudumbashree recognizes that access to markets is a critical factor in the success o agribusiness ventures. The project helps women establish market linkages, provides them with marketing support, and enables them to sell their products at competitive prices Moreover, it encourages women to open their bank accounts and access financial services making them financially literate and self-reliant.The impact of Kudumbashree on women's economic empowerment and rural development is profound. It has not only improved the livelihoods of thousands of women but has also contributed significantly to the overall socio-economic development of Kerala. By empowering women to engage in agribusiness, the project has increased income levels, reduced poverty, and enhanced the social status of women in rural communities.

Conclusion

The Kudumbashree Project stands as an outstanding model for making agribusiness florish and travelled the distance from farms to markets very efficiently through empowering women. Through its multi-tiered structure, sustainable practices, and market-focused approach, Kudumbashree has not only transformed the lives of women but has also brought about positive changes in the agricultural landscape of Kerala. This project serves as an inspiration for other regions and countries looking to empower women, boost agricultural productivity, and foster rural development. Kudumbashree demonstrates that when women are given the tools and opportunities to take the lead in agribusiness, they can make a substantial impact in bringing the bounty of farms to the waiting markets, all while empowering themselves and their communities.

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Government Degree College Thindim Kreeri, India

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Dedicated to my parents and grandfather, whose courage and hard work made me a dedicated and hardworking human being.

Editorial Advisory Board

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The monitoring and classification of volatile organic compounds (VOCs) in soil and groundwater is a critical task in guaranteeing environmental protection and remediation of contaminated sites. Traditional methods of sample collection and off-site analysis could be expensive, laborious, and may not accurately represent in-situ conditions. To address these encounters, state-of-the-art sensing solutions using chemiresistor sensor technology have been developed for instantaneous, uninterrupted, and long-term monitoring of VOCs in the subsurface. The chemiresistor comprises of a chemically-sensitive polymer dissolved in a solvent and mixed with conductive carbon particles. The resultant ink is deposited onto thin-film platinum traces on a solid substrate. When VOCs come into interaction with the polymers, they are absorbed, initiating the polymers to swell and change the resistance of the electrode. This variation in resistance can be measured and recorded, providing information about the concentration of the VOCs.

Intelligent sensing and vigilant monitoring of CO2 gas is immensely significant, as the concentration of CO2 gas in atmosphere is increasing day by day due to anthropogenic activities which enhances the natural greenhouse effect and makes the earth warmer. Besides global warming, CO2 is also a toxicant in enclosed environments causing asphyxiation by hypoxia, unconsciousness almost instantaneously, and respiratory arrest within one minute. Another area where sensing of CO2 is imperative are agriculture and food industry. For these conditions, sensors should be capable of working under extreme temperatures, pressure, and interference due to the inherent complex materials and microorganisms. This chapter focuses on the information regarding the different types of CO2 sensors available with special emphasis on electrochemical sensors and optical chemical sensors, which showed fluorescent and spectrophotometric variation on detection of CO2, a detailed analysis of their detection process and sensing mechanism.

Water pollution is a global crisis impacting ecosystems, health, and economies. This chapter explores strategies to combat it, stressing advanced water quality sensors' vital role. It scrutinizes pollutants, emphasizing modern sensor tech's importance in ensuring water safety. Tackling pollution is crucial for biodiversity, human health, and clean water access. Pollutants include heavy metals, chemicals, pathogens, and sediments, requiring precise monitoring by sensors using various technologies. They offer real-time detection and response, covering chemical, biological, physical, remote sensing, and IoT-enabled sensors. Challenges like maintenance persist, requiring protocols and training. Collaboration and sensor tech are pivotal in ensuring cleaner water. This chapter highlights technology's role in managing water quality, emphasizing innovation for safeguarding this vital resource.

This chapter presents an overview of water pollutants and sensor technologies for monitoring them. The chapter emphasizes detection and quantification techniques while discussing chemical, physical, and biological contaminants in surface and groundwater. In addition to examining real-time monitoring advancements, this study delves into critical sensors, including spectroscopic, electrochemical, biosensor, and remote sensing technologies that are emerging, lab-on-a-chip, and nanomaterials. An analysis is conducted on the prospects of water pollutant sensors that progressively improve sensitivity, selectivity, and cost-effectiveness. This extensive evaluation enhances comprehension and resolution of water pollution issues while advocating for sustainable water management strategies that benefit ecosystems and human health.

Due to the increasing contamination and pollution of drinking water, water pollution has emerged as a major concern in recent years. Infectious illnesses spread by contaminated water have a domino effect on ecological life cycles. Early detection of water contamination allows for the implementation of appropriate solutions, therefore preventing potentially disastrous circumstances. It is important to monitor the water quality in real-time to ensure a steady supply of clean water. Improvements in sensor technology, connectivity, and the internet of things (IoT) have led to a rise in the importance of smart solutions for water pollution monitoring. This chapter presents a comprehensive overview of recent developments in the field of smart water pollution monitoring systems. An efficient and cost-effective smart water quality monitoring system that continuously checks quality indicators is proposed in this research. After running the model on three different water samples, the parameters are sent to the server in the cloud for further processing.

The quality of marine environments is influenced by a range of anthropogenic and natural hazards, which may adversely affect human health, living resources, and the general ecosystem. The most common anthropogenic wastes found in marine environments are dredged spoils, sewage, and industrial and municipal discharges. These wastes generally contain a wide range of pollutants, notably heavy metals, petroleum hydrocarbons, polycyclic aromatic hydrocarbons, and others. Real-time measurements of pollutants, toxins, and pathogens across a range of spatial scales are required to adequately monitor these hazards, manage the consequences, and to understand the processes governing their magnitude and distribution. Significant technological advancements have been made in recent years for the detection and analysis of such marine hazards. This chapter aims to review the availability and application of sensor technology for the detection of marine hazards and for observing marine ecosystem status.

Recently, much effort has been made to reach to an effective strategy for wastewater monitoring. Several pieces of evidence support the special role of biosensors in plans for the administration of water resources. Concerning this fact, there are some technical and practical limitations and complications, which should be overcome to develop more efficient and commercial applicable biosensors. To achieve this goal for the detection of a broad range of wastewater pollutants, it is necessary to design novel sensing systems with larger detection range and capability for the simultaneous detection of several compounds. Additionally, the limit of detection in the lower concentration range should be possible, and also biosensor should have long-storage stability. This chapter explores the various ways by which heavy metals can be removed from wastewater. Different biosensors are under investigation that can be used to remove different pollutants form different ecosystems. This will help to solve the problem of water pollution and will also help to reduce human health impact.

Oceans are the largest means of survival for millions of people and also the source of many life forms. Human activities have made the environmental conditions in marine habitats more dire for the last fifty years. The discharge of agricultural nutrients, heavy metals, and persistent organic pollutants (plastics, pesticides) threaten the coastal zones. Chemical compounds containing one or more radioisotope atoms are known as radiotracers, which are particularly useful for identifying and analysing pollutants as they can readily identify trace amounts of a particular radioisotope and short-lived isotope decays. It is thus important to identify such sources of contaminants by quantifying essential pollutants separately and gathering dependable information regarding their origin, movement, and ultimate destination. Nuclear and isotope techniques help in gathering such data. This book chapter gives an overview of the modern techniques available for probing the various contaminants across marine ecosystems and several drawbacks and controversies associated with the same.

Environmental pollution is becoming a major global concern, especially about new pollutants, poisonous heavy metals, and other dangerous agents. Pollutants have a profound impact on ecosystems and present serious threats to the health of both the natural world and human communities. Water is one of the most important resources on the planet, since it is required for all species' survival and well-being. Surface water in an aquatic system is referred to as an inland water environment and is divided into lentic and lotic systems. In contrast to lotic water ecosystems, which share continuous habitats through the connection of many basins in unidirectional flow within the dendritic structure of river networks, lentic water ecosystems display discontinuous habitats as aquatic matrices inside the terrestrial system. The lentic water ecology is more similar to terrestrial waters than the lentic water ecosystem, which differs greatly. Aquatic ecosystems are diverse and, despite making up just a little of the planet's surface, are essential for several reasons.

Increasing concern about levels of pollution in the aquatic environment has led to the adoption of a number of preventive measures to assist in maintaining the quality of water bodies. The development of new user-friendly, portable, and low-cost bioanalytical methods is the focus of research, and biosensors are in the forefront of these research works. Biosensors have various prospective and existing applications in the detection of contaminants in the aquatic environment by transducing a signal. Biosensors are able to detect a wide range of analytes in complex matrices and have proven a great potential in environment monitoring, clinical diagnostics and food analysis Hence, the aim of this work is to provide a description of the state of the art about the development and application of biosensors to detect contaminants in freshwater ecosystems.

Environmental monitoring is essential to safeguard our planet's ecosystems, public health, and natural resources. Biosensors have emerged as powerful tools for assessing environmental parameters due to their sensitivity, specificity, and versatility. From the detection of pollutants to the monitoring of water and air quality, biosensors offer a wide array of applications that contribute to comprehensive environmental assessment. In this chapter, the principles, applications, and significance of biosensors in the context of environmental monitoring are explored in detail. Future prospects and challenges are discussed as well.

The present chapter elucidates progressions in the surveillance of soil pollution, with a specific emphasis on integrated systems and sensor technologies. Future trends (e.g., enhanced selectivity, regulatory adoption), deployment platforms (field-deployable, wireless networks), and sensor types (electrochemical,

as bioindicators, the varying degrees of stress that various aquatic species can withstand might provide light on the nature of a given environmental problem. Zooplankton species such as Branchionus sp., Molina sp., Keratella cochlearis, Daphnia sp., and Cyclopus sp., as well as phytoplankton species such as Euglena viridis, Oscillatoria limosa, Nitzschia palea, and Scenedesmus quadricauda, are indicators of water pollution. The goal of this study is to showcase some new plankton research that focuses on their potential and uses as bioindicators of water quality.

The expansion of urban areas, the acceleration of traffic, the acceleration of economic growth, and the excessive use of energy are all characteristics of industrialized nations that have contributed to the worsening of air pollution. The integrity of the natural world is compromised by all these elements, which have a domino effect on one another and work together to harm it. A major ecological problem is the regional effects of air pollution on various plant species. Unlike animal populations, plant populations are constantly (24/7) and directly exposed to the danger of pollution. Biochemical, physiological, morphological, and anatomical reactions are among the many ways in which these organisms take in, store, and process contaminants that land on their surfaces. This research aims to find out how two possible therapeutic plant species Catharanthus roseus L. and Ocimum sanctum L. react to different levels of air pollution (vehicular pollution) in terms of their morphology, physiology, biochemistry, and pharmacognosy.

This chapter discusses the role of whole-cell biosensors in monitoring the impact of human advancements on the environment, leading to an imbalance that threatens ecosystems. Biosensors are cost-effective devices known for their specificity, sensitivity, and portability. The advancement in biosensors includes using genetically engineered microbial cells as whole-cell biosensors. These manipulated cells respond to external stresses, making them effective tools for detecting pollutants. The stress-response mechanisms of bacterial species are harnessed for environmental monitoring. The customizable nature of whole-cell biosensors is displayed in the text, and it also discusses applications such as water contamination detection and the design of engineered bacterial cells. The chapter aims to provide a comprehensive understanding of whole-cell biosensors, their principles, and their applications in addressing environmental issues in air, water, and soil pollution.

The process of urbanization is characterized by the rapid growth and development of urban areas, and now has become a global concern with far-reaching implications for the environment and public health. This study explores the complex impact of urbanization on both the environment and human health,

Foreword

Environmental monitoring, identification, and assessment rely on various sensors capable of detecting and measuring different parameters to identify and assess various pollutants in different ecosystems. These sensors detect pollutants such as particulate matter (PM), volatile organic compounds (VOCs), carbon monoxide (CO), nitrogen dioxide (NO_2), sulfur dioxide (SO_2), and ozone (O_3) in the air. They help in assessing air pollution levels and ensuring compliance with air quality standards. Water quality sensors measure parameters such as pH, dissolved oxygen (DO), conductivity, turbidity, and various contaminants (e.g., heavy metals, pesticides, bacteria) in water bodies. They play a crucial role in monitoring the health of aquatic ecosystems, drinking water sources, and industrial discharge and even in extreme environments. Noise sensors, or sound level meters, measure the intensity of sound in the environment. They help assess noise pollution levels and identify sources of excessive noise that may impact human health and wildlife. Radiation sensors detect ionizing radiation levels in the environment, including gamma rays, X-rays, and alpha and beta particles. They are used in nuclear power plants, medical facilities, and areas affected by radioactive contamination to ensure public safety. Light sensors measure ambient light levels, including both natural and artificial light sources. They are used in applications such as monitoring light pollution, optimizing indoor lighting systems for energy efficiency, and studying plant growth. Weather sensors measure various meteorological parameters such as atmospheric pressure, wind speed and direction, rainfall, and solar radiation. They are critical for weather forecasting, climate research, and agriculture. Soil sensors measure soil moisture, temperature, pH, and nutrient levels. They are used in agriculture, environmental science, and geotechnical engineering to monitor soil health, optimize irrigation practices, and assess soil contamination. Gas sensors detect the presence and concentration of gases in the environment, including combustible gases, toxic gases, and greenhouse gases. They are used in industrial safety monitoring, indoor air quality assessment, and environmental pollution detection. These sensors are often deployed in networks or integrated into monitoring devices and systems to provide real-time data for environmental assessment and decision-making. Advances in sensor technology, including miniaturization, wireless connectivity, and data analytics, are continually improving their accuracy, reliability, and applicability in environmental monitoring efforts. The book presents amalgam of 22 chapters on different sensors that will revolutionize environmental research and provide a roadmap for tackling pollution head-on. This comprehensive guide is poised to make a significant impact on scholars, environmentalists, planners, researchers, industrialists, and academics globally. By delving into the diverse realms of environmental sensors, the book equips readers with the knowledge and tools necessary to identify pollutants in varied ecosystems and adopt sustainable approaches for clean-up. Its recommended topics cover critical areas such as air pollution, noise pollution, waste management, advancements in sensor technology, and the detection of pollutants in soil, water, air, and oceans that will solve different problems of environmental contamination that were previously unsolved.

Ebru Kafkas
University of Çukurova, Adana, Turkey

Preface

Sensors for Environmental Monitoring, Identification, and Assessment, curated by Khursheed Ahmad Wani, delves into the pressing issue of environmental contamination that continues to challenge our ecosystems worldwide. As editor, it is my privilege to present this comprehensive reference book that addresses the urgent need for effective environmental monitoring and assessment tools.

In our modern era, the proliferation of air, water, and soil contaminants has reached alarming levels, posing significant threats to both environmental equilibrium and human health. Despite numerous attempts by scholars to mitigate these issues, we find ourselves still in the nascent stages of understanding and combating environmental pollutants. Many researchers grapple with identifying the types of pollutants and assessing their impact on ecosystems, underscoring the crucial role of environmental sensors in this endeavor.

This book serves as a beacon of knowledge, illuminating the path for researchers, environmentalists, planners, industrialists, and academics from diverse fields. By exploring a myriad of sensor technologies, ranging from chemical sensors to hyperspectral imaging, it equips readers with the tools necessary to detect and address environmental contaminants across various ecosystems.

The intended audience encompasses individuals and institutions globally, spanning both developed and developing nations. From seasoned environmental experts to aspiring students in fields such as Environmental Science, Agriculture, Economics, and Nanotechnology, this book offers valuable insights and practical solutions.

Throughout its pages, readers will encounter in-depth discussions on topics including the scope and validity of environmental sensors in extreme conditions, the efficacy of indoor pollution sensors, and the evolving technology of sensor development. Additionally, the book explores cutting-edge research on topics such as chemical sensor arrays, real-time detection of volatile organic compounds, and the application of sensors in waste management and limnology.

By fostering collaboration and knowledge exchange, this book endeavors to inspire meaningful action towards a cleaner, healthier planet. I extend my gratitude to the contributors whose expertise and dedication have enriched this compilation. It is my hope that this book will serve as a catalyst for transformative research and contribute to the collective effort of safeguarding our environment for generations to come.

Organization of the Book

Chapter 1 focuses on recent developments in sensor technology and their potential to revolutionize environmental monitoring, identification, and assessment. The chapter examines the evolving role of sensors in various fields, including safety, pollution control, medical engineering, and more. It emphasizes the importance of real-time data collection and analysis for understanding environmental conditions and making informed decisions to protect the environment.

In Chapter 2, the paramount significance and intricate challenges associated with this critical environmental and public health concern are explored. Focusing on the mission to improve air quality, the chapter underscores the profound impact of poor air quality on human health, particularly in densely populated urban areas. Emphasis is placed on safeguarding ecosystems and biodiversity through the reduction of air pollution, acknowledging its widespread ecological implications. The chapter delves into international and national regulations and initiatives, such as the Clean Air Act and the Paris Agreement, representing concerted global efforts to combat air pollution and address climate change. A detailed examination of concerns related to various air pollutants, including Particulate Matter, gases like NO_2 and SO_2, and airborne toxic substances, sheds light on the health risks and environmental consequences.

Chapter 3 describes chemiresistor sensor technology that have been developed for instantaneous, uninterrupted, and long-term monitoring of VOCs in the subsurface. The chemiresistor comprises of a chemically-sensitive polymer dissolved in a solvent and mixed with conductive carbon particles. The resultant ink is deposited onto thin-film platinum traces on a solid substrate. When VOCs come into interaction with the polymers, they are absorbed, initiating the polymers to swell and change the resistance of the electrode. This variation in resistance can be measured and recorded, providing information about the concentration of the VOCs.

Chapter 4 focuses on optical and electrochemical chemosensors for the identification of carbon dioxide gas. The chapter emphasizes the importance of intelligent sensing and monitoring of CO_2 gas due to its increasing concentration in the atmosphere and its harmful effects on the environment and human health. Various types of CO_2 sensors, including electrochemical and optical sensors, are discussed, along with their detection processes and sensing mechanisms. The chapter aims to provide insights into the development of sensors capable of detecting CO_2 gas under extreme conditions, such as those found in agriculture, food industries, and enclosed environments.

Chapter 5 provides an overview of water pollutants and sensor technologies for monitoring them. The chapter examines detection and quantification techniques for chemical, physical, and biological contaminants in surface and groundwater. It explores advancements in real-time monitoring and critical sensor technologies, including spectroscopic, electrochemical, biosensor, and remote sensing technologies. The chapter emphasizes the importance of improving sensor sensitivity, selectivity, and cost-effectiveness to address water pollution issues and promote sustainable water management strategies.

Chapter 6 explores the increasing concern about levels of pollution in the Aquatic environment, which has led to the adoption of a number of preventive measures to assist in maintaining the quality of water bodies. The development of new user-friendly, portable and low-cost bioanalytical methods is in the focus of research and biosensors are in the forefront of these research works. Biosensors have various prospective and existing applications in the detection of contaminants in the aquatic environment by transducing a signal. Biosensors are able to detect a wide range of analytes in complex matrices and have proven a great potential in environment monitoring, clinical diagnostics and food analysis Hence, the aim of this work is to provide a description of the state of the art about the development and application of biosensors to detect contaminants in fresh water ecosystems.

Chapter 7 presents a comprehensive overview of recent developments in the field of smart water pollution monitoring systems. An efficient and cost-effective smart water quality monitoring system that continuously checks quality indicators is proposed in this research. After running the model on three different water samples, the parameters are sent to the server in the cloud for further processing. Due to the increasing contamination and pollution of drinking water, water pollution has emerged as a major concern in recent years. Infectious illnesses spread by contaminated water have a domino effect on ecological life cycles. Early detection of water contamination allows for the implementation of appropriate solutions, therefore preventing potentially disastrous circumstances. It is important to monitor the water quality in real-time to ensure a steady supply of clean water. Improvements in sensor technology, connectivity, and the Internet of Things (IoT) have led to a rise in the importance of smart solutions for water pollution monitoring.

Chapter 8 aims to review the availability and application of sensor technology for the detection of marine hazards and for observing marine ecosystem status. The quality of marine environments is influenced by a range of anthropogenic and natural hazards, which may adversely affect human health, living resources and the general ecosystem. The most common anthropogenic wastes found in marine environments are dredged spoils, sewage and industrial and municipal discharges. These wastes generally contain a wide range of pollutants notably heavy metals, petroleum hydrocarbons, polycyclic aromatic hydrocarbons and other. Real-time measurements of pollutants, toxins, and pathogens across a range of spatial scales are required to adequately monitor these hazards, manage the consequences, and to understand the processes governing their magnitude and distribution. Significant technological advancements have been made in recent years for the detection and analysis of such marine hazards.

In Chapter 9, the removal of heavy metals from wastewater using biosensors is examined. The chapter explores the role of biosensors in wastewater monitoring and highlights the technical and practical limitations that need to be addressed to develop more efficient sensing systems. Various biosensors under investigation for detecting different pollutants are discussed, with a focus on their potential to solve water pollution problems and reduce human health impacts.

Chapter 10 presents an overview of the modern techniques available for probing the various contaminants across marine ecosystems and several drawbacks and controversies associated with the same. It is thus important to identify such sources of contaminants by quantifying essential pollutants separately and gathering dependable information regarding their origin, movement, and ultimate destination. Now a day's different types of Nuclear sensors have been developed to identify pollutants in varied environments.

In Chapter 11, the focus shifts to the identification of different pollutants in lotic and lentic ecosystems using biosensors. The chapter examines the diverse pollutants threatening aquatic ecosystems and discusses the role of biosensors in detecting and monitoring these pollutants. By exploring various biosensor technologies, the chapter aims to provide insights into addressing water pollution and minimizing its impact on human health and the environment.

Chapter 12 addresses water pollution as a global crisis impacting ecosystems, health, and economies. The chapter explores strategies to combat water pollution, emphasizing the vital role of advanced water quality sensors. It examines various pollutants and discusses modern sensor technologies' importance in ensuring water safety and managing pollution. The chapter highlights collaboration and innovation as key factors in managing water quality and safeguarding this vital resource.

In Chapter 13, the principles, applications, and significance of biosensors in the context of environmental monitoring are explored in detail. Future prospects and challenges are discussed as well. Environmental monitoring is essential to safeguard our planet's ecosystems, public health, and natural resources. Biosensors have emerged as powerful tools for assessing environmental parameters due to their sensitivity, specificity, and versatility. From the detection of pollutants to the monitoring of water and air quality, biosensors offer a wide array of applications that contribute to comprehensive environmental assessment.

In Chapter 14, the focus is on the advancements in sensor technologies aimed at detecting soil pollution. The discussion delves into integrated systems and sensor technologies, exploring future trends like enhanced selectivity and regulatory adoption. The chapter emphasizes the importance of increasing sensitivity and specificity, facilitating on-site, real-time analysis, and integrating sensing with remediation strategies to effectively manage soil pollution. Collaboration among stakeholders is highlighted as crucial for successful implementation of sensor-based approaches and driving innovation in environmental monitoring and management.

Chapter 15 explores the use of sensor technologies in waste management applications. The chapter discusses various types of sensors used in waste management, from simple bin-level sensors to advanced technologies like remote sensing and IoT-based systems. It highlights the advantages of sensor-driven waste management, including improved efficiency, cost reduction, and enhanced environmental sustainability. The chapter underscores the pivotal role of sensor technologies in revolutionizing waste management practices and achieving a more sustainable future.

Chapter 16 delves into the application of environmental sensors in addressing the issue of improper disposal of sanitary pads. It discusses the pollutants associated with this problem and explores the role of environmental sensors in mitigating it. By harnessing advanced sensing technologies, the chapter aims to provide insights into the environmental impact of sanitary pad disposal and offers guidance for creating sustainable solutions to safeguard the ecosystem.

Chapter 17 centers on the use of bioindicators to assess environmental pollution, particularly in wetlands. It highlights how bioindicators offer valuable insights into the quality of an environment by measuring species' adaptability to various stresses. The chapter underscores the significance of bioindicators in detecting indirect biotic impacts of contaminants, providing a nuanced understanding of environmental problems. Various plankton species are discussed as indicators of water pollution, showcasing the potential of bioindicators to improve water resource management.

In Chapter 18, the focus shifts to the impact of air pollution on plant species, with specific attention given to *Catharanthus roseus* L. and *Ocimum sanctum* L. The chapter examines how urbanization and industrial activities contribute to air pollution, posing ecological challenges for various plant species. It explores the biochemical, physiological, morphological, and anatomical reactions of these plants to air pollutants, aiming to understand their response to different pollution levels. The research aims to shed light on how these plant species can serve as indicators of air pollution, contributing to environmental monitoring efforts.

Chapter 19 discusses the role of whole-cell biosensors in environmental monitoring, emphasizing their specificity, sensitivity, and portability. The chapter explores the use of genetically engineered microbial cells as biosensors to detect pollutants in air, water, and soil. It showcases the customizable nature of whole-cell biosensors and their applications in addressing environmental issues, offering a comprehensive understanding of their principles and functionalities.

In Chapter 20, the impact of urbanization on the environment and public health is explored, with a focus on the role of environmental sensors in monitoring and mitigating these effects. The chapter delves into various types of sensors used to assess pollution levels in urban areas, including air quality sensors, water quality sensors, noise monitors, and solid waste sensors. By integrating real-time data from these sensors, the chapter highlights how policymakers can formulate effective strategies to address environmental degradation and improve public health in urban settings.

Chapter 21 focuses on many potentially harmful chemicals, released by industries and human activities, which can contaminate water, soil, or air and further impact the extreme environments. For this aim, sensors have captivated the attention of many scientists in modern time by virtue of their eco-friendliness, cost-effectiveness, miniaturization ability, and rapidness. Environmental samples, however are very complex and unexpectedly relative to other ecosystems. Thus far, environmental sensors have been developed with greater sensitivity, simpler and more efficient detection, better environmental adaptation and etc. for pollutant detection in extreme environments.

In Chapter 22, the focus is on understanding and predicting the effects of forest fires using a comprehensive framework integrating system dynamics and remote sensing approaches. The chapter aims to develop a conceptual model to analyze the consequences of forest fires on the environment, operational sources, and economic sectors. By combining system dynamics and remote sensing technology, the chapter seeks to provide conclusive insights into forest fire management strategies.

IN CONCLUSION

As editor of this edited reference book on *Sensors for Environmental Monitoring, Identification, and Assessment,* I am honored to present a culmination of diverse perspectives, insights, and advancements in sensor technologies aimed at safeguarding our planet's ecosystems.

Throughout the chapters, esteemed contributors have delved into critical issues such as soil pollution, water quality, air pollution, waste management, and the impacts of urbanization and forest fires. They have highlighted the indispensable role of sensor technologies in detecting, monitoring, and mitigating environmental pollutants, paving the way for more effective environmental management strategies.

From the exploration of bioindicators in wetlands to the application of whole-cell biosensors for environmental monitoring, each chapter offers valuable contributions to our understanding of environmental challenges and solutions. The chapters on identifying pollutants in lotic and lentic ecosystems, removing heavy metals from wastewater, and monitoring water pollutants underscore the urgency of addressing water pollution, a global crisis impacting biodiversity and human health.

Moreover, the discussions on sensors for air pollution, sanitary pad disposal, and carbon dioxide gas detection shed light on the diverse applications of sensor technologies in tackling specific environmental issues. The chapters on waste management sensors and advancements in sensor technology highlight the transformative potential of sensor-driven approaches in revolutionizing waste management practices and enhancing environmental sustainability.

As I conclude this preface, I extend my heartfelt appreciation to all the contributors who have shared their expertise and insights, making this edited reference book a comprehensive resource for researchers, practitioners, policymakers, and students alike. I hope that the knowledge and innovations presented in this book will inspire collaboration, drive innovation, and contribute to the collective effort of safeguarding our environment for future generations.

Together, let us harness the power of sensor technologies to create a cleaner, healthier, and more sustainable planet for all.

Khursheed Ahmad Wani
University of Kashmir, India

Chapter 1
Technology of Sensors:
Ways Ahead

Surendra Prakash Gupta
https://orcid.org/0000-0002-4873-6346
Shri Vaishnav Vidhyapeeth Viswavidhayalaya, India

Ankur Bhardwaj
https://orcid.org/0000-0003-0687-8810
Shri Vaishnav Vidhyapeeth Viswavidhayalaya, India

ABSTRACT

The technology of sensors is continuously evolving to meet the demands of various fields such as safety, pollution, medical engineering, and more. Sensors play a significant role in improving human working styles and routine tasks by converting real-world actions into electrical signals. They can be used to measure a wide range of environmental parameters, including air quality, water quality, soil quality, noise levels, and weather conditions. Sensors can be used to monitor environmental conditions in real time, or they can be used to collect data over time to identify trends and patterns. Sensor data can also be used to create models of environmental systems, which can be used to predict future conditions and assess the impact of human activities. This chapter is focused on the recent development in sensor technology that has the potential to revolutionize environmental monitoring, identification, and assessment. By providing real-time data on environmental conditions, sensors can help us to better understand our environment and make informed decisions about how to protect it.

INTRODUCTION

In recent years, there has been significant progress in sensor technology, with a focus on wearable sensing devices. A key advancement is the integration of ambient light sensors into LCD displays using advanced fabrication techniques and sensor structures like amorphous silicon and low-temperature polycrystalline silicon. These sensors are valuable for data collection and processing. However, a challenge lies in optimizing sensor coverage while minimizing costs and energy usage. This involves designing sensors

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effectively and ensuring efficient data transfer between them. Different strategies such as solving complex optimization problems and using weighted criteria convolution have been suggested. Mathematical models and IT systems have been developed to control sensor coverage radius for optimal results.

In the field of environmental monitoring and analysis, sensor-based technology is essential. It permits real-time data gathering from multiple sources, including wireless sensor networks (WSNs) (Dai et al., 2021) and the fusion of data from multiple sensors (Yin, 2022). The quality of the air can be monitored thanks to these technologies (Yuan et al., 2022), landscape patterns, and indoor environment quality (IEQ) (Liu et al., 2021). They additionally aid in the assessment of the general functioning of the building and the welfare of its occupants. This technology is used to optimize the computational efficiency of deep learning models on embedded platforms for mobile robots. It enables the autonomous positioning and navigation of autonomous guided vehicles (AGVs) in dynamic storage environments. In addition, this technology provides valuable insights into the environment, enabling effective monitoring, analysis, and decision-making processes.

SENSORS TOOLS FOR IDENTIFICATION, MONITORING, AND ASSESSMENT FOR ENVIRONMENTAL ASPECTS

Sensors and monitoring tools are essential for identifying, monitoring, and assessing various environmental aspects. In the field of underground mining, real-time monitoring and assessment of climatic conditions using sensors and Geographic Information System (GIS) tools can help identify potential hazards and create a safe working environment (Jha & Tukkaraja, 2020). In the context of pharmaceutical contamination, screen-printed voltammetric sensors offer a simple, reliable, and cost-effective method for monitoring painkiller residues in environmental water samples (Tyszczuk-Rotko et al., 2022). Green analytical chemistry emphasizes the use of bio-chemical sensors for sustainable qualitative and quantitative analysis, with examples including the use of green nanoparticles, colorimetric assays with smart phone cameras, and sensor arrays coupled with machine learning algorithms (del Valle, 2020). In coastal areas, high-resolution hydrodynamic models and remote sensing products can be used to monitor and describe the evolution of oil spills, providing valuable information for validation and operational applications. Environmental monitoring and control rely heavily on in-situ and real-time measurement techniques, which enable global earth monitoring systems, early warning systems, and automation for surface water and wastewater management.

WATER QUALITY ASSESSMENT

Numerous studies have looked into the use of sensors for measuring water quality. There are several sources of waste residue contamination of surface and subsurface waters, including the pharmaceutical industry, veterinary and agricultural practices, homes, and healthcare facilities. A portable, low-cost sensor-based system for accurate data collection and real-time water quality monitoring has drawn a lot of interest. In a prior study, wireless sensor networks were utilized to develop a real-time water quality monitoring system using turbidity, TDS, and pH sensors (Irawan et al., 2021); Mokua et al., 2021).

In addition to tiny particles and pollutants like heavy metals, microplastics, and detergents, sewage effluent is a complex mixture of water. These particles alter the surface tension of water according to the quantity of impurities present. It is helpful to have appropriate criteria for water monitoring since Sridhar and Reddy had established the connection between surface tension and water-borne contamination (Sridhar & Reddy, 1984).

AIR QUALITY

Air quality monitoring is important for assessing pollution levels and their impact on public health and wellbeing. Recent technical developments provide new solutions for smart sensors that can measure pollutants in real-time and at small scales and have attracted the interest of a broad range of environmental researchers as well as authorities and local communities (Nagendra et al., 2021) . Wireless Sensor Networks (WSNs) offer a solution by providing high-resolution data collection and analysis capabilities. These networks can detect, calculate, and gather information about pollutants, enabling assessment at high resolutions (Broday, 2017). However, sensors measurements can be affected by environmental factors and require frequent calibrations.

SENSOR-BIOLOGY INTERFACE

A sensor-biology interface refers to a device or system that connects sensors to biological entities, such as the human body or biological reaction containers, in order to collect and process data. These interfaces are designed to improve the precision and functionality of sensor data collection. They can support multiple types of sensors without the need for switches, reducing manufacturing and maintenance costs (Wang et al., 2023). The sensitivity and stretchability of sensor are the two most important parameters to assess the performance of the device. Recently, Graphenes nanoparticles (GNs) based sensor are exploited as the appealing conductive nanofillers. However, the weak interaction between GNs and polymer matrix affect the sensitivity of the strain sensor.

The sensor interface can be enhanced with the use of other composite modifications and the ultrasonic method. By making these changes, the sensor's electrical and mechanical qualities can be enhanced. A multifunctional biological electric sensor that can measure pressure, bioelectricity, and environmental parameters is one example. Additionally, a bioelectricity signal adjusting controller is included to increase the bioelectricity signal detection precision. According to McGrath et al., an additional illustration is a sensor interface device that attaches to a sensor's pin and has circuits for both detection and power supply to accommodate various sensor kinds (McGrath et al., 2014). A bioreactor sensing system additionally consists of a biological reaction container equipped with sensing apparatus for monitoring the contents of the container and monitoring interfaces. These sensor-biology interfaces are essential for transforming the electrical signals that sensors record into data that can be used for tracking and analysis.

IoT AND SENSOR IN ENVIRONMENT

Managing sensors spread in the environment can be a valuable process for a variety of applications in domains such as agriculture, smart homes, medical technology, and healthcare, where context-aware features and a smart interpretation of the surrounding environment is necessary (Kapitsaki et al., 2021).

These sensors, deployed in large-scale IoT networks, enable the collection and monitoring of data in real-world applications such as environment monitoring, transportation, urban security, smart energy management, agriculture, and health care.

Recent advances in sensor technology and wireless communications have opened up new possibilities for deploying extensive networks of sensors, significantly expanding their potential applications. These developments are particularly beneficial for environmental monitoring purposes as they enable more comprehensive and effective data collection and analysis. The Internet of Things (IoT) and sensor technology find significant applications in environmental monitoring and control. IoT systems, consisting of interconnected devices and sensors, can be used to manage various aspects of the environment such as temperature, lighting, air quality and water quality. In industrial environments, IoT sensors can monitor air and water quality and provide real-time data on pollutants and water parameters. This information can help industry take proactive measures to reduce pollution and improve air and water quality. First, IoT sensor networks coupled with edge computing (IoTEC) can significantly reduce data latency, reduce data transmission, and increase power duration, leading to cost reduction in environmental monitoring (Roostaei et al., 2023). Secondly, the concept of Green IoT (G-IoT) aims to replace current technologies, IoT and economies with greener alternatives, thereby contributing to sustainable development and a greener world (Prakash & Singh, 2023).

Thirdly, the successful monitoring and management of air quality, radiation pollution, and water pollution is made possible by the integration of IoT devices and wireless sensors with smart environment monitoring (SEM) systems. This promotes sustainable development and a healthier society. Additionally, IoT applications for smart environmental monitoring such as soil, water, and air monitoring are essential for enhancing environmental quality and tackling environmental and industrial challenges. Furthermore, using sensors, IoT systems can monitor and analyze various pollutants, like nitrogen dioxide (NO_2) and carbon monoxide (CO), to determine how they affect respiratory diseases and assist decision-making by authorities (Ramachandran, 2023).

TYPES OF SENSORS

Small sensors known as miniature sensors find use in a variety of fields, including medical, defense, and personal electronics. An A.I. powered sensors make use of artificial intelligence technology to improve their sensing performance and facilitate wise decision-making. Conversely, wireless sensors are those that don’t require wired connections to function, giving them more flexibility and making deployment simpler. Numerous energy harvesting technologies, such as those that use solar, thermal, mechanical, or chemical energy, can power these sensors. In general, the creation of miniature, A.I. powered and wireless sensors have created new avenues for sensor applications across multiple domains, providing enhanced functionality and convenience.

Our comprehension and engagement with the surroundings are being transformed by the mutually beneficial relationship between the environment and miniature sensors. Because they use thermal inspection for in-situ analysis, these sensors are regarded as non-destructive testing tools. With the help of these sensors, we can get up-to-date information on a variety of environmental parameters, including humidity, temperature, and air quality. We can use this important information to protect the environment and enhance our general well-being by making wise decisions and acting appropriately. It is essential to comprehend the analysis of microplastics (MPs) and nanoplastics (NPs) found in the environment in order to fully utilize the potential of miniaturized sensors. Because of their potential to impact both living organisms and the ecosystem in which they reside, MPs and NPs have been identified as hazardous substances. Because they can be ingested by both marine and land animals and linger in the environment for extended periods of time, they pose an ecological risk. Consuming tainted seafood along with other foods and drinks allows them to also enter the human food chain. The most important environmental issues facing the world today are the removal and identification of MPs and NPs. They are dependable, sensitive, accurate, and precise. For environmental data integrity to be guaranteed and for efficient decision-making in a variety of domains, including agriculture, urban planning, industrial monitoring, and wildlife conservation, miniaturized sensors must possess accurate and dependable performance characteristics.

In addition to having the potential to drastically alter how humans interact with our surroundings, miniature sensors have already started to revolutionize a number of industries. With the use of these sensors, farmers will be able to optimize irrigation, increase crop yield, and preserve water resources with real-time data on soil moisture. Smarter and more sustainable cities can be developed by using these sensors to monitor noise levels and air quality by urban planners. Miniaturized sensors make industrial monitoring safer for workers and less likely to cause environmental accidents by identifying and reporting hazardous conditions. Smaller spectrometers, a new breed of portable diagnostic tools, can be connected to automated data processing systems, simplifying the interpretation of the findings for non-specialist technicians. Near infrared (NIR) spectrometers are designed to enable fast, non-invasive readings and are used in the development of miniature analytical instruments. The fields of agro-food, pharmaceutical, and forensic diagnostics have all made use of miniature NIR spectrometers (Catelli et al. by 2020). Micro spectrometers have also become more portable and smaller as a result of the incorporation of nanomaterials into their design.

Additionally, by incorporating miniature sensors into wildlife conservation initiatives additionally enables the observation of animal behavior and environmental conditions, contributing to the maintenance of vulnerable species and ecosystems. These sensors' potential applications in sustainability and environmental protection will only grow as technological developments continue to improve their capabilities. The performance and adaptability of miniaturized sensors can be further enhanced by continuous research and development, as this emphasizes.

With the use of environmental sensors and artificial intelligence, AIEn Sensor is a cutting-edge technology that collects and analyzes environmental data. Among the many environmental variables that this cutting-edge system can identify are temperature, humidity, noise levels, and air quality. One of the most amazing features of the AIEnsensor is its ability to send real-time data to a centralized dashboard; by continuously monitoring these parameters, users can watch and study the environment from any location. The AIEn sensor is an invaluable resource for businesses, academic institutions, and environmental organizations due to its high degree of accessibility and connectivity. Furthermore, the AIEnsensor's design promotes sustainability by utilizing low energy consumption and recyclable materials. It can be used for extended periods of time in a variety of environmental settings due to its sturdy construction, which ensures dependability and longevity. The AIEn sensor can be used for a wide range of tasks, from monitoring urban air quality to assessing indoor environments for safety and comfort. Because of the rapid advancement of sensor technology, which continuously enhances our comprehension and response to environmental challenges, the AIEn sensor is at the forefront of innovation.

SENSORS IN ENVIRONMENT MONITORING: SIGNIFICANCE AND APPLICATIONS

Maintaining the sustainability of our natural resources and comprehending how human activity affects the environment depend on environmental monitoring. Real-time data on pollution levels, weather patterns, air and water quality, and other topics is provided by sensors, which are essential in this field. Decisions to reduce environmental risks and safeguard ecosystems can be made by scientists and policymakers with the help of this data collection and analysis. The concentration of pollutants like particulate matter, nitrogen dioxide, and ozone is measured by sensors, which are widely used in air quality monitoring. In addition to assisting in determining the health risks connected to air pollution, this data is helpful in locating the sources of pollution and developing efficient response strategies.

In the realm of water quality monitoring, sensors are deployed to measure parameters like pH, dissolved oxygen, turbidity, and nutrient levels in bodies of water. This data is vital for managing water resources, safeguarding aquatic habitats, and ensuring safe drinking water for communities. Furthermore, sensors are integral to monitoring weather and climate conditions, aiding in early detection of extreme weather events, forecasting climate trends, and assessing the impact of climate change on ecosystems. With the advancements in sensor technology, the applications of environmental monitoring continue to expand, encompassing areas such as precision agriculture, wildlife conservation, and urban planning. These developments underscore the growing significance of sensors in environmental monitoring and the need for continued research and innovation in this field.

FUTURE SCOPE OF SENSORS IN ENVIRONMENTAL MONITORING

As a vital component of environmental monitoring, sensors provide data in real time on a range of environmental parameters, including temperature, humidity, pollution levels, and the quality of the air and water. Despite the immense potential of sensors, there is ample space in the sensing field to develop quick, inexpensive sensors that have negligible to no environmental impact. Future environmental monitoring applications have a lot of promise thanks to the development of sensor technology. The integration and downsizing of sensors into wearable technology is a crucial area of future development that will enable people to track their individual exposure to environmental contaminants. This could have significant implications for public health and awareness.

Furthermore, the use of advanced data analytics and machine learning algorithms can enable the interpretation of complex environmental data collected by sensors, leading to more accurate predictions and early warning systems for natural disasters and environmental hazards. In addition, the development of low-cost, energy-efficient sensors will make it possible to deploy large-scale sensor networks for monitoring environmental parameters in remote and inaccessible locations. This could provide valuable data for conservation efforts and ecosystem management.

Moreover, new opportunities for thorough and real-time environmental monitoring on a global scale will arise from the integration of sensors with emerging technologies like the Internet of Things and remote sensing satellites. As deforestation, climate patterns, and ecosystem changes occur, a growing number of remote sensors including satellites and drones will be used in large-scale environmental monitoring programs. In general, sensors have a bright future in environmental monitoring, helping to reduce the negative effects of human activity on the environment and deepen our understanding of the natural world. Sensors raise awareness of environmental challenges as technology advances by improving our understanding and ability to solve environmental problems.

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List of Abbreviations

IoT= Internet of Things
LCD= Liquid Crystal Display
AGV= Automated guided Vehicles
IEQ=Indoor environment quality
WSN= Wireless sensor network
GIS= Geographic Information System
GNs = Graphenes nanoparticles
MP = microplastics
NP=-nanoplastics
NIR=Near infrared
SEM= smart environment monitoring

Chapter 2
Air Sensors and Their Capabilities

Prashantkumar Bharatbhai Sathvara
https://orcid.org/0000-0002-3548-5584
Nims Institute of Allied Medical Science and Technology, Jaipur, India

Anuradha Jayaraman
Nims Institute of Allied Medical Science and Technology, Jaipur, India

Sandeep Tripathi
Nims Institute of Allied Medical Science and Technology, Jaipur, India

Sanjeevi Ramakrishnan
Nims Institute of Allied Medical Science and Technology, Jaipur, India

ABSTRACT

In this comprehensive chapter on air quality, the paramount significance and intricate challenges associated with this critical environmental and public health concern are explored. Focusing on the mission to improve air quality, the chapter underscores the profound impact of poor air quality on human health, particularly in densely populated urban areas. Emphasis is placed on safeguarding ecosystems and biodiversity through the reduction of air pollution, acknowledging its widespread ecological implications. The chapter delves into international and national regulations and initiatives, such as the Clean Air Act and the Paris Agreement, representing concerted global efforts to combat air pollution and address climate change. A detailed examination of concerns related to various air pollutants, including Particulate Matter, gases like NO2 and SO2, and airborne toxic substances, sheds light on the health risks and environmental consequences.

INTRODUCTION

Air pollution has emerged as a critical global concern, posing significant threats to public health, the environment, and climate change. The primary contributors to this issue are diverse, encompassing in-

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dustrial emissions, vehicular exhaust, deforestation, and agricultural practices. These activities release a myriad of pollutants, including particulate matter, nitrogen oxides, sulfur dioxide, ozone, and volatile organic compounds, into the atmosphere (Zhang & Srinivasan, 2020). The World Health Organization estimates that millions of premature deaths occur annually worldwide due to outdoor air pollution, disproportionately impacting vulnerable populations. International collaboration has become imperative to address this global challenge. Agreements like the Paris Agreement and Sustainable Development Goals underscore the shared responsibility among nations to combat air pollution collectively. These frameworks aim to establish global targets and encourage coordinated efforts to reduce emissions and mitigate environmental impact.

In the Indian context, the nation grapples with severe air pollution challenges driven by rapid urbanization, industrial growth, and agricultural practices. Sources of pollution in India include vehicular emissions, industrial activities, agricultural burning, and household pollution. The government has responded to this crisis by initiating programs such as the National Clean Air Programme, intending to curb pollution levels in key cities through measures like stricter emission norms, promotion of public transportation, and increased green cover. However, despite these efforts, challenges persist on multiple fronts. Enforcement of regulations remains inadequate, monitoring infrastructure is insufficient, and behavioral changes necessary to reduce pollution are slow to materialize. Achieving meaningful progress in tackling air pollution demands comprehensive and sustained efforts (Dhall et al., 2021).

To address this multifaceted problem, a holistic approach is crucial. Coordinated efforts are needed, involving sustainable urban planning to reduce emissions from transportation and industrial activities. Adoption of cleaner technologies, such as renewable energy sources and cleaner industrial processes, is vital for a sustainable future. Equally important is increasing public awareness and fostering a societal shift towards environmentally conscious practices. Protecting the health and well-being of populations globally, as well as in India, necessitates a paradigm shift in how societies perceive and interact with their environment. It requires not only stringent regulations and technological advancements but also active participation and awareness at the individual and community levels (Saini et al., 2021). Air pollution is a complex global challenge that demands collaborative and concerted efforts. It requires nations to work together, share responsibilities, and implement sustainable solutions. The Indian government's initiatives are commendable, but ongoing commitment and innovation are imperative to overcome persistent challenges. Only through coordinated international and local actions can the detrimental effects of air pollution be mitigated, ensuring a healthier and sustainable future for all.

Air quality detection is a critical component in the ongoing efforts to safeguard public health and preserve the environment. Utilizing specialized sensors and monitoring technologies, this process focuses on assessing the concentration of pollutants in the air, including particulate matter, nitrogen dioxide, sulfur dioxide, ozone, and volatile organic compounds. The significance of air quality detection stems from the severe risks associated with air pollution, ranging from respiratory diseases to environmental degradation and climate change. Various monitoring technologies, such as air quality sensors, satellite-based observations, and ground-based stations, contribute to comprehensive assessments. Parameters monitored encompass particulate matter, gaseous pollutants, and meteorological conditions. Applications of air quality detection include health protection, environmental monitoring, regulatory compliance, and influencing urban planning decisions for sustainable development (Javaid, Haleem, Rab, et al., 2021). Despite advancements, challenges like standardized calibration methods and data accuracy persist. The future involves integrating emerging technologies like artificial intelligence, expanding monitoring networks, and promoting public awareness to create a healthier and more sustainable global environment.

Air Quality, Vulnerable Populations, and Asthma

Asthma, a persistent medical condition, frequently leads to heightened disease activity, some instances of which necessitate hospitalization. Air quality indicators, including PM2.5, NO2, O3, and dampness-related contaminants, exert a significant influence on both the exacerbation of asthma and its overall progression. Notably, asthmatic children allocate approximately 60% of their waking hours to school environments (Schweitzer & Zhou, 2010). A recent expansive study revealed a synergistic correlation between co-exposure to elevated endotoxin levels and PM2.5, leading to an increase in emergency room visits, particularly concerning asthma among children. Furthermore, exposure to elevated concentrations of endotoxin and NO2 demonstrated a synergistic association with an upsurge in asthma attacks. It is noteworthy that these associations persisted, even when geometric mean concentrations of PM2.5, O3, and NO2 were below the standards set by the EPA NAAQ (Sathvara et al., 2023; Spurr et al., 2014).

Indoor air quality (IAQ) plays a pivotal role in respiratory health, particularly for vulnerable populations such as children, the elderly, and individuals with pre-existing conditions like asthma. This concise research note delves into the intricate connection between IAQ and asthma, shedding light on the impact of indoor air pollutants on those most susceptible. Common indoor pollutants include particulate matter, volatile organic compounds (VOCs), mold, and allergens. These pollutants originate from various sources within homes, such as cooking, cleaning products, and inadequate ventilation. Particular attention must be paid to the impact of these pollutants on vulnerable populations, as exposure can exacerbate asthma symptoms and lead to respiratory distress (DR. SANJEEVI RAMAKRISHNAN et al., 2023; Sanjeevi et al., 2017).

Children, with their developing respiratory systems, are especially vulnerable to the effects of indoor pollutants. Early exposure can impede lung development and increase the risk of respiratory issues, making IAQ crucial for their overall well-being. The elderly are prone to respiratory issues, and poor IAQ further exacerbates these challenges. Age-related factors, coupled with prolonged exposure to indoor pollutants, contribute to respiratory complications, emphasizing the need for targeted interventions. For those with asthma, indoor air quality directly impacts their respiratory health. Triggers such as dust mites, pet dander, and mold can provoke asthma attacks. Understanding and mitigating these triggers are essential to managing asthma in affected individuals (Saini et al., 2021).

Adequate ventilation is a fundamental strategy for improving IAQ. Properly functioning ventilation systems help in reducing indoor pollutants by allowing fresh outdoor air to replace the contaminated indoor air. Air purifiers equipped with HEPA filters can effectively remove particulate matter and allergens, providing a supplementary measure to enhance IAQ. However, choosing the right type of purifier and ensuring regular maintenance are crucial for optimal effectiveness. Simple lifestyle adjustments, such as reducing tobacco smoke indoors, using environmentally friendly cleaning products, and proper waste management, contribute significantly to IAQ improvement. Educating individuals about these practices is vital for fostering healthier indoor environments (Ankitkumar B Rathod et al., 2023; Bearg, 2019).

In conclusion, recognizing the nexus between IAQ, vulnerable populations, and asthma is imperative for public health. The impact of indoor pollutants on children, the elderly, and individuals with asthma underscores the need for targeted interventions. Implementing ventilation improvements, utilizing air purifiers, and promoting awareness of IAQ-friendly behaviors collectively form a holistic approach to mitigate the adverse effects of indoor air pollution. As we navigate the challenges posed by indoor pollutants, prioritizing research, policy initiatives, and public awareness campaigns will be pivotal in safeguarding the respiratory health of vulnerable populations.

Common Air Pollutants That Affect IAQ

The most prevalent air pollutants impacting Indoor Air Quality (IAQ) encompass O3, CO, CO2, SO2, NO2, PM, and VOCs. Each of these pollutants possesses distinct pathophysiologic mechanisms: Resulting from a chemical reaction between NO2 and VOCs exposed to sunlight, O3 concentrations can intensify in both hot and cold environments. Emitted by chemical solvents, electric utilities, and gasoline vapors, O3 induces lung inflammation and airway constriction. Vulnerable populations, including individuals with underlying diseases, children, and the elderly, face elevated risks from O3 exposure. An odorless, colorless, and tasteless toxic gas, CO stems from various sources such as unvented fuel and gas space heaters, leaky chimneys, tobacco smoke, and combustion devices. Exposure to CO can lead to fatigue, chest pain, reduced brain function, impaired vision, and fetal death. Designated as an anthropogenic air pollutant by the EPA and IPCC, CO2 is colorless and odorless, primarily originating from occupant respiration. Elevated CO2 concentrations, as indicated by the US EPA BASE, are associated with increased prevalence of Sick Building Syndrome (SBS) symptoms (Mamun & Yuce, n.d.). A major precursor to ambient PM2.5, SO2 concentrations derive from the combustion of sulfur-containing coal, oil, and gas. Short-term exposure to SO2 can cause respiratory illnesses, airway inflammation, and toxic symptoms. Asthmatics, children, and older adults are particularly susceptible. A highly reactive gas related to ozone and PM2.5 development, NO2 primarily enters the air from fuel combustion. Similar to sulfur dioxide, NO2 causes respiratory symptoms and airway inflammation, posing higher risks for asthmatics, children, and older adults. A mixture of solid and liquid particles in the air, PM categorizes into PM10, PM2.5, and PM1.0 based on size. PM10 affects upper respiratory tracts, while PM2.5 and PM1.0 can penetrate deeper into the respiratory system and even internal organs. PM is associated with various health issues and is estimated to cause 3.3 million deaths annually worldwide. A diverse set of hazardous organic chemicals participating in atmospheric reactions, VOCs are major contributors to SBS (Ramakrishnan & Jayaraman, 2019; Singh et al., 2021). Indoor VOC concentrations, especially benzene, formaldehyde, and toluene, can surpass outdoor levels. Asthmatics, young children, and the elderly are more susceptible to the carcinogenic, irritant, and toxic effects of VOC exposure. In addition to these pollutants, indoor temperature and relative humidity significantly influence IAQ. Studies have demonstrated a linear correlation between acceptability and enthalpy of IAQ, indicating that IAQ declines with increased temperature and humidity. Temperature has a stronger linear effect on IAQ than humidity, with lower relative humidity levels considered more acceptable for IAQ performance. Understanding these mechanisms is crucial for formulating effective strategies to mitigate the impact of indoor air pollutants on human health (Abbasi et al., 2012; Parry & Hubbard, 2023).

Air Quality Sensors, Measurement Tolerances

In recent years, air quality sensor technology has emerged from several laboratories for practical application, as they can be used to support real-time, spatial, and temporal data resolution for the monitoring of air concentration levels. Additionally, more and more companies provide their own air quality sensor products. The principles of operation for the low-cost gas-phase sensors are typically based on five major components (Anwar Abdelrahman Aly et al., 2016; Chow, 1995). Studies have shown that modern air quality sensor provide useful qualitative information for scientific research, as well as for end-users. However, due to the embedded technical uncertainties and lack of cross-validation and verification, there are certain limitations when comparing them to the expensive conventional equipment.

Air quality sensors play a pivotal role in monitoring and assessing the levels of various pollutants in the atmosphere, contributing valuable data for environmental health studies and regulatory compliance. However, achieving accurate measurements demands an understanding of the inherent tolerances associated with these sensors. This discussion explores the importance of air quality sensors, their measurement tolerances, and strategies to enhance precision in environmental monitoring. Air quality sensors, commonly known as air quality monitors or detectors, are devices designed to measure the concentration of pollutants present in the air. These pollutants may include particulate matter (PM), nitrogen dioxide (NO2), ozone (O3), sulfur dioxide (SO2), carbon monoxide (CO), and volatile organic compounds (VOCs). These sensors are deployed in various settings, ranging from industrial facilities and urban areas to homes and personal devices (R. Sanjeevi et al., 2022; Ródenas García et al., 2022).

Measurement tolerances refer to the allowable range of deviation in sensor readings from the true value. Several factors contribute to the tolerances in air quality sensor measurements: Different sensor technologies, such as electrochemical, optical, and semiconductor-based sensors, have varying levels of precision. Understanding the technology used in a sensor is crucial for interpreting measurement tolerances. Regular calibration is essential to maintain accuracy. Sensor calibration involves adjusting the device to a standard reference to ensure reliable and consistent measurements. Deviations from calibrated values may contribute to measurement tolerances. Factors like temperature, humidity, and air pressure can influence sensor performance (Cheng & Lee, 2016). Manufacturers often specify operational conditions, and deviations from these conditions may affect measurement accuracy. Over time, sensors may experience wear and tear, impacting their accuracy. Regular maintenance and replacement of sensors, when necessary, help minimize measurement tolerances. Some sensors may be sensitive to multiple pollutants, leading to cross-sensitivity. Understanding and compensating for cross-sensitivity are vital for accurate measurements of specific pollutants.

To enhance precision in air quality measurements and minimize tolerances, the following strategies are recommended: Schedule routine calibration checks to ensure that sensors are aligned with reference standards, reducing measurement deviations. Source sensors from reputable manufacturers with a track record of producing accurate and reliable devices. Follow recommended maintenance procedures to extend sensor lifespan. Consider the environmental conditions where sensors are deployed. Implement corrective measures or adjustments when sensors operate outside specified conditions. Implement data validation techniques to identify and address outliers or anomalous readings. This helps ensure that reported measurements are consistent and reliable (Abbasi et al., 2013; Cheng & Lee, 2016). Maintain detailed calibration records, including calibration dates and any adjustments made. This documentation aids in identifying trends in sensor performance over time.

In conclusion, understanding the tolerances associated with air quality sensors is imperative for reliable environmental monitoring. By incorporating precision-enhancing strategies, such as regular calibration and quality assurance measures, the accuracy and reliability of air quality measurements can be significantly improved, contributing to more informed decision-making in environmental management and public health (Villa et al., 2016).

AIR SENSORS AND THEIR CAPABILITIES

Air sensors are vital devices employed to detect and measure the presence and concentration of gases or particles in the air. They serve a crucial role in various applications, encompassing environmental monitoring, industrial process control, and healthcare. These sensors enable us to safeguard human health and preserve the environment by providing valuable insights into air quality (Javaid, Haleem, Singh, et al., 2021).

Classification of Air Sensors: Air sensors can be broadly classified into two main types based on their functionality:

1. Gas Sensors:

Gas sensors are specialized devices crafted to identify and measure the levels of particular gases in the air. They play a crucial role in various applications, with common examples targeting gases like carbon monoxide (CO), nitrogen dioxide (NO2), and sulfur dioxide (SO2). These sensors are vital for detecting hazardous gas leaks, maintaining workplace and residential air safety, and monitoring air pollution levels. By providing real-time data on gas concentrations, gas sensors contribute significantly to ensuring environmental health and safety. Their applications extend from industrial settings to everyday environments, enhancing our ability to respond promptly to potential threats and create healthier living and working conditions (Nikolic et al., 2020).

2. Particle Sensors:

Particle sensors are devices designed to detect and quantify particulate matter (PM) concentrations in the air. These sensors play a critical role in monitoring air quality by measuring the presence of particles of various sizes, such as PM10, PM2.5, and PM1.0. Commonly used in environmental monitoring, industrial settings, and indoor air quality assessments, particle sensors provide valuable insights into the levels of fine and coarse particles that may pose health risks. They operate based on diverse technologies, including optical methods and laser scattering, allowing for real-time measurement of particle concentrations (Wang et al., 2015). By offering data on airborne particulates, particle sensors contribute to our understanding of pollution sources, potential health impacts, and the effectiveness of pollution control measures. This information is essential for making informed decisions to mitigate the adverse effects of particulate pollution on public health and the environment.

Air sensors Technologies employ various sensing technologies to detect and measure gases or particles. Here are some commonly used technologies:

1. Electrochemical Sensors:

Electrochemical sensors employ chemical reactions to produce electrical signals directly correlated with the concentration of the targeted gas. This technology is extensively utilized for detecting toxic and flammable gases, including carbon monoxide (CO), nitrogen dioxide (NO2), and hydrogen sulfide (H2S). The sensors typically consist of a working electrode, a reference electrode, and an electrolyte. When the target gas interacts with the working electrode, a chemical reaction occurs, leading to a flow of electrons and the creation of an electrical signal (Murthy et al., 2022). This signal is then measured and translated into a concentration value. Due to their high sensitivity, accuracy, and specificity, electrochemical sensors are crucial in various applications, such as industrial safety, environmental monitoring, and indoor air quality assessments.

2. Metal Oxide Semiconductor (MOS) Sensors:

Metal Oxide Semiconductor (MOS) sensors operate on the principle of measuring alterations in electrical resistance resulting from the interaction between a target gas and a metal oxide semiconductor material. These sensors are widely employed for their versatility in detecting various gases, encompassing carbon monoxide (CO), nitrogen dioxide (NO2), and volatile organic compounds (VOCs). When the target gas contacts the semiconductor surface, it induces a change in the conductivity of the material, leading to a measurable shift in electrical resistance (*Metal Oxide Semiconductor - an Overview | ScienceDirect Topics*, n.d.). This change is then translated into a quantifiable gas concentration. MOS sensors are known for their effectiveness, cost-efficiency, and applicability in applications such as indoor air quality monitoring and industrial safety, where detecting a diverse range of gases is essential for maintaining a safe and healthy environment.

3. Optical Sensors:

Figure 1. Electrochemical sensors
(Murthy et al., 2022)

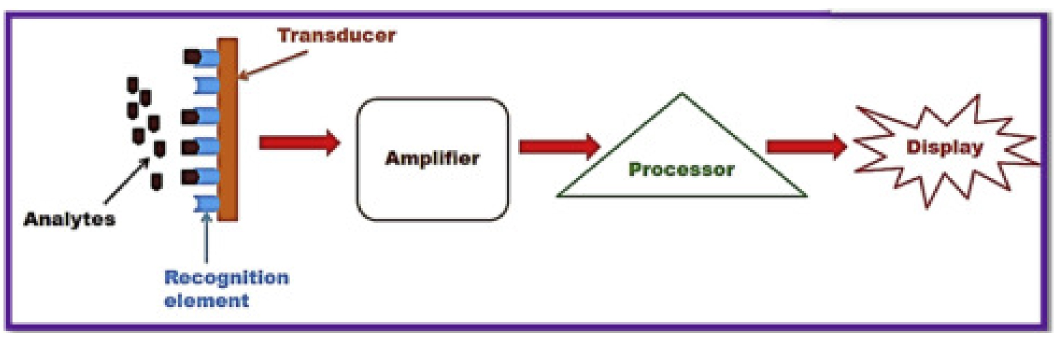
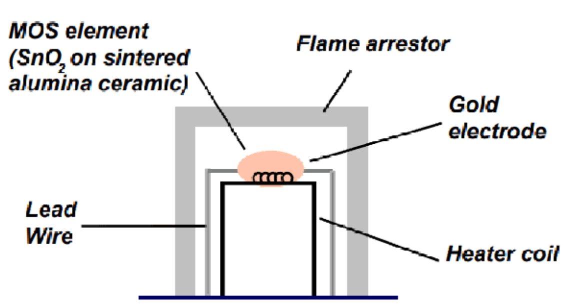


Figure 2. Metal Oxide Semiconductor (MOS) sensors
(Metal Oxide Semiconductor - an Overview | ScienceDirect Topics, n.d.)



Optical sensors harness light to gauge the concentration of gases or particles in the air, employing methods like absorption, scattering, or fluorescence. In absorption-based optical sensors, specific wavelengths of light are absorbed by target substances, and the extent of absorption is correlated with their concentration. Scattering-based sensors measure changes in the direction of light as it encounters particles, providing insights into particle concentrations. Fluorescence-based sensors utilize the emission of light by certain substances when exposed to specific wavelengths, offering a distinctive signal for identification and quantification (Agarwal, 2017; Prashantkumar B. Sathvara et al., 2023). Optical sensors are versatile, allowing for the detection and quantification of various substances, including gases and particles. Their applications range from environmental monitoring and industrial safety to medical diagnostics, showcasing their significance in obtaining accurate and reliable data about air quality and composition.

4. Light Scattering Sensors:

Light scattering sensors utilize the principle of light interaction with particles in the air to assess their size and concentration. These sensors are particularly effective in detecting and monitoring particulate matter, including PM2.5 (fine particles with a diameter of 2.5 micrometers or smaller) and PM10 (particles with a diameter of 10 micrometers or smaller). When light encounters particles, the scattering pattern provides information about particle characteristics. Light scattering sensors can differentiate between various particle sizes, aiding in the identification of fine and coarse particulate matter. These sensors play a crucial role in environmental monitoring, providing real-time data on air quality and helping to assess the potential health impacts associated with airborne particles (Chicea et al., 2021). Their application extends to indoor air quality assessments, industrial settings, and regulatory compliance for maintaining a safe and healthy atmosphere.

5. Photoionization Sensors:

Photoionization sensors employ ultraviolet (UV) light to ionize particles in the air, measuring the resulting electrical current to determine particle concentration. Particularly effective in detecting and quantifying volatile organic compounds (VOCs) and other organic vapors, these sensors operate based on the principle that UV light ionizes molecules, creating positively charged ions. The generated ions

Figure 3. Optical sensors
(Agarwal, 2017)

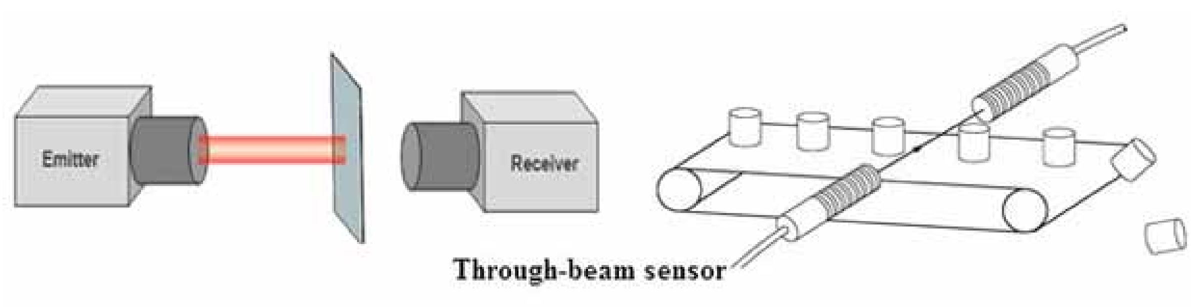
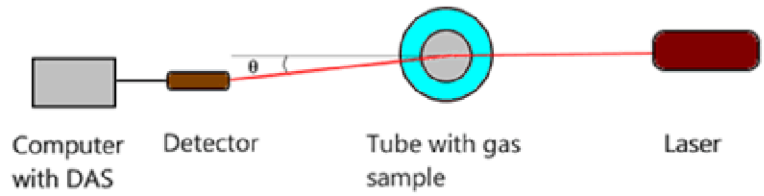


Figure 4. Light scattering sensors
(Chicea et al., 2021)



contribute to an electrical current, the magnitude of which is proportional to the concentration of the targeted particles. Photoionization sensors are widely used in applications where the detection of VOCs is crucial, such as environmental monitoring, industrial safety, and indoor air quality assessments (Fumian et al., 2020). Their high sensitivity and specificity make them valuable tools for identifying and mitigating potential health and safety risks associated with exposure to specific organic compounds.

6. Beta Attenuation Sensors:

Beta attenuation sensors utilize a radioactive source to measure the mass of particles present in the air. These sensors are distinguished by their high sensitivity and accuracy in detecting particulate matter, making them valuable tools for various applications, especially in continuous emissions monitoring systems (CEMS). The radioactive source emits beta particles, and as these particles pass through the air, their attenuation is measured. The extent of attenuation is proportional to the mass concentration of particles. Beta attenuation sensors are particularly effective in industrial settings where precise monitoring of particulate emissions is crucial for regulatory compliance and environmental impact assessment (Shukla & Aggarwal, 2022). Their continuous and real-time monitoring capabilities contribute to maintaining air quality standards, ensuring workplace safety, and minimizing environmental pollution.

Figure 5. Photoionization sensors
(Fumian et al., 2020)

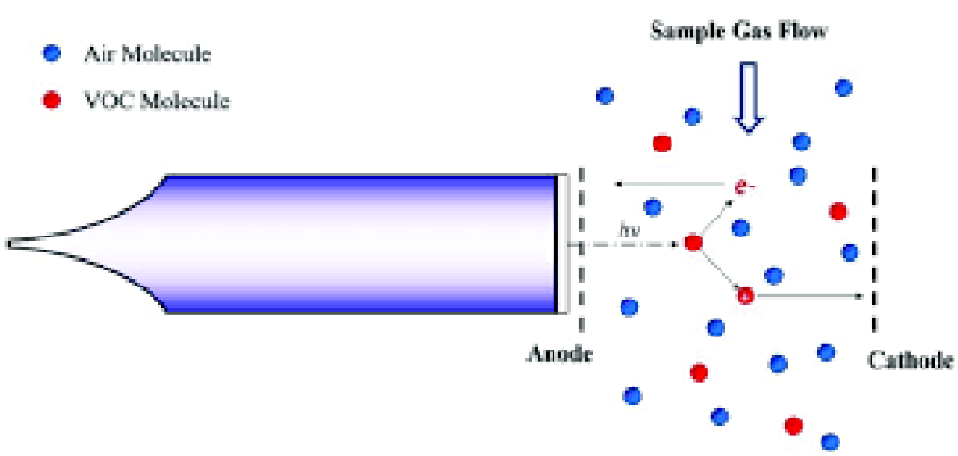
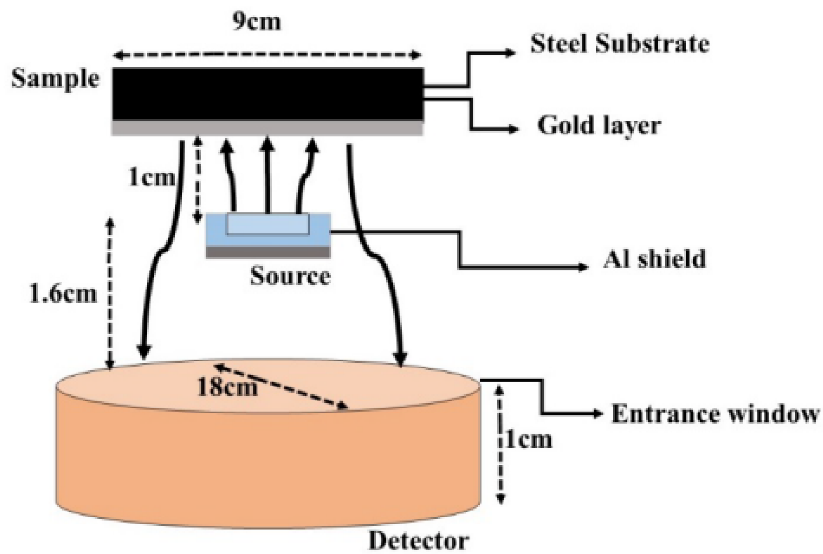


Figure 6. Beta attenuation sensors
(Shukla & Aggarwal, 2022)



Applications of Air Sensors

Air sensors are extensively employed in a diverse range of applications, including:

1. Environmental Monitoring:

Air sensors are essential instruments for monitoring and evaluating air quality in diverse environments, including both indoor and outdoor settings. These sensors play a crucial role in identifying pollution sources, assessing air quality trends, and enforcing regulations to safeguard public health and the environment. In outdoor spaces, air sensors contribute to understanding the concentration levels of pollutants such as ozone, particulate matter, and nitrogen dioxide, aiding in the formulation of effective pollution control measures. Indoor air sensors are vital for detecting volatile organic compounds, carbon monoxide, and other indoor pollutants, ensuring a healthy indoor environment. By providing real-time data and insights, air sensors empower regulatory bodies, researchers, and the general public to make informed decisions for mitigating the impact of pollution and creating healthier living and working conditions.

2. Industrial Process Control:

In industrial settings, air sensors play a pivotal role in monitoring and controlling air quality throughout various processes. These sensors are instrumental in ensuring worker safety by detecting and quantifying the concentration of potentially harmful airborne substances. By providing real-time data on pollutant levels, air sensors contribute to preventing emissions that could adversely affect both the environment and human health. Additionally, in industries subject to regulatory standards, air sensors assist in maintaining compliance by continuously monitoring and reporting air quality parameters. Whether it's the detection of gases, particulate matter, or volatile compounds, these sensors enhance the overall safety and environmental performance of industrial operations, creating healthier working conditions and minimizing the impact of industrial activities on the surrounding air quality.

3. Healthcare:

In healthcare facilities, air sensors play a crucial role in maintaining a clean and safe environment for patients and staff. These sensors contribute significantly to infection control by preventing the spread of airborne infections. By continuously monitoring air quality, particularly in critical areas such as operating rooms and patient care spaces, air sensors aid in identifying potential contaminants and ensuring optimal conditions for patient recovery. The real-time data provided by these sensors enables swift responses to changes in air quality, contributing to improved patient outcomes and reducing the risk of healthcare-associated infections. With their ability to enhance indoor air quality management, air sensors are indispensable tools for healthcare facilities, supporting a healthy and safe environment conducive to patient healing and staff well-being.

4. Smart Cities and Buildings:

Air sensors play a vital role in the development of smart cities and buildings by providing real-time data on air quality. Integrated into these environments, these sensors continuously monitor pollutants and particulate matter levels, offering crucial insights for residents, workers, and policymakers. The accessibility of real-time air quality information empowers individuals to make informed decisions concerning their health and surroundings. Residents can adjust daily activities based on current air quality conditions, promoting a healthier lifestyle. Additionally, city planners and authorities can utilize this data to implement targeted interventions, improving overall environmental quality and urban sustainability. By fostering awareness and enabling proactive measures, air sensors contribute to the creation of healthier and more environmentally conscious communities within the framework of smart cities and buildings.

5. Research and Development:

Air sensors play a pivotal role in advancing scientific research and development by supplying valuable data on various aspects of the atmosphere. These sensors contribute crucial information on air pollution, aiding researchers in understanding the sources, levels, and distribution of pollutants. Additionally, in the context of climate change, air sensors assist in monitoring greenhouse gas concentrations and studying climate-related variables. The data collected by these sensors also enhances our understanding of atmospheric chemistry, helping scientists unravel complex interactions between different chemical compounds in the air. The insights gained from air sensor data contribute to the formulation of effective environmental policies and strategies for mitigating the impacts of air pollution and climate change. This synergy between air sensors and scientific research is essential for creating a sustainable and healthier environment.

CONCLUSION

Air sensors stand as indispensable tools in safeguarding human health and preserving the environment. Their diverse applications, ranging from environmental monitoring to industrial process control and healthcare, underscore their significance in maintaining clean air and protecting public well-being. Through continuous advancements in sensing technologies and data analytics, air sensors will continue to play a pivotal role in shaping a healthier and sustainable future for our planet.

Indoor air pollutants significantly impact human health, leading international agencies to continually develop guidelines for effective indoor air quality management. This study aims to enhance comprehension of major standards and guidelines concerning indoor air pollutants and their health implications. The paper reviews diverse pollutants, encompassing their specified limits, enforcement levels, applicable demographics, and operational protocols. Emphasizing the necessity of real-time, spatial, and temporal monitoring for comprehensive air quality management, the research underscores the importance of technology in achieving this goal. Additionally, the paper delves into the specifications of existing air quality sensor technologies, covering aspects like detection range, measurement tolerance, data resolution, response time, current consumption, and market pricing. While acknowledging the transformative potential of air quality sensors, the study highlights current limitations, emphasizing the need for further advancements before widespread regulatory implementation, particularly regarding robustness, repeatability, and standardized testing protocols. Gaseous sensors, compared to fine particulate matter sensors, exhibit additional uncertainties and data variations.

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Chapter 3
Pioneering Sensing Solutions for In-Situ Monitoring of Volatile Organic Compounds in Soil and Groundwater Using Chemiresistor Sensor Technology

Periasamy Palanisamy
https://orcid.org/0000-0003-1069-5822
Nehru Institute of Engineering and Technology, Anna University, India

Maheswaran M.
Nehru Institute of Engineering and Technology, Anna University, India

ABSTRACT

The monitoring and classification of volatile organic compounds (VOCs) in soil and groundwater is a critical task in guaranteeing environmental protection and remediation of contaminated sites. Traditional methods of sample collection and off-site analysis could be expensive, laborious, and may not accurately represent in-situ conditions. To address these encounters, state-of-the-art sensing solutions using chemiresistor sensor technology have been developed for instantaneous, uninterrupted, and long-term monitoring of VOCs in the subsurface. The chemiresistor comprises of a chemically-sensitive polymer dissolved in a solvent and mixed with conductive carbon particles. The resultant ink is deposited onto thin-film platinum traces on a solid substrate. When VOCs come into interaction with the polymers, they are absorbed, initiating the polymers to swell and change the resistance of the electrode. This variation in resistance can be measured and recorded, providing information about the concentration of the VOCs.

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INTRODUCTION

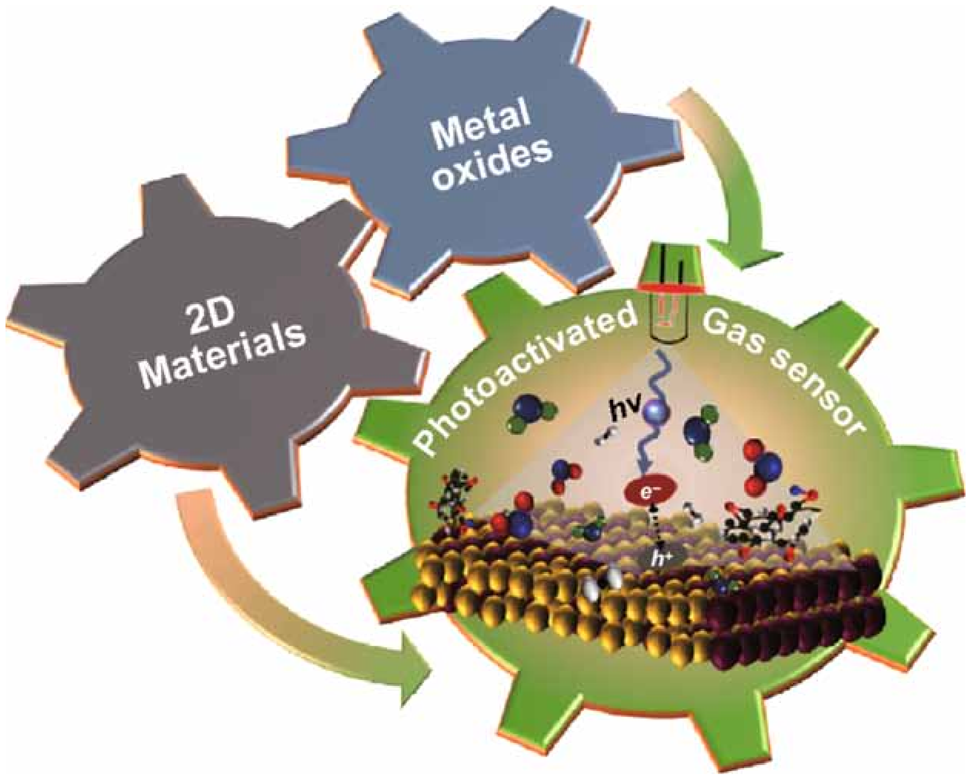
In the recent decades, organic thin film devices have reaped a lot of interest for their broad range of applications, which include printing inks, colorants, photoconductors, solar cells, electrochromic sensors, and gas sensors. The microfabrication of gas sensors that are established with the nanostructured materials and have a very low power consumption are technologies which are very necessary for today's sophistication(Wu et al., 2020). Such sensors are employed in a variety of industries, including the excavating industry for the purpose of detecting mine methane, the automotive industry for the tenacity of sensing combustion gases from vehicles, medical applications for bioelectronic noses which mimic human olfaction, and air quality monitoring for the purpose of estimating greenhouse gas emissions(Chen et al., 2021). Other applications of chemical sensors include the detection of gases, the observing of water and soil pollutants, the monitoring of temperature, speed, magnetic fields, and the regulation of emissions. such kind of electronic circuit element is known as a chemical sensor. This category of sensor endures a change in both its physical and chemical structure, when it captivates a chemical stimulant in the surface layer. Owing of this, the electrical characteristics of the sensors are changed, and such changes are translated into values that can be measured(Chen et al., 2021),(Hooshmand et al., 2023),(Hsieh & Yao, 2018).

Carbon dioxide (CO_2), nitrogen oxides (NO_x), sulphur oxides (SO_x), hydrocarbons (HC), carbon monoxide (CO), lead (Pb), and volatile organic compounds (VOCs) are some of the crucial contaminants that have the potential to have a detrimental effect on both the environment and human health, ensuing in respiratory illnesses(David & Niculescu, 2021). Combustion activities in industrial settings and at high temperatures, as well as the use of chemical poisons in agriculture without discernment associated to the ongoing innovation in technology, all have an impact on the features of the atmosphere, which ultimately results in harmful levels of air pollution. Air pollution in urban areas that is caused by nitrogen dioxide, sometimes known as NO_2, is a global problem. Long-term exposure to nitrogen dioxide (NO_2) has been shown to have negative effects on human health and is responsible for a wide range of disorders that affect the cardiovascular and respiratory systems. Personal sensitivity and vulnerability are determined by a combination of biological variables and genetic inclination as individuals. The factors of age, gender, education level, socioeconomic class, area of residence, and employment all have a role in determining an individual's susceptibility to the dangers of pollution. There is a significant effect that air pollution has on the health and well-being of individuals, especially on the most vulnerable groups, such as children, women, and those living in underdeveloped nations. The combustion processes used in high-temperature manufacturing environments and the unrestricted use of chemical toxins in agriculture, which are linked to ongoing technical advancements, have an impact on atmospheric characteristics and cause air pollution (David & Niculescu, 2021),(Hooshmand et al., 2023).

NO_2 pollution in urban areas is a global issue of great concern. Prolonged exposure to NO_2 leads to detrimental effects on human health and is responsible for many respiratory and cardiovascular disorders. Individual sensitivity and susceptibility are determined by biological variables and genetic predisposition. Socioeconomic level, place of residence, and employment are factors that contribute to individual susceptibility to pollution dangers. The presence of air pollution has detrimental effects on the health and overall state of well-being of individuals, especially those who are most susceptible such as children, women, and those residing in underdeveloped nations. Air pollution incurs significant economic costs that hinder sustainable development (David & Niculescu, 2021).

Engaging in economic development that tolerates air pollution and disregards the consequences on public health and the environment is morally wrong and cannot be maintained in the long term. Fur-

Figure 1. Gas sensor (Metal oxides to 2D materials)
(reproduced from (Kumar et al., 2020) under CC BY 4.0)



thermore, pollution-related disorders contribute approximately 7% of the total national health budget in terms of healthcare expenses(Caballero et al., 2012). The emission of hazardous chemicals and vapors poses a significant and concerning risk to the ecosystems inside the biosphere(Remoundou & Koundouri, 2009). Pristine air and water are crucial components for sustaining life on Earth, and the presence of air pollution poses a significant danger to the long-term viability of Earth's environment. Early identification and monitoring are necessary to address the concerning increase in pollutant concentrations in urban environments. The use of passive diffusion tube sampling methods has been implemented to examine the geographical and temporal fluctuations in NO_2 concentrations. The validity of measurements is crucially dependent on the automated techniques used for pipe extraction, preparation, and co-location(X. Zhang et al., 2022),(Caballero et al., 2012).

Urban areas with high levels of NO_2 pollution serve as concentrated locations for sample sites, offering specific geographic information and further data on the distribution, dispersion, and human exposure to pollutants in urban contexts. Utilizing a solitary NOx diffusion tube method simplifies the process of pinpointing areas with high concentrations of NO_2 by providing accurate geographical information on the locations where air quality is degraded(Caballero et al., 2012). This is achieved via sampling over a span of 12 months, including all variations throughout the seasons. Several literary techniques that compare metropolitan areas provide a preliminary tool for screening air quality and air pollution. This tool is designed to assist in conducting research on air quality evaluation. Utilizing these empirical models to calculate the conversion rate from NO_x to NO_2 is crucial for enhancing air quality and mitigating the possible harm to human health and ecosystems via air pollution mitigation strategies. Precise monitoring systems and gas sensors play a vital role in detecting gas in industrial environments as well as in buildings that demand high air quality (Norris & Larson, 1999), (Niepsch et al., 2022), (Vîrghileanu et al., 2020).

Typically, these devices are outfitted with a chemically selective layer that interacts with its environment in the capacity of a sensor layer (Fig.1). The contact causes a modification in the characteristics of the sensing layer, such as changes in conductivities, which occur due to the adsorption of the analyte molecule on the surface of the layer. An organic semiconductor gas sensor, using sophisticated nano- and microfabrication technology, offers many benefits over existing semiconductor gas sensors in terms of manufacture, cost, and operation at room temperature(Bai et al., 2015). The contribution of nanotechnologies is in the development of novel materials with a significantly increased surface area, which enhances the absorption of gaseous molecules and improves sensing performance. Graphene, a kind of carbon-based nanomaterial, has been extensively used as a sensor for detecting NO_2 at normal room temperature. Multiple methodologies have substantiated the effectiveness of electrically conductive polymeric materials and graphene composites, owing to their exceptional conductivity and extensive surface area. These materials have been used in gas sensors as well as electrochemical biosensors(Krishnakumar et al., 2009).

A recent set of laboratory experiments involved the use of polypyrrole/graphene oxide reduced and polypyrrole/graphene oxide covalently bound nanocomposites, combined with 4-carboxybenzene diazonium aryl salt nanocomposites. These nanocomposites were tested to assess their chemical properties in detecting NO_2 gases at room temperature(Guettiche et al., 2021). The nanocomposite ppy-graphene has been synthesized by incorporating graphene into the polymeric solution and during the polymerization process. Graphene and other carbon-based nanofillers have been used to enhance gas detection capabilities and increase both sensitivity and specificity. However, the clumping together of graphene particles negatively impacts the polymer matrix. Furthermore, other chemicals have undergone testing for the same purpose. Combinations of carbon nanotubes and ZnO (CNTs&/ZnO) have shown enhanced electrical performance when exposed to CO, with a 60% increase in reaction time compared to ZnO alone(Sara et al., 2022). Zinc oxide (ZnO) nanostructures has multifunctional features, including a large surface area, high crystallinity, and an ordered molecular structure, making them well-suited for various sensing and selective applications. ZnO nanocomposites have recently been used for the production of NO_2 gas sensors because of its temperature resistance, stability, and flexibility. These characteristics prompted several endeavors to enhance the semiconductor's performance for gas sensing applications via the development of novel morphologies and crystallographic forms of ZnO (Krishnan et al., 2019).

The volatile organic compound (VOC) sensor is a vital tool for indoor air quality (IAQ) monitoring, as it senses the contaminants that exhibit a threat to human health (Krishnan et al., 2019). VOCs are chemical ingredients with high vapor pressure at room temperature and are released into the environment, generally found in consumer products, gasolines, and industrial processes. Examples of VOCs comprises benzene, toluene, ethylene, formaldehyde, and xylene. VOCs can have adverse impacts on human wellness and the environment, including respiratory irritation, headaches, eye and nose irritation, and contribute to the creation of ground-level ozone, a major component of smog. VOC sensors work by means of a sensitive chemical (David & Niculescu, 2021) element or electronic components to identify the presence of VOCs (Fig.2).

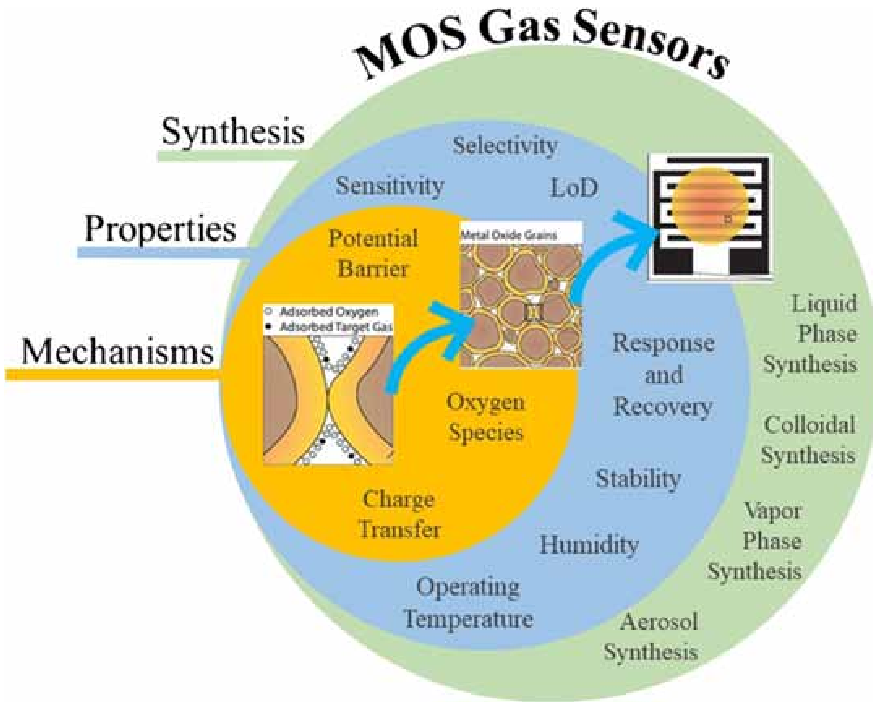
When VOCs are contemporary in the air, they react with the chemicals present in the sensor and produce an electrical charge, which is then calibrated by the sensor and the concentration of VOCs can be determined. VOC sensors are used in several applications such as automotive emissions monitoring, indoor air quality monitoring, industrial process monitoring, and environmental monitoring. VOC sensors classically use one of two different types of method to measure the presence of VOCs: photoionization detectors (PIDs) or metal oxide semiconductor (MOS) sensors. Photoionization detectors detect the concentration of VOCs by ionizing the molecules of the VOCs with a UV light, which are then passed through a chamber anywhere they are sensed and measured by an electrostatic field. The measured ions are rehabilitated into a measureable electrical current and passed to a read-out device for further analysis(Pathak et al., 2023). There are 3 main types of common VOC gas sensors centred on their working principles: electrochemical VOC sensors, optical VOC sensors, and mass VOC sensors. Electrochemical VOC sensors encompass the adsorption or reaction (physical or chemical) of VOC gases on the surface of a gas-sensitive material, which results in fluctuations in its electrical properties. Amid the most broadly used types of VOC sensor based on semiconductor metal oxides is the conductive type, which plays a significant role in the current gas sensing field(Epping & Koch, 2023).

They can be divided into common two-electrode conductive detection systems in addition to three-electrode field-effect transistor detection systems. Based on the VOC gas-sensitive materials, they can be characterized as semiconductor metal oxides, conductive polymers, nanomaterials, and porous materials. The volatile organic compound sensor is crucial for confirming a healthy indoor environment and preventing harmful contaminants from entering the air. Semiconductor metal oxide conductivity sensors are amongst the primary and most mature gas sensors, developed in 1936. These sensors sense the gases by exploiting the property that the resistance or work function of a semiconductor changes when it comes into encounter with a gas. Though, they have boundaries such as working at high temperatures, poor gas selectivity, and prone to poisoning(P. Zhang et al., 2021),(Verma et al., 2024).

Zero-dimensional nanomaterial conductivity sensors are a hopeful material due to their exclusive physical and chemical properties. Gold nanoclusters demonstrates quantum dot behavior and surface interactions with ligands, providing a selective adsorption interface for VOCs. The electrical response characteristics of monolayer gold nanoclusters to VOCs are linked to variations in electronic conductivity between the gold cores triggered by adsorption of VOCs and activation energy. Organic thiol kinds and structures are premeditated and selected based on the interaction forces between unlike functionalized gold nanoclusters and VOCs. A VOC sensing array is fabricated based on the cross-selective response characteristics of diverse gold nanoclusters to VOCs. Conductivity gas sensors based on nanoporous materials, precisely nano-porous silicon photonic crystals, are also employed due to their high surface area and gas adsorption capabilities. Conductive polymer materials are generally used in gas sensors due to their specular electrical and optical properties, mechanical flexibility, and electrochemical redox characteristics. conjugated polymer materials such as phthalocyanine polymers, polypyrrole, polyaniline, and porphyrins and metalloporphyrin complexes are employed as gas sensor materials. Optical VOC sensors have the benefits of strong anti-electromagnetic interference, fast response, and easy implementation for online monitoring of organic gases. There are several types of optical sensors based on their working principles, together with reflective interference method, ultraviolet-visible absorption photometry, colorimetric method, fluorescence method, surface plasmon resonance method, and fiber optic sensing technology. Spectroscopic absorption gas sensors identify VOCs based on the intensity or displacement change of the absorption spectrum of gas-sensitive materials after adsorbing VOCs.

Color-based visual VOC sensors signify the characteristic information of smells in the form of images, also recognized as visual olfaction. The colorimetric output signal mode is the utmost straightforward sensing platform for evolving naked-eye detection technology, minimizing the need for signal conversion equipment modules. Presently reported sensing materials for VOC picturing include polydiacetylene paper chips, methylene yellow 6 nanofibers, Fabry-Perot interference micro-porous polymers, and supramolecu-

Figure 2. Schematic diagram of sensors response
(reproduced from (Isaac et al., 2022) under CC BY 4.0)

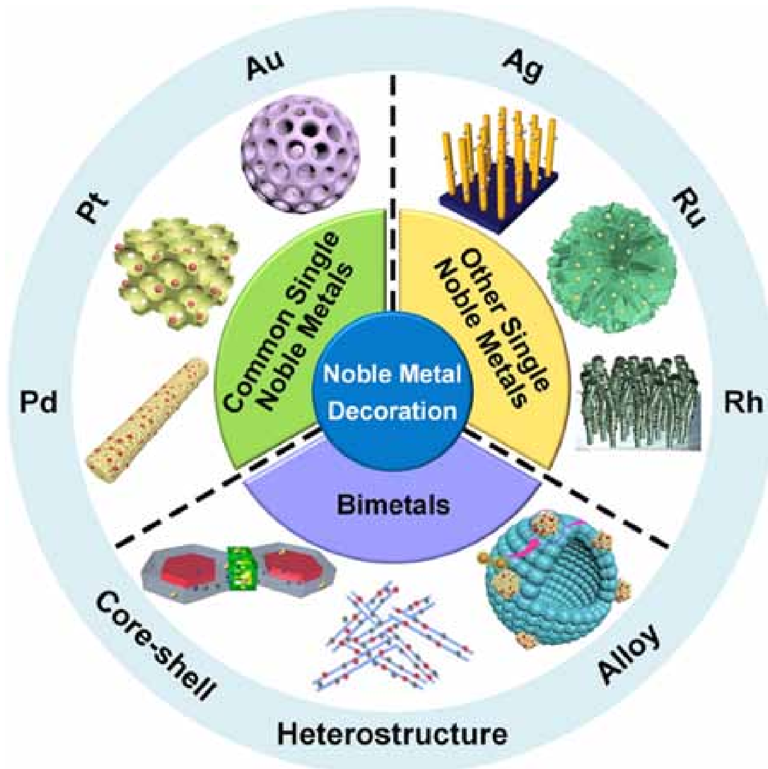


lar host-guest complexes. VOC sensors grounded on the optical interference principle involve photonic crystals (PCs) with periodic variations in refractive index in space. PCs have the function of filtering, selectively allowing certain bands of light to pass through and hindering other wavelengths of light.

Fluorescence VOC sensors are substantial advancements in analytical chemistry, contribute high sensitivity, good selectivity, and strong resistance to electromagnetic interference (Fig.3). Though, they often face tasks such as difficult cataloguing and poor repeatability due to peripheral factors such as humidity, polarity, and pH. Surface plasmon resonance (SPR) is a physical optical phenomenon of the momentary field that arises when light undergoes total internal reflection at the boundary between glass and a metal film, producing a momentary wave that can induce surface plasmon waves on the metal surface by generating free electrons. Underneath certain circumstances of incident angle or wavelength, the frequency and wave number of the surface plasmon wave and the temporary wave resonate, and the incident light is absorbed, subsequent in a resonance peak in the reflection spectrum. SPR technology is a novel gas detection method with the compensations of simple structure, high sensitivity, and wide detection range.

A recent published studies reports the development of a highly sensitive VOC sensor based on olfactory receptors reconstituted into a lipid bilayer and used in a precisely designed gas flow system for rapid parts per billion (ppb)–level detection. The study validates the potential for using biological odorant sensing in breath analysis systems and environmental monitoring. Olfactory receptors in living organisms can identify various VOCs with a level of detection corresponding to a single molecule, making them far greater in selectivity and sensitivity compared with current VOC sensors using artificial materials. VOC sensors work by sensing the changes in electrical conductivity when VOC molecules bind to the sensor's

Figure 3. Metal oxide nanomaterials for chemiresistive gas sensors
(reproduced from (L. Y. Zhu et al., 2023) under CC By 4.0)



surface. The sensors are fabricated of a thin film of a conducting polymer, coated with a layer of a material that absorbs specific VOCs. When VOCs predicament to the absorber layer, they alter the electrical conductivity of the conducting polymer film, which can be measured and used to notice the presence and concentration of the VOC. Current advances in VOC sensor technology include the use of machine learning algorithms to advance sensor accurateness and the development of flexible, wearable sensors.

SENSOR MEASUREMENT SETUP

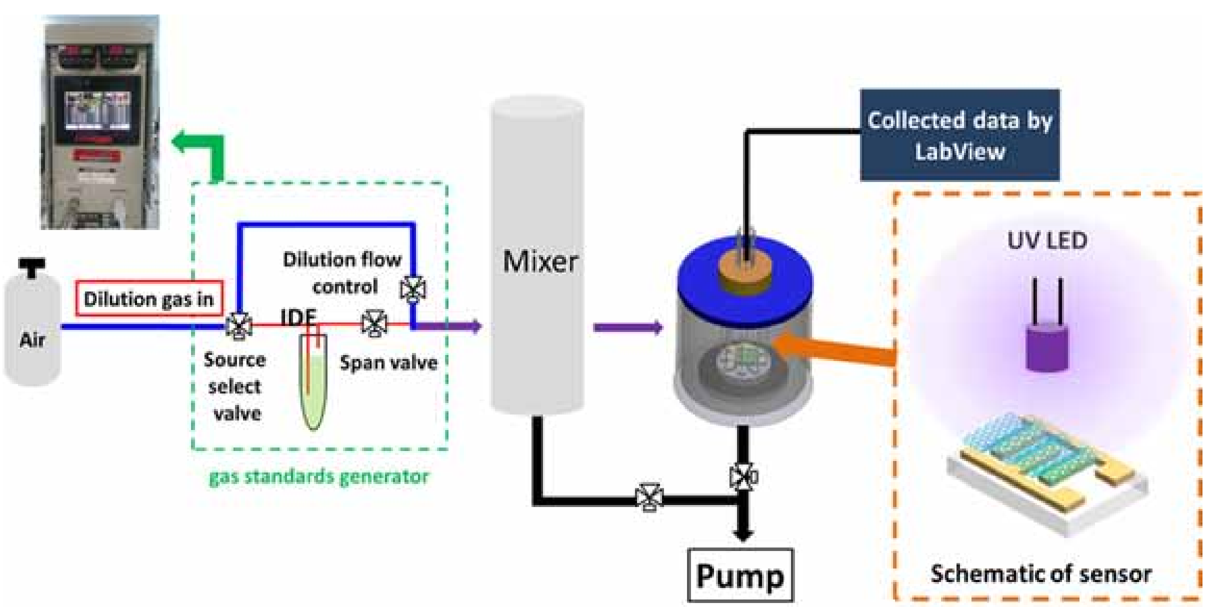
In order to carry out the gas-sensing measurements, the chemiresistor gas sensors were positioned within the gas chamber. Materials that are resistant to chemical reactions, such as polytetrafluoroethylene (PTFE) and stainless steel, have been used in the construction of the measuring gas chamber, which has intake and exit pipes with a diameter of 4 millimeters. Within the measuring chamber, quartz windows were used, and the constructions were lighted using ultraviolet light emitting diodes (UV LEDs) with a wavelength of 390 nanometers. A base that was fitted with a Pt100 sensor was put on top of four chemically resistive constructions of gas sensors in order to monitor the changes in temperature (Figure 4).

The use of a test gas bench was necessary in order to carry out the optical characterization of the layers that were susceptible to gas combinations. The test bench is comprised of a digital mass flow controller interface, a gas test chamber equipped with the required sensors, pressurized gas cylinders, a digital interface, a personal computer, and a Keithley measuring equipment. In order to establish stability of the sensor active surface and a stable baseline resistance, the gas chamber was illuminated by ultraviolet light for one or two hours while synthetic airflow was present. This was done in preparation for gas-sensing measurements using ultraviolet light.

For the duration of the measurement procedure, the flow rate over the sensing chamber was maintained at a constant rate of 200 milliliters per hour for the synthetic air flow meter counter 1 and 200 milliliters per hour for the synthetic air flow meter counter 2. After two hours (about 0.5 9 104 seconds), the chemiresistor gas sensors were subjected to low concentrations of nitrogen dioxide (500 parts per billion) while being exposed to continual UV radiation and dry synthetic air flow. Furthermore, the flow cycle was repeated three times, which corresponded to approximately ten hours. During the times when the flow of NOx was allowed to continue, the synthetic air counter 2 was closed. It was always open at the synthetic air counter number 1. To prevent interference from humidity and non-uniform pressure, the target gases were first mixed in a gas mixing chamber before being introduced into the gas sensor chamber. This chamber maintains a consistent pressure and humidity level in order to prevent any potential interference. In the presence of ultraviolet light, a physicochemical interaction is produced between oxides of nitrogen (NOx) and sensitive compounds that are located on the substrate of chemiresistors. As a consequence of the molecule of nitrogen dioxide being adsorbent on the surface of the ZnO/graft comb copolymer, it is able to ensnare the electrical charge that is present in the nanomaterial's conduction band, which ultimately leads to an increase in the sensor's resistance.

During the process of data gathering, a sensor was equipped with the capability to detect and record the operating temperature of the gas analyte that was contained inside the gas mixing chamber. It was possible to keep the temperature conditions consistent despite the fact that the temperature fluctuated between 23.5 and 24.6 degrees Celsius, with an average value of 23.7 degrees Celsius. The temperature

Figure 4. Sensor measurement setup
(reproduced from (Roy et al., 2010) under CC BY-NC-ND)



of the chamber decreased as the flow of nitrogen oxide gas was introduced, despite the fact that the synthetic air gas injection caused a modest rise in temperature during the first stage. It is quite likely that the variations in gas pressure were the source of the problem. Throughout the course of the measurements, the sensing structures were continuously irradiated by the ultraviolet light. The humidity was measured inside the chamber that was used for mixing the gas. The value of humidity that was measured fluctuated approximately 3.5% during the whole process of dosing the gaseous analytes and the carrier gas, and it remained steady throughout the time that the measurements were being taken.

ADVANTAGES OF IN-SITU MONITORING OF VOLATILE ORGANIC COMPOUND GASES

In-situ monitoring of VOCs using chemiresistor sensors offers several advantages over traditional methods. Firstly, it eliminates the need for manual sample collection and expensive off-site analysis. Instead, real-time monitoring provides continuous data, allowing for immediate detection of changes in VOC concentrations. This enables prompt response and intervention when necessary. Additionally, in-situ monitoring reduces the risk of evaporation and loss of VOCs during sample handling and storage, providing more accurate measurements of in-situ concentrations. Another advantage of in-situ monitoring is the ability to gather data in challenging environments, such as flammable or explosive sites (Wiśniewska & Szyłak-Szydłowski, 2022). Chemiresistor sensors are immune to electrical noises and can operate in these hazardous conditions safely. Moreover, the miniaturization and geometrical flexibility of the sensors allow for measurements in small sample volumes and remote sensing in inaccessible or harsh environments(Sara et al., 2022).

It has been shown (Davis et al., 2005) that the incorporation of a micro fabricated preconcentrator into a chemiresistor chemical sensor results in an increase in sensitivity and a reduction in the detection limits for m-xylene. In the absence of the preconcentrator, our PEVA chemiresistor demonstrated the capability to detect concentrations up to 0.12% of the saturated vapor pressure of m-xylene (at a temperature of 3 degrees Celsius). The detection limit was reduced to roughly five one-millionths (0.0005%) of the saturation vapor pressure of m-xylene (at 3σ) when a preconcentrator was added to the mixture. This improvement of more than two orders of magnitude may make it possible for the chemiresistor to be used in applications that demand lower detection limits. One example of such an application is the detection of controlled pollutants in geologic medium. It is important to note that there is a contrast between the detection limit, which is constrained by the noise values stated earlier, and the accuracy or uncertainty in the concentrations that are measured. The preconcentrator also has the benefit of knowing the exact timing of the heat pulse, which enables the baseline drift of the chemiresistor to be adjusted without the need for pumps, valves, and purge gases to be used in the field. Pumps and valves are used in the collection of data that is shown in Figure 4. If the low concentrations were to fluctuate slowly and in an unpredictable manner, it would be more challenging to differentiate between them. The preconcentrator timing enables a more definite detection of low concentrations, which is a significant advantage.

The calibration and prediction of chemiresistor arrays across various environmental conditions presents significant challenges(Rivera et al., 2003). Both intended sequences and non-designed sequences have statistically equal calibration results, with R2 values of 0:94 and 0.96, respectively, and CVSEPs of 750 and 650 ppm, respectively. In short-term prediction, the model derived from designed sequences has an R2 of ¼ 0:93 and a SEP of ¼ 900 ppm, while the model derived from non-designed sequences also predicts designed data with an R2 of ¼ 0:87 and a SEP of ¼ 1100 ppm. In long-term prediction, the model formed from the intended sequence produces an R2 of ¼ 0:91 with a SEP of ¼ 920 ppm, while the model built from non-designed data produces an R2 of ¼ 0:81 with a SEP of ¼ 1340 ppm. This difference in prediction statistics suggests that models constructed using the planned data set provide more accurate predictions for the given circumstances. A strategically constructed experiment involving random sampling sequences with repeat samples was used to calibrate microsensor data to TCE at various temperatures and humidity. This experiment was more reliable in forecasting TCE concentrations for both short and long periods following calibration. The study also demonstrated the effects of temperature and humidity on the chemiresistor response and PLS calibration. The calibration model's capacity to make accurate predictions cannot be evaluated solely based on leave-one-out cross-validation outcomes during calibration. To determine the model's capability, a genuine prediction is necessary.

A resistive sensor capable of detecting the presence of volatile organic compounds (VOCs) in water at a concentration of µg/L was prepared by (Rivadeneyra et al., 2016). The device was manufactured using a flexible substrate and printing procedures, specifically using silver electrodes and a resistive composite made of graphite and polystyrene. The study investigated various manufacturing parameters and their reaction to various volatile organic compounds. Higher resistance values were achieved with composites with reduced graphite concentration, but they also had worse repeatability. Composites with the maximum amount of graphite had higher repeatability. Lower mesh density resulted in lesser pattern definition and lower resistance values but also provided greater repeatability in a wider range of graphite content. Serpentine electrodes provided around 12% higher resistance than interdigitated electrodes. The dynamic reaction of these resistors showed a more rapid and intense response to toluene than pure water. The composite with a graphite content of fifty percent had the fastest reaction when printed with a 120 T/cm screen. The maximum sensitivity was found to be benzene, followed by o-xylene, p-xylene, m-xylene, and toluene.

A microfluidic water monitoring system with an integrated microhotplate gas sensor was fabricated to evaluate the performance of the water monitoring sensor platform [REMOVED HYPERLINK FIELD] (L. Zhu et al., 2007). The liquid/gas channel overlap was chosen based on observation of data, suggesting that larger overlaps do not provide significant improvements in gasphase analyte concentration. A syringe pump was used to deliver precise flow of water/solvent mixture in the liquid channel, and a mass flow controller was used to deliver dry air flow in the gas channel. A laptop computer provided temperature control and monitoring of conductometric response for the integrated gas sensor elements. The flow rate of dry air was set to the minimum value supported by the mass flow controller of 500 L/min, and the flow rate of liquid was set to a relatively high value of 20 L/min. The evaluation of toluene and 1,2-dichloroethane were of particular interest since these solvents are chemical contaminants listed by the US EPA. The Guterman–Boger set of algorithms was employed to train the large-scale Artificial Neural Networks (ANNs) for the methanol, toluene, and 1,2-dichloroethane TPS data measured using the integrated microfluidic platform. The resulting ANN model was applied to both the training and validation data sets.

Based on the measured data, approximate detection limits for the fabricated system are 1 ppm for methanol, 10 ppm for toluene, and 100 ppm for 1,2-dichloroethane. The maximum contamination levels (MCLs) in drinking water have been set by the EPA-enforced Safe Drinking Water Act at 0.2 ppm for toluene, and 0.9 ppb for 1,2-dichloroethane. There are several reasons for the relatively low sensitivity of the water monitoring system to both toluene and 1,2-dichloroethane. First, the overall gas phase mass transfer coefficients for toluene and 1,2-dichloroethane are substantially smaller than for methanol. Second, toluene and 1,2-dichloroethane are readily absorbed by the polycarbonate substrate, lowering their concentrations in both the liquid and vapor phases.

A water monitoring platform combines a silicon-based microhotplate sensor chip for conductometric measurement of organic solvents in the gas phase with a microfluidic two-phase flow network for solvent extraction. The system's sensitivity to a suite of volatile organic compounds (VOCs) diluted in water was evaluated, with detection limits of 1 ppm for methanol, 10 ppm for toluene, and 100 ppm for 1,2-dichloroethane. Although the sensitivity is lower than for drinking water supplies, the system could be useful for monitoring point source contaminant emissions. Further study is needed to optimize the selectivity of the system for specific analytes, especially in the presence of water vapor. The siliconin-plastic fabrication process could be used to integrate additional functionality into the sensor platform, enhancing its potential for unattended and remote operation (L. Zhu et al., 2007).

Microbial communities play a crucial role in developing sustainable bioremediation strategies, especially for sites contaminated with mixed chlorinated volatile organic compounds (CVOCs) (Hussain et al., 2023). The study found that sensitive taxa like Proteobacteria and Acidobacteriota are lost, while CVOCs-resistant taxa like Campilobacterota are enriched in contaminated sites. The abundance of crucial enzymes involved in CVOC sequential biodegradation also varies depending on the contamination level. Genera like Sulfurospirillum, Azospira, Trichlorobacter, Acidiphilium, and Magnetospririllum can survive higher levels of CVOC contamination, while pH, ORP, and temperature negatively affect their abundance and distribution. Dechloromonas, Thiobacillus, Pseudarcicella, Hydrogenophaga, and Sulfuritalea show a negative relationship with CVOC contamination, highlighting their sensitivity. These findings offer insights into the ecological responses, groundwater bacterial community, and functionality in response to mixed CVOC contamination.

The environmental impacts and costs of three options for remediating groundwater contaminated by volatile organic compounds (VOCs) at a closed pesticide manufacturing plant site was studied by (Ding et al., 2022). The options include a combination of MNA and BC (MNA + BC), BC, and pump and treat (PT). The environmental impacts were assessed using a Life Cycle Assessment (LCA) using the ReCiPe 2016 method, and the costs were evaluated using a Life Cycle Cost (LCC) method created in SimaPro. The LCA results show that the overall environmental impacts follow a sequence of PT > BC > MNA + BC, with MNA + BC showing evident primary impacts. The environmental hotspots in PT include cement, electricity, steel, and operation energy. In MNA + BC and BC, electricity for feedstock pyrolysis is the environmental hotspot, while the use of BC by-products has positive environmental credit. The LCC results show that PT yields the highest cost, with cement and electricity being the two most expensive items. The study provides scientific support for developing and optimizing green remediation solutions for VOCs contaminated groundwater.

Thermal conductive heating (TCH) is a popular method for removing organic contaminants from subsurface, but it is often considered unsustainable due to high carbon emissions, energy consumption, and high costs(Yang et al., 2023). TCH-ISCO, a combination of TCH and in situ chemical oxidation, has gained attention for its ability to achieve groundwater remediation goals at lower temperatures. However, there is a lack of quantitative assessment on the sustainability of TCH-ISCO based on field data. A quantitative life cycle assessment approach was developed to assess the sustainability of TCH-ISCO for chlorinated aliphatic hydrocarbons (CAHs) contaminated soil and groundwater remediation. The results showed that TCH-ISCO and TCH contributed to 68% and 93% of adverse environmental impacts, respectively. TCH-ISCO had significantly lower carbon emissions and direct costs. The overall sustainability scores of TCH-ISCO and TCH were 89.6 and 61.9, respectively, indicating its superior performance.

Light-Non-Aqueous phase liquids (LNAPLs) are significant soil contamination sources, and groundwater fluctuations can significantly impact their migration and release (Cavelan et al., 2024). Risk assessment is complex due to the continuous three-phase fluid redistribution caused by water table level variations. To improve monitoring methods, a lysimetric contaminated soil column was developed, combining in-situ monitoring, direct water and gas sampling, and analyses. The experiment assessed the effects of controlled rainfalls and water table fluctuation patterns on LNAPL vertical soil saturation distribution and release. The results showed that 7.5% of the contamination was remobilized towards the dissolved and gaseous phase after 120 days. Groundwater level variations were responsible for free LNAPL soil spreading and trapping, modifying dissolved LNAPL concentrations. However, part of the dissolved contamination was rapidly biodegraded, leaving only the most bio-resistant components in water. This highlights the need for new experimental devices to assess the effect of climate-related parameters on LNAPL fate at contaminated sites.

Ozone-permeable membranes were used as a novel in-situ treatment method for groundwater contamination caused by organic compounds(Bein et al., 2024). The researchers found that ozone depletion was faster in the presence of sub-stoichiometric benzoic acid (BA) than in non-aromatic 1,4-dioxane (DIOX), with lower removal of 5 mg L−1 BA (52.7%) compared to DIOX (60.6%). The study also found that reactive porous media did not significantly change in-situ DIOX oxidation, although a stronger impact was hypothesized. The researchers determined experimental ozone mass transfer coefficients and compared them to modeled values for different membrane types. A mathematical model was developed to support upscaling efforts. The study concluded that contaminant properties are crucial for the feasibility assessment of in-situ ozone membrane treatment technology.

A system for monitoring groundwater contamination by aromatic VOCs has been developed using a gas-water separation unit and APPI-FAIMS(Joksimoski et al., 2022). The system successfully reduced humidity in the sample flow to $\leq$1.6 ppmv before analyte ionization. Toluene was chosen as a model aromatic VOC to test the system's feasibility and the impact of humidity on the signal produced by APPI-FAIMS. With increased humidity, the toluene signal increased by about 30%, allowing for the formation and detection of water clusters. Similar effects were observed for benzene. However, single contaminants like indane and trimethylbenzenes were not detected even at high humidity. On-site, continuous groundwater monitoring of aromatic VOC contamination was successfully carried out with the gas-water separation APPI-FAIMS at low humidity, simplifying the monitoring of a specific, total aromatic VOC signal in groundwater.

A novel electrolyzed catalytic system (ECS) was designed to produce nanobubble-contained electrolyzed catalytic (NEC) water for the remediation of petroleum-hydrocarbon-contaminated soils and groundwater(Ho et al., 2023). The ECS uses high voltage (220 V) with direct current, titanium electrodes coated with iridium dioxide, and iron-copper hybrid oxide catalysts to enhance the hydroxyl radical production rate. The system uses electron paramagnetic resonance (EPR) and Rhodamine B (RhB) methods for the generated radical species and concentration determination. During operation, high concentrations of nanobubbles are produced due to the cavitation mechanism, which prevents bubble aggregations and extends their lifetime in NEC water. The radicals produced after the bursting of nanobubbles increase the radical concentration and subsequent petroleum hydrocarbon oxidation. Highly oxidized NEC water can be produced with a radical concentration of 9.5×10^{-9} M. In a pilot-scale study, the prototype system was applied to clean up petroleum-hydrocarbon polluted soils at a diesel-oil spill site via an on-site slurry-phase soil washing process. Results showed that up to 74.4% of TPH could be removed from soils after four rounds of NEC water treatment.

Traditional methods have limitations such as safety concerns, rebound of contaminants, and difficulty in reaching all contamination areas. To address these, Controlled-Release Biodegradable Polymer (CRBP) pellets containing $KMnO_4$ were designed and tested (Lamssali et al., 2023). The CRBP pellets were encapsulated in Polyvinyl Acetate (CRBP-PVAc) and Polyethylene Oxide (CRBP-PEO) at different weight percentages, baking temperatures, and time. The highest release percentage and rate were found in CRBP-PVAc pellets with 60% $KMnO_4$ and baked at 120°C for 2 minutes. Natural organic matter was also considered for in-field applications due to its potential reducing effect. CRBP pellets offer an innovative and sustainable solution for remediating contaminated groundwater systems, reducing the need for multiple injections and minimizing safety and handling concerns.

Chlorinated volatile organic compounds (CVOCs) are often combined with 1,4-dioxane, a solvent stabilizer, for biodegradation. However, anaerobic conditions are needed for CVOC biodegradation(Abaie et al., 2024). Conventional adsorbents like activated carbon and carbonaceous resins have high adsorption capacities for these compounds but lack selectivity, limiting their use for separation. This study examined two macrocyclic adsorbents, β-CD-TFN and Res-TFN, for selective adsorption of chlorinated ethenes in the presence of 1,4-dioxane. Both adsorbents showed rapid adsorption of CVOCs and minimal adsorption of 1,4-dioxane. Res-TFN had a higher adsorption capacity for CVOCs and was highly selective for CVOCs. Its greater adsorption and selectivity suggest it can be used as a selective adsorbent for CVOC separation from 1,4-dioxane, allowing separate biodegradation.

A microfabricated gas chromatograph was used to analyze sub-parts-per-billion concentrations of trichloroethylene (TCE) in mixtures, addressing the issue of TCE vapor intrusion in homes and offices(Chang et al., 2010). The system uses a MEMS focuser, dual MEMS separation columns, and MEMS interconnects, along with a microsensor array. It is interfaced to a non-MEMS front-end pre-trap and high-volume sampler module to reduce analysis time. The response patterns generated from the sensor array are combined with chromatographic retention time to identify and differentiate VOC mixture components. A chemometric method based on multivariate curve resolution is also developed for partially resolved mixture components. Results show TCE concentration at 0.185 ppb, with a projected detection limit of 0.030 ppb.

CONCLUSION

The development of chemiresistor sensor technology for in-situ monitoring of volatile organic compounds in soil and groundwater is a substantial progress in environmental monitoring and remediation. This state-of-the-art sensing solution provides real-time, continuous, and long-term monitoring capabilities, reducing the reliance on manual sample collection and off-site analysis. The integration of chemiresistor sensors with a waterproof housing and the development of characterization methods contribute to the precise identification and characterization of VOCs in the subsurface. Field testing and collaborations with commercial and academic institutions further validate and enhance the performance of the sensor system. The continuous improvement and optimization of chemiresistor sensor technology hold great promise for the efficient and effective management of contaminated sites and the protection of environmental resources.

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Chapter 4
Optical and Electrochemical Chemosensors for Identification of Carbon Dioxide Gas

Kirandeep Kaur
Maharaja Ranjit Singh Punjab Technical University, Bathinda, India

Sudhanshu Pratap Singh
Maharaja Ranjit Singh Punjab Technical University, Bathinda, India

Navdeep Singh Gill
https://orcid.org/0009-0002-9995-1756
Australian Maritime College, University of Tasmania, Australia

ABSTRACT

Intelligent sensing and vigilant monitoring of C_o2 gas is immensely significant, as the concentration of C_o2 gas in atmosphere is increasing day by day due to anthropogenic activities which enhances the natural greenhouse effect and makes the earth warmer. Besides global warming, C_o2 is also a toxicant in enclosed environments causing asphyxiation by hypoxia, unconsciousness almost instantaneously, and respiratory arrest within one minute. Another area where sensing of C_o2 is imperative are agriculture and food industry. For these conditions, sensors should be capable of working under extreme temperatures, pressure, and interference due to the inherent complex materials and microorganisms. This chapter focuses on the information regarding the different types of C_o2 sensors available with special emphasis on electrochemical sensors and optical chemical sensors, which showed fluorescent and spectrophotometric variation on detection of C_o2, a detailed analysis of their detection process and sensing mechanism.

INTRODUCTION

There exist only few analytically investigable targeted entities as crucial as carbon dioxide, as it is the primary chemical feed stock for life. Photosynthesis process convert carbon dioxide into fuel and feed,

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primarily required for continual survival of all life forms.

$$CO_2 + H_2O \xrightarrow{\text{Sunlight}} C(H_2O) + O_2 \text{ (I)}$$

The backward chemical reaction of photosynthesis is the metabolic chemical reaction for most of the cells, liberating energy for biotic communities. Carbon dioxide is crucial for producing necessary chemicals for life and is commonly utilized as an indicator of life's presence and health measurement. This makes carbon dioxide an imperative analytical entity, as a measure of health. For instance, in medical domain blood analysis includes the analysis of dissolved oxygen, pH and CO_2 (Mills, 2009). In capnography, (the branch devoted to measurement of CO_2 levels in breath) the levels and temporary variation in CO_2 are monitored for diagnostic data (Gravenstein & Jaffe, 2021). Similarly, in anesthesiology monitoring of CO_2 have a crucial role to play. Contemporary studies show that the carbon dioxide levels in cellular environment is directly related to many biophysiological processes which include respiration, pH levels in biosystems, carcinogenesis, genetic information transformation, synthesis of nucleic acid and cell proliferations (Mills, 2009).

Although carbon dioxide is a primary requirement for existence of life but its continuous increasing levels in environment has significant impacts on global climate and human health. In recent years, because of its greenhouse effect, global warming is growing at a concerning pace and adversely affecting the season pattern all over the world. Oceans are assimilating CO_2 from the environment, which consequently causes ocean acidification, climate deterioration and environmental pollution. In addition excessive CO_2 inhalation culminate towards diseases such as asthma and bronchitis. Burning of fuels in transportation means, industries, power generation, domestic burning, degradative oxidation of biomass and fermentation are the major causes of carbon dioxide level increment in biosphere (Chen et al., 2016; Wang & Yang, 2014; Ziebart et al., 2014; Finn et al., 2012)

The gas under discussion is also one of the important indicators for determining the constitution along with safety standards of packaged food. After packaging of the food material, its deterioration starts immediately because of multiplication of microbes accompanying evolution of carbon dioxide gas as catabolic product. In modified atmospheric packaging (MAP) the food package is flushed with carbon dioxide and sealed. Low levels of oxygen thus prevents microbial spoilage allows the food item to stay fresh longer. Carbon dioxide act as active packaging gas in packaging mechanism as it can prevent the spoilage even in presence of oxygen. As a result the recognition and monitoring of carbon dioxide levels is highly imperative and this requires development of highly sensitive and selective sensing devices (Puligundla et al., 2012).

An efficient sensing device is defined by three basic characteristic feature selectivity, sensitivity and time of response (Kaur & Baral, 2014). Sensitivity may be defined as the capability of the sensing system to accurately quantify the analyte under the imposed conditions. The sensitivity of the sensor is controlled by the intense physico- chemical nature of the solvent system employed for the matrix preparations. Selectivity of the sensing material may be defined as its capability to recognize a targeted analyte free from interferences. Time of response is the count of quickness of attainment of maximum variation in signal upon varying the concentration of analyte. Additionally, reversibility, prolonged stability, dimensions and illumination source and some other factors that can manipulate the efficiency of the sensor. Thus, sensor can be stated precisely as a mechanism, which includes controlling and machine running electronic system, software coupled with networking module that detects and reacts to a variation in observable physico-chemical quantity, resulting an output which can be measured and directly proportional to the quantity (Wencel et al., 2014). The optical sensor must address some of the concerns:

1. They should be dissolved to form transparent solution, making them suitable for quantitative sensing spectrometrically.
2. They should be non-reactive chemically, photostable and thermally stable
3. Involve less complicated matrix preparation process
4. The matrix material could be moldable to various shapes.

Optical sensor have four basic modules:

1. Sample cross section unit, the area for the surficial chemical reaction to occur
2. The transduction unit
3. Digital signal analysis electronics unit
4. Signal output system

Sensor for gaseous analyte has two significant operations, first is to identify the analyte followed by the conversion of identification event into a functional signal. Finally the transduction unit convert functional signal to readable form. The chemical activity occurring at the sample cross section brings out the variation in properties of the chemical system like pH, resistivity, conductance, resulting from chemical reaction of the analyte and sensing motif (Neethirajan et al., 2009).

The qualitative and quantitative analytical investigations of CO_2 gas is often carried out using infrared spectroscopy, electrochemical method, gas chromatographic technique, mass spectrophotometry, and field effect transistors etc. When CO_2 is present in gas form, the Infrared spectroscopic method is usually employed. However, the method inherent the disadvantage of being unfriendly to pocket and sensitive to water vapors (Zhua et al., 2018). Severinghaus sensing technique for CO_2 sensing includes an aqueous bicarbonate solution containing glass electrodes enclosed in a gas permeable and water & electrolyte impermeable material. Carbon dioxide results in carbonic acid formation in aqueous medium followed by disintegration of carbonic acid into bicarbonate anion and a proton and thereby varying the pH of the electrolytic solution which is sensed by probe. In this process the carbon dioxide is recognized indirectly in its ionic form. Volatile acidic or basic gaseous material may interfere in pH measurements. Gas chromatographic technique absorb the carbon dioxide gas selectivity and elute through the column. While in mass spectrometry the analyte gas is bombarded with highly energetic electrons, converting gas in fragmentations which is further get separated based on charge and mass under the influence of magnetic field. Mass spectrometry is able to measure in near real time but it is not cost efficient, while gas chromatography is inexpensive as compared to mass spectrometry but it has long response time. (Qazi et al., 2012). Subsequent research suggested use of optical chemical sensors to get around the drawbacks of other approaches. Over the last ten or so years, numerous optical CO_2 detectors have been proposed working on the principle of origination of pH variation on addition of CO_2. These detectors often used in the form of planar or fiber optic machines and employing a range of sensing techniques which include fluorescence intensity detection, fluorescence resonance energy transfer, dual luminophore, DLR and many more.

Depending upon the mechanistic pathway of sensing, the sensing methods for carbon dioxide for carbon dioxide can be widely classified into two major types:

a. Optical sensor b. Electrochemical sensor

OPTICAL SENSORS

An optical sensor for carbon dioxide has following main components:

a. A dye molecule responsive towards pH (Deprotonated dye: A^{-1}, protonated dye: HA) these two forms either have dissimilar color/ optical profiles.
b. An aqueous/non aqueous solution as medium along with base/phase transfer reagent to solubilize the dye
c. A integument which is penetrable to gas and non-penetrable for ions

The optodes for carbon dioxide operate on similar principles as that of the Severinghaus type sensor. In a standard optode for CO_2, the diffusion of the gas occurs towards the solvent (liquid or gas phase) through the gas-penetrable layer and attains equilibration with the enclosed water layer that contains the pH-sensitive color inducing pigment (dye molecule). Enclosed aqueous medium containing dye molecule, on exposure to carbon dioxide establishes the equilibrium as per the following equations:

$$CO_2\,(g) \xrightarrow{K_a} CO_2\,(l) \quad K_a = 3.3 \text{ x } 10^{-2} \text{ mol/dm}^3 \text{ .atm (II)}$$

$$CO_2(aq) + H_2O \xrightarrow{K_b} H_2CO_3 \quad K_b = 2.6 \text{ X } 10^{-3} \text{ mol/dm}^3\text{.atm (III)}$$

$$H_2CO_3 \xrightarrow{K_c} H^+ + HCO_3^- \quad K_c = 1.72 \text{ X } 10^{-4} \text{ mol/dm}^3 \text{ .atm (IV)}$$

$$HCO_3^- \xrightarrow{K_d} H^+ + CO_3^{-2} \quad K_d = 5.59 \text{ X } 10^{-11} \text{ mol/dm}^3 \text{ .atm (V)}$$

When the base concentration is notably high, approximately 10^2 mol/dm^3, the above equilibrium equation results in a relation between P_{CO2} (ambient partial pressure of carbon dioxide) and concentration of H^+ ions present in enclosed water layer.

$$\alpha.\ P_{CO2} = [H_2CO_3\ ] = [H^+][Na^+]/K_3 \quad \alpha = \text{constant (VI)}$$

pH responsive dye molecule exists in protonated and deprotonated species results in following equilibrium:

$$HA \xleftrightarrow{K_a} H^+ + A^- \quad K_a\text{=acid dissociation constant of the dye (VII)}$$

Equations VI and VII gives the relation:

$$P_{CO2} = K'\ [AH]/[A^-]\ K' = \text{constant}$$

The protonated and deprotonated species of dye molecules usually absorbs in quite different regions of electronic spectra and the molar absorptivity of protonated form is usually very small as compared deprotonated form at wavelength of maximum absorbance of deprotonated form. This yields a direct relation between absorbance of deprotonated form (A_d) and its concentration ([A]). On exposure to carbon dioxide the dye molecules usually remain in deprotonated form, then absorbance A_{do} of this form varies linearly with the entire dye concentration. Thus, the ambient partial pressure of the gas is related to the absorbance of deprotonated and protonated forms as follows:

$$P_{CO2} = K^{'} (A_{do} - A_d)/A_d$$

Thus, measuring the absorbance of protonated and deprotonated form directly yields $P_{CO2.}$

Another type of optodes (sensing materials) for CO_2 are those which employs phase transfer agents like tetraoctyl ammonium hydroxide, ($Q^+ OH^-$), to solubilize deprotonated form of pH responsive dye in a hydrophobic solvent containing water insoluble polymeric matrix. The phase transfer agent ($Q^+ OH^-$) when added to dye (A^-), it form an ion pair Q^+A^-. This ion pair can be easily solubilized in non-aqueous solvents. A salient characteristic of this ion couple in not only to get solubilize in hydro-repellent organic solvents but in addition it associates some water molecules with it (it can be written as $Q^+A^-. xH_2O$) and set up the ensuing equilibrium:

$$Q^+A^-. xH_2O + CO_2 \xrightarrow{K''} Q^+HCO_3^-.(x\text{-}1)\ H_2O.HA \quad K'' = \text{equilibrium constant (VIII)}$$

To facilitate the penetration of the gas across the polymeric matrix usually a plasticizer like tributyl phosphate is used as a component in the film ensemble. This ensemble of dye, phase transfer reagent, plasticizer, hydrophobic polymer and organic solvent offers sufficient potential to develop dry carbon dioxide sensors for routine use. If the above equilibrium is assumed to be decisive equilibrium event, then a new measuring factor R can be defined taking into account the practically measurable optical event as given below:

$$R = (A_{A0} - A_A)/A_A = K''.P_{CO2}$$

A_{A0} = Absorbance of Q+ A- .xH_2O on non-existence of CO_2

A_A = Absorbance of Q+ A- .xH_2O in presence of CO_2.

Both the methods (first one measuring absorbance in aqueous medium (wet method) and other one in presence of organic solvent and phase transfer agents (dry method)) follows similar equilibrium equations as it has been assumed that at wavelength of maximum absorption only Q+ A- .xH_2O absorbs and the dye exists as deprotonated negatively charged species on non-exposure to carbon dioxide (Mills & Hodgen, 2005)

The most often employed and readily accessible fluorescent active indicator in sensing of carbon dioxide optically is 8-hydroxypyrene-1,3,6-trisulfonate(HPTS) (Dansby-Sparks et al., 2010). Unfortunately, there are situations where green emission and blue-spectrum excitation are not the best choices, especially when working with medium that have significant levels of scattering and autofluorescence.

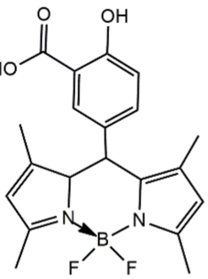
In addition, its pKa of ~ 7.3 makes it more difficult to design sensors to resolve environmental carbon dioxide levels. To get beyond the aforementioned constraints other categories of dye molecules were tried which include, diketopyrrolopyrroles (Schutting et al., 2013), perylene bisimides (Pfeifer et al., 2018), azaphthalocyanines (Lochman et al., 2017) etc. but the modulation of spectroscopic and sensing abilities still remain a major challenge. Among the most often used fluorophoric molecules are 4,4-difluoro-4-bora-3a,4a-diaza-*s*-indacene (BODIPY)dyes, which have high fluorogenic quantum yields and sufficient molar absorptivity coefficients (Loudet et al., 2007). The flourophore become even more appealing as flourogenic sensor for sensing and (bio) imaging, when the absorptivity and emissivity spectral features are elongated into the near-infrared region. Taking into consideration these characteristics, a series of BODIPY pH responsive sensors DI,D2,D3,D4,D5 (Figure 1)were synthesized for sensing CO_2 optically. The core BODIPY chromophoric molecule which absorbs at 505 nm was derivatized to extend the π-conjugation and the resulted derivatives demonstrated absorption at longer wavelength i.e 635 and 665 nm along with large molar absorptivity, fluorescent quantum efficiency and unmatched photostability. The phenol functionalized BODIPY chromophore becomes more sensitive towards pH variations due to the initiation of fluorescent intensity quenching process, in its anionic form. Theses dyes were loaded on ethyl cellulose polymeric matrix coupled with tetraoctylammonium hydrogencarbonate. The functionalized receptor bearing carboxylic group at ortho location to hydroxyl functional group shown considerably sensitive behavior with detection limit of 0.009hPa while the other sensors based on other dye molecules showed LOD from 0.2 to 60 hPa and from 20 to 400 hPa.

di-OH-aza-BODIPYs (D6) (Figure 2) another phenolic functionalized derivative of BODIPY, was developed as colorimetric sensor by Schutting et al. (2015) and it displayed maximum absorption in the NIR region (670–700 nm in neutral state, 725–760 nm in mono-basic form, 785–830 nm in di-basic form), sufficiently large molar absorption coefficients estimated as 77 000 M^{-1} cm^{-1} and stable photonically. The protonable behavior can be tuned by substituting electron-withdrawing or electron-donating functional groups (pKa values 8.7–10.7) hence these sensors offers diverse span enabling their applicability in diversified fields. Another 4-anilineboron-dipyrromethene (BODIPY) based fluorophore (D7) (Figure 2) was introduced by Pan et al. (2014) as sensitive towards acidic pH sensing via fluorescence phenomenon which can be excited in the visible region following PET mechanistic pathway. The pH metric titration demonstrates 500 fold increment in fluorescent intensity in pH span 4.12–1.42 having pKa 3.24 in aqueous methanolic mixture (1:1, v/v) medium, that is necessary to carry out studies in acidic environment. The probe is also found to respond colorimetrically towards dissolved carbon dioxide (CO_2) gas.

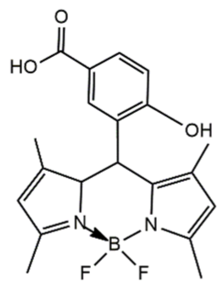
Aggregation Induced Emission Based Small Florogenic Sensors for CO_2

Luminophoric materials demonstrating aggregation-induced emission (AIE) phenomenon show negligible electromagnetic radiative outflow in less concentrated solutions but exhibit measurable fluorescence when the ‘restriction of intramolecular rotation’ (RIR) is brought about by agglomeration or elevated viscous behavior. Aggregation-induced emission (AIE) is an unusual photophysical phenomenon, which occurs when nonemissive luminophores are efficiently driven to emit during the aggregate development. AIE was introduced by Luo et al. (2001), overcoming the limitation of previous aggregation-caused quenching materials. The functioning mechanistic process of AIE has been established as the restriction of intramolecular movements (RIM) .The unique solubility between an AIE/AEE (carrying amine as one of the functional group) compound’s neutral/salt state will cause a phase change to disaggregated form from an aggregated form when used for CO_2 sensing. It will also cause a noticeable increase in

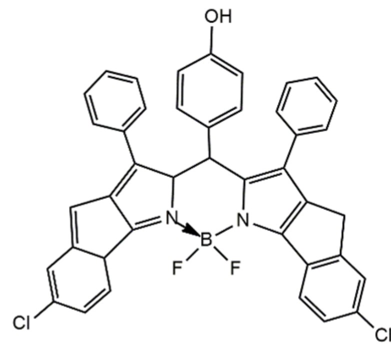
Figure 1. Molecular structures of D1, D2, D3, D4 and D5



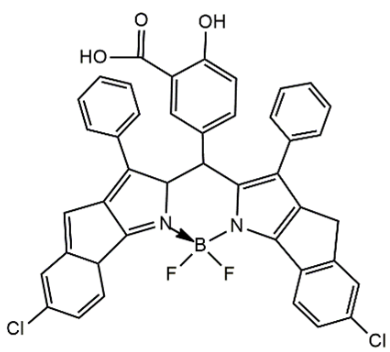
D1



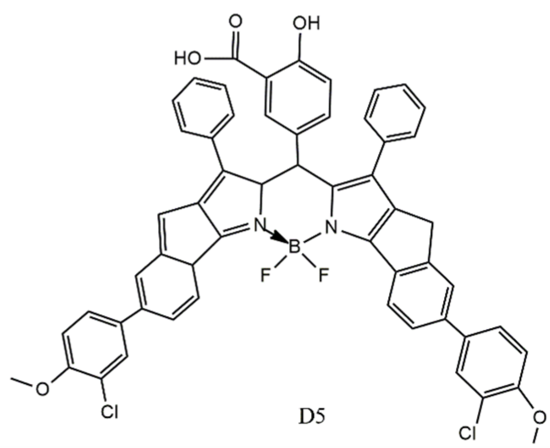
D2



D3

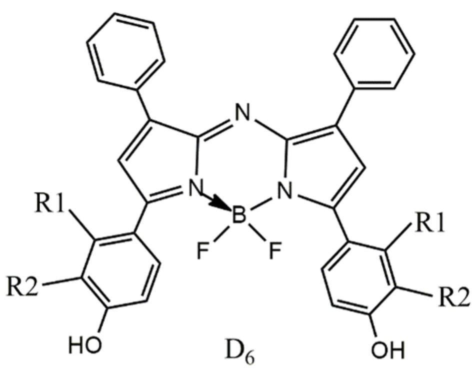


D4

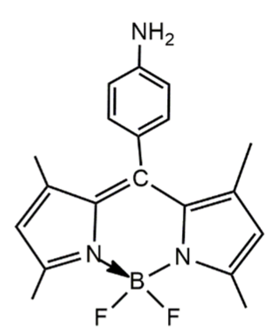


D5

Figure 2. Molecular structures of D6 and D7



D_6



D7

R1=R2=H, di-OH-Complex
R1=H, R2=F, di-F-di-OH Complex
R2=H, R1=Cl, di-Cl-di-OH Complex
R1= CH_3, R2=OH, di-CH_3-di-OH Complex

viscosity due to the formation of electrolytes. These physical changes lead to a pronounced fluorescence integration and hence facilitate the detection of carbon dioxide.

One such AIE/AEE based fluorescent sensor employing dipropylamine solution of hexaphenylsilole as aggregation induced fluorescent system that can recognize carbon dioxide via variation in emission intensity as result of emergence of carbamate ionic liquid of high viscosity. Sun et al. (2013) prepared optically active probe utilizing tetraphenylethene (TPE) as an AIE molecule and 1,8-diazabi-cyclo-[5,4,0]-undec-7-ene (DBU) as an amidine containing molecule. The probe offers a simple and visible method of sensing and detecting CO_2 because they are sensitive to the rise in viscosity caused due to emergence of ionic liquid via specific interaction between amidine moiety and CO_2 (Figure 3). However, these techniques are inappropriate when dealing with biological systems.

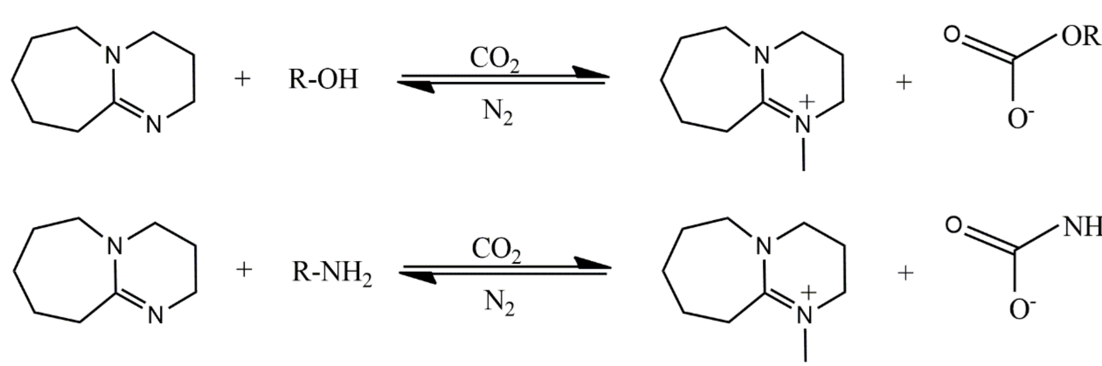
With the intention of enhancing the analysis's sensitiveness, lower the LOD, and improving applicability aqueous medium, the phase transition and AIE/AEE features are used in combination to enhance the measurable signal changes in order to detect low concentration of carbon dioxide.

Wang et al. (2015), prepared the molecules based on 1,2,5-triphenyl-pyrrole (TPP) core containing a different number of tertiary amine moieties, 2-(dimethylamino)ethyl 4-(2,5-diphenyl-1H-pyrrol-1-yl) benzoate(TPP-DMAE), bis(2-(dimethylamino)ethyl) 4,4' -(1-phenyl-1H-pyrrole-2,5-diyl)dibenzoate(TPP-BDMAE) and tris(2-(dimethylamino)ethyl) 4,4', 4''-(1H-pyrrole-1,2,5-triyl)tri-benzoate(TPP-TDMAE). The inherited AEE property and amine functional moiety by the TPP core molecule, TPP-TDMAE among various sensors showed the notable frequency variations on titrating even with a lesser concentration (0.031 to 5%) of CO_2.

Mishra et al. (2019) synthesized cyano derivitized p-phenylenevinylene molecule possessing tertiary amine fragment at terminal position, which aggregates and exhibits fluorogenic and Raman spectral response for C_O2. The aggregation induced emission along with aggregation enhanced Raman scattering of the derivative in aqueous medium diminished on exposure to even a minute quantity of carbon dioxide resulting in its facile and quick recognition in various samples of neutral gases. Furthermore, this AIE based CO_2 assay found to be effective in identifying CO_2 in biological specimens.

Mai et al. (2020) prepared two carbon dioxide fluorogenic chemical signalers, TPE-amidine-L(liquid) and TPE-amidine-S(solid) based on (N,N-dimethyl-N'-(4-(1,2,2-triphenylvinyl)phenyl)acetimidamide. These sensing ensembles demonstrated substantial fluorescent variations initiated by CO_2 and both could be regenerated on exposure to triethylamine. The liquid probe showed the lowest CO_2 detection limit of

Figure 3. Representation of formation of ionic liquid on exposure to carbon dioxide through amidine containing molecule (DBU)



24.6 ppm, while the solid probe made from a polyacrylamide hydrogel framework is capable of serving as a convenient CO_2 fluorescent indicator for in situation monitoring of CO_2. Ma et al. (2015) developed an another fluorescent chemosensor for carbon dioxide gas exhibiting AIE phenomenon, which consists of sodium phenolic salt (ONa^+), as hydro loving moiety, incorporated onto tetraphenylethene (TPE) to obtain TPE-ONa, which is found to be soluble in aqueous medium and displays no emission. On passing CO_2 through the reaction medium, a notable color variation and fluorescence intensity increment is observed. The detection of gas by TPE-ONa in aqueous medium is fast and the detection limit is estimated to be 2.4 $\times 10^{-6}$ M. To realize the operationalization of TPE-ONa, it is conglomerated with sodium carboxymethyl cellulose in aqueous solution to fabricate a porous film and observed sufficient sensing ability. Additionally, TPE-ONa demonstrates low cytotoxicity for live cells and displays the potential to observe external CO_2 concentration variations in living cells.

One more TPE-derived sensing ensemble, sodium-4-(4-(1,2,2-triphenylvinyl)phenoxy)butane-1-sulfonate(TPE-SO_3^{-1}) in combination with a easily procurable polymer(chitosan) utilizes AIE phenomenon of TPE core and act as sensing device for carbon dioxide (Khandare et al., 2015). Dissolved carbon dioxide disintegrate to release H^+ ions resulting in protonation of chitosan which act as befitting counter ion for the (TPE-SO_3^{-1}). (TPE-SO_3^{-1}) molecules assemble with one another in a particular pattern on a polymeric branches of chitosan on account of electrostatic attractive forces between them, resulting in AIE leading to increased fluorescence intensity. Fluorescence emission of the sensor varies linearly with the span of aggregation and depended on the charge density of the polymeric entity, thus amount of dissolved carbon dioxide could be measured by it. This method was applied to live samples and the results displayed were satisfactory. The sensor demonstrated high sensitivity leading to LOD of 0.00127 hPa.

An additional, fluorogenic sensor, tris(2-(dimethylamino)ethyl)-4,4',4''-(1H-pyrrole-1,2,5-triyl) tribenzoate(TPP-TMAE), possessing AEE property synthesized by Chen et al. (2016) demonstrates extreme selectivity, specificity, and respond instantly even to minute quantity of carbon dioxide (CO_2). A notable decrement in TPP-TMAE fluorescent integration by almost 20 times in just 12 s may be attributed to disassembling mechanism coupled by neutralization of amine due to presence of carbon dioxide in aqueous medium. This fluorogenic sensor can quantitatively measure carbon dioxide concentration under the limits 0.031%-5%, which almost enclose the whole range of carbon dioxide gas concentration produced from cell metabolic reactions. This typical feature allows TPP-TMAE to be employed as a biomarker for in-situ measurement of the rate of the target gas production in the course of metabolic reactions a single living cell which enables distinguishability between cancer cells and normal cells.

α-Cyanostilbenes are another class of fluorogenic molecules demonstrating aggregation-based emission as a result of formation of aggregates due to π-π conjugated stacking effect. These molecular frameworks display intense fluorescent emission in combination with adequate photostability in agglomerated conditions in comparison to less concentrated solution. In addition, photoluminescence attributes of these molecules can be modulated by substituting functional arrangement of terminal aryls. Besides, these molecules can be tailored as a turn-on fluorophores, capable of using AIE feature, by substituting various substituents to assist self-assembling.

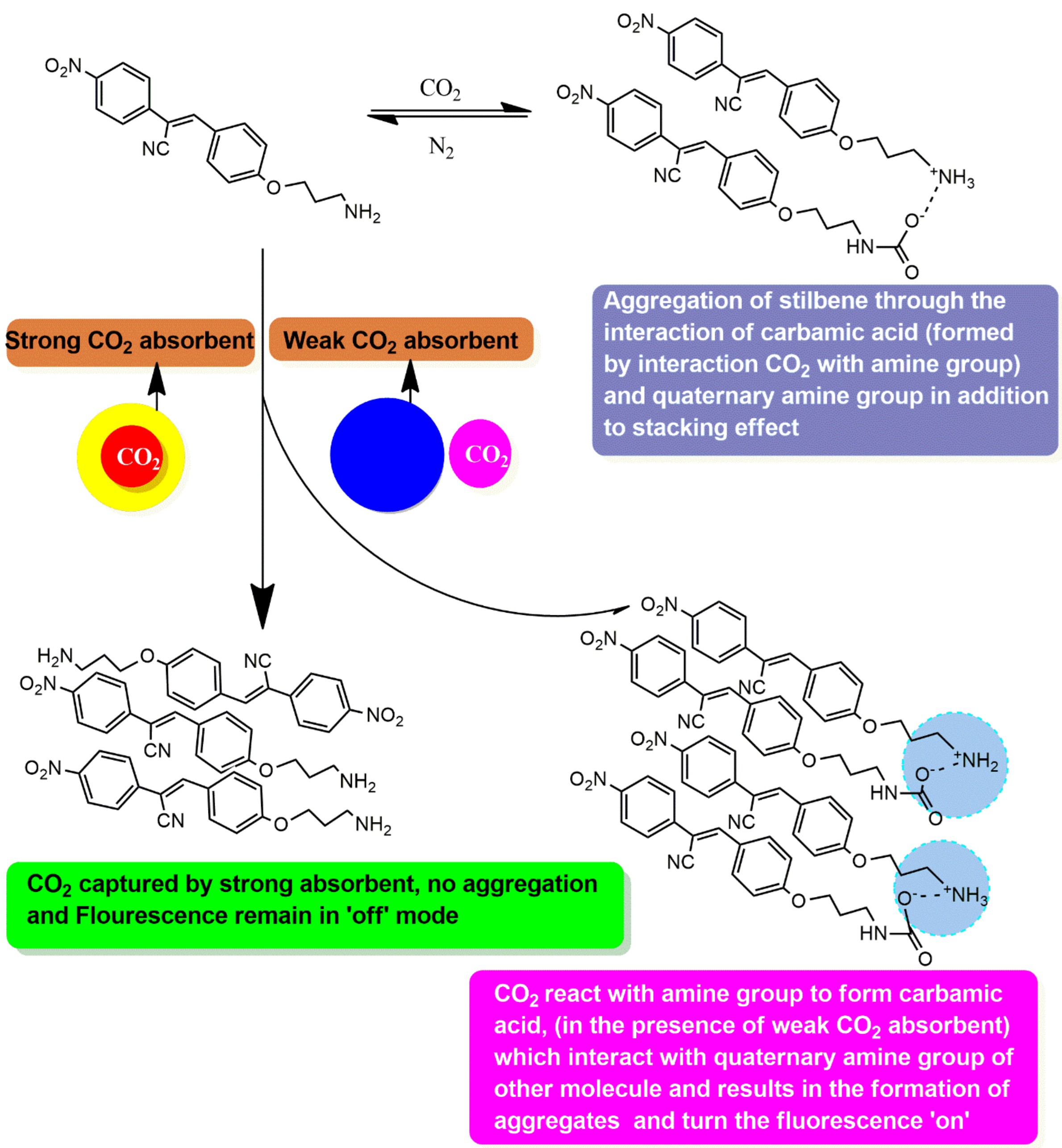
Jang et al. (2019) prepared another probe from α-cyanostilbene[(Z)-3-(4-(3-Aminopropoxy)phenyl)-2-(4-16 nitrophenyl)acrylonitrile], which consists of a primary amino group, for analyzing carbon dioxide quantitatively. It reacts with the target gas and facilitate turn-on fluorescence caused by aggregation-induced emission. More essentially, it does not require any additives like an amine medium for sensing of carbon dioxide gas, and exhibit LOD as ~26 ppm. The current sensing ensemble is further utilized in screening of adsorbents for target gas and it revealed that this system can be employed to create effective throughput screening technique to assess the effectiveness of CO_2 absorbing molecules. The amino group of the sensor reacts with the target gas (CO_2) resulting in formation of carbamic acid, which further reacts with other amine molecules forming salt bridges. Thus, the resulting electronic attractive forces between carbamate and ammonium salt produces self-congregation leads to increased fluorescence. This process can be reversed by bubbling nitrogen gas. As a result, this ensemble exhibiting reversible 'turn-on' fluorescence activity can be used repeatedly and enables the determination of CO_2 quantitatively (Figure 4).

Anion Activated Fluorescent Molecules for Carbon Dioxide Sensing

In addition to aggregation induced emission (AIE) mechanism for fluorescent molecule for recognizing the carbon dioxide, an ancillary mechanism is to activate the fluorescent molecule through anions. N-heterocyclic carbenes (NHCs) are typically formed through deprotonation of appropriate salts of imidazole fragment have the ability to react with carbon dioxide to produce imidazolium carboxylates (Ausdall et al., 2009). The molecules carrying imidazolium fragments react with anionic species present in the vicinity to form a firm $(C{-}H)^{+} \cdots X^{-}$ interaction (Xu et al., 2010). This particular bonds in combination with electrostatic interactions are believed to act as the foundation for the properties of molecular recognition. However, it was speculated that anion is responsible for the activation of imidazolium functional moiety and make them able to interact with CO_2 through the development of NHC (in absence of any additional base). This mechanism proceed in acidic imidazolium arrangement and demonstrated deprotonation-based absorptivity or emissivity within the visible region, it might serve as the foundation for a novel category of optical CO_2 sensing chemical devices. One such recognition mechanism is realized using tetrapropyl benzobisimidazolium salts (TBBI). Guo et al. (2012) submitted a benzobisimidazolium (BBI) salts that work as carbene containing ligating molecule towards metallic entities and found to be fluorescent many time. One of the reports established that the BBI derivative can behave as redox analog in some anion-catalyzed electron transfer mechanism consisting of calix[4]- pyrrole. The referred investigations show that structural alteration can be used to tune the inherent electronic characteristics of BBI cations. A vital property of these fluorogens is the possibility of functional modification at carbon number one (C1) of imidazole fragment that enable tuning of photophysical features demonstrated by these salts, as evidenced by the corresponding variations observed in photophysical properties. Taking these observations into consideration, it has been thought that functional substitution at C1 of derivatized BBI would enable the preparation of efficient sensor system for carbon dioxide gas. To accomplish the target the research group particularly added F^- ion, which is not a strong base, might result in a species with some NHC characteristics thus resulting in interaction with carbon dioxide gas. As a result of these associative type interactions optical variations occur which enables the detection. The researchers synthesized tetrapropylbenzobisimidazolium salt (TBBI) an organic-soluble NHC precursor. Spectrometric and theoretical investigation revealed that on addition of fluoride ions, N-heterocyclic carbene intermediate is formed that interact with carbon dioxide to result in imidazolium carboxylate. The method demonstrates a notable selective response towards fluoride ion with a low LOD of 30 ppm and quick response both fluorometrically and colorimetrically (Figure 5).

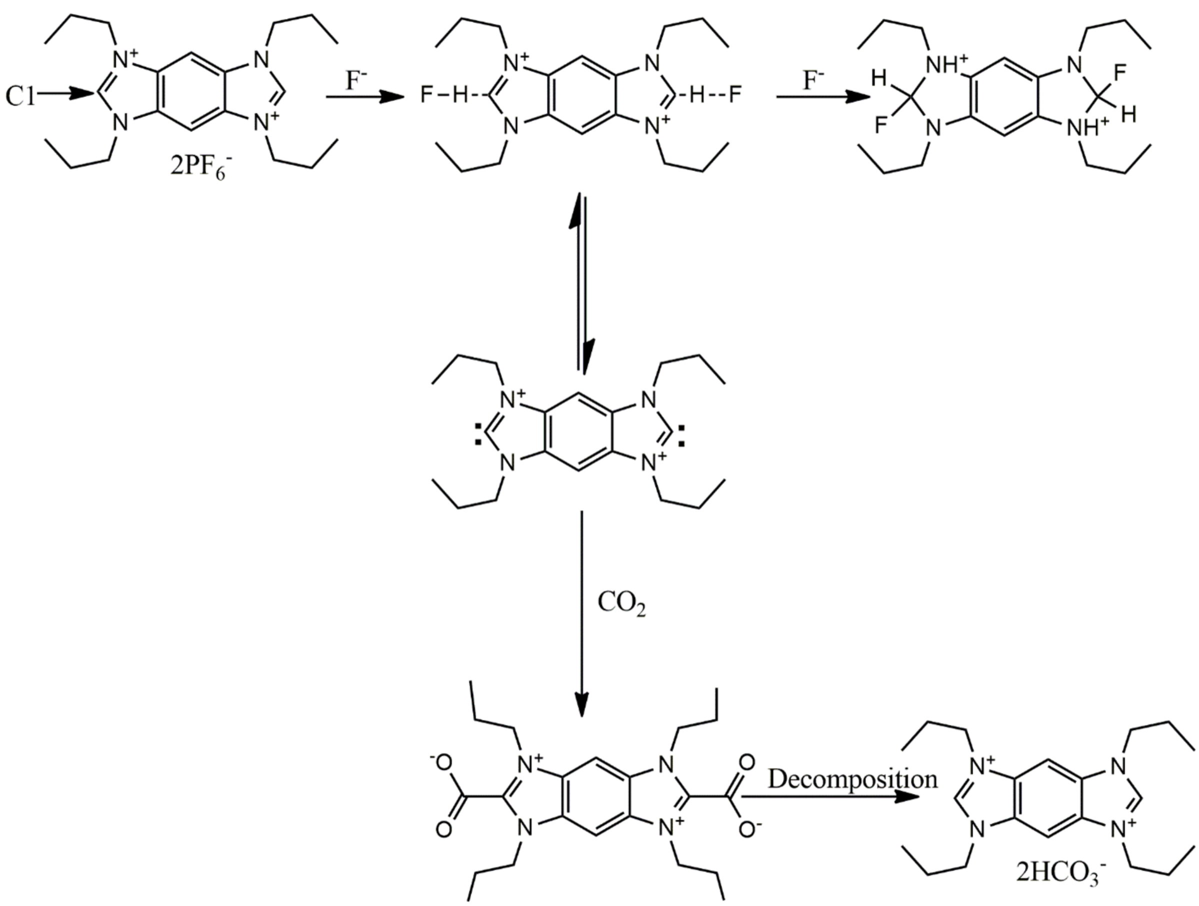
Kwon et al. (2009) prepared two naphthoimidazolium derivatives (D8, D9) (Figure 6) activated through fluoride and cyanide ions and employed to sense CO_2. In the pool of different ions only F^- and CN^{-1} ions are able to bring out the optical changes in acetonitrile medium. These variations can be assigned to $[(C{-}H)^{+}$–negatively charge specie] hydrogen bond type attractive forces associated with imidazolium

Figure 4. Carbon dioxide sensing through aggregation induced emission phenomenon by α-cyanostilbene based fluorescent chemosensor



salts and anions. A notable observation is that the wavelength of maximum emission (465 nm) shifted hysochromically (375 nm) on exposure to F^- and CN^- ions. Additionally, on exposing CN^- activated fluorogen to CO_2 allows shifting towards red region for the emission maximum to 465 nm. The detection limit of the one of the derivatives towards carbon dioxide with F^- activated sensor was estimated

Figure 5. Plausible mechanism of fluoride activation of TBBI molecule at C1 position and sensing of carbon dioxide

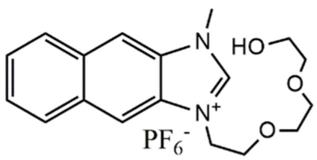


as 1.96 × 10^{-4} M and 4.45 × 10^{-3} M with CN^- activated sensor. For the other derivative, the calculated LOD is 8.44 × 10^{-6} M and 1.16 × 10^{-5} M.

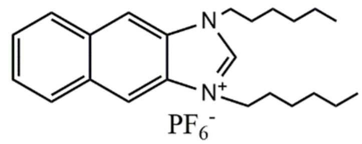
Adding further, Ishida et al. (2013) synthesized N-fused aza-indacene-based (D10) (Figure 6) fluorogen through the condensation involving benzimidazole-carbinol, trifluoroacetic acid and indole. The N-fused aza-indacenes behaves as optical chemical sensors for CO_2 which is supposed to work through fluoride anion-mediated deprotonation. The fluorescence intensity of the sensor diminishes on addition of fluoride ion, indicating deprotonation of the sensor and this deprotonation event has occurred only on addition of fluoride ion not with other ions. When fluoride pre-treated sensor brought into contact with carbon dioxide a pronounced variation was observed in optical spectra. It was thought theoretically that this contact will aid in the retrieval of the fluorogen. This thought was further supported by the ^{1}H-NMR studies, the spectra of original sensor and that of the sensor after treatment with CO_2 corroborate well. The detection limit for CO_2 under these conditions was thus calculated to be 4.1 x 10^{-7} M.

Lee et al. (2015) prepared naphthalimide derivative, N-[2-(2-hydroxyethoxy)ethyl]-4,5-di{[(2-methylthio)ethyl]amino}-1,8-naphthalimide(D11) (Figure 6) as a carbon dioxide sensor activated by anion taking cognizance of previous studies. They introduced naphthalimide amine derivatives as sensors for carbon

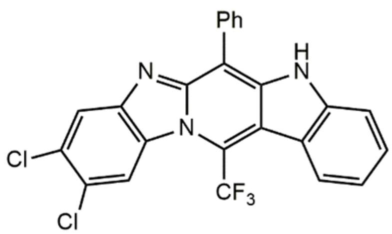
Figure 6. Molecular structures of sensor D8, D9, D10, and D11



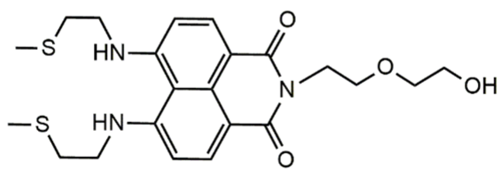
D8



D9



D10



D11

dioxide gas following the fluoride activated deprotonation of amine functional group and consequential interaction with carbon dioxide. The molecule displayed selectivity towards fluoride and cyanide ions both fluorometrically and colorimetrically, which may be because of strong hydrogen bonding attraction of hydrogen of amine functional and anions. On addition of CO_2 the color and fluorescence of the molecule is retrieved and showed distinct "On-Off-On" fluorescence emission variations. The LOD of the anion activated system for carbon dioxide is calculated to be 2.04×10^{-7} M.

A category of chemical dyes known as squaraine dyes exhibits strong fluorescence and substantial absorption coefficient, usually in the red and NIR spectral regions. Considerable absorbance, fluorescence spectral features and ample fluorescence quantum efficiency makes them a suitable as signaling fragment in various chemical sensors and dosimeters (Mayerhöfer et al., 2012). Realizing the successful applicability of squaraine based chemosensors towards anions, Xia et al. (2015) thought to use anion (anion used here is $[Bu_4N]F$) activated squaraine based molecules for visible and reversible recognition of carbon dioxide gas. Between the two isomers (i.e. 1,2 or 1,3 derivatized) of squaraine, the hydrogen bond donor type capability of 1,3 substituted isomer is more as compared to other, which makes it a potent contender for hydrogen bond involving anion sensing. Considering this, the group has prepared unsymmetrical 1,3-squaraine (Figure 7) and investigated its sensory behavior for carbon dioxide in detail through UV-VIS spectrophotometry and ^{1} HNMR spectroscopy in dimethylsulphoxide medium. In presence of 20 folds of fluoride ions the sensor turned green in color owing to large bathochromic shift from 445 nm to 655 nm. When this green solution was kept in open air, the intensity of the signal at 655 showed decrement and the peak at 525 nm showed increment in intensity and green color turned back to purple. This observation suggests that atmospheric CO_2 gas responds to sensor. Hence, increasing concentration of CO_2 gas was given to the sensor solution pretreated with 20 folds of fluoride ions and the spectrum overlapped with that of 5 fold fluoride ions added solution. These features enable the sensing system to behave as a carbon dioxide and fluoride controlled "OFF-ON-OFF" molecular switch. The LOD of the molecule towards the gas was calculated as 15.6 ppm along with immediate reaction.

The plausible mechanistic pathway for the detection is given in the Figure 7. On F^- ion addition, the sensor SH_2 deprotonate following the equilibrium:

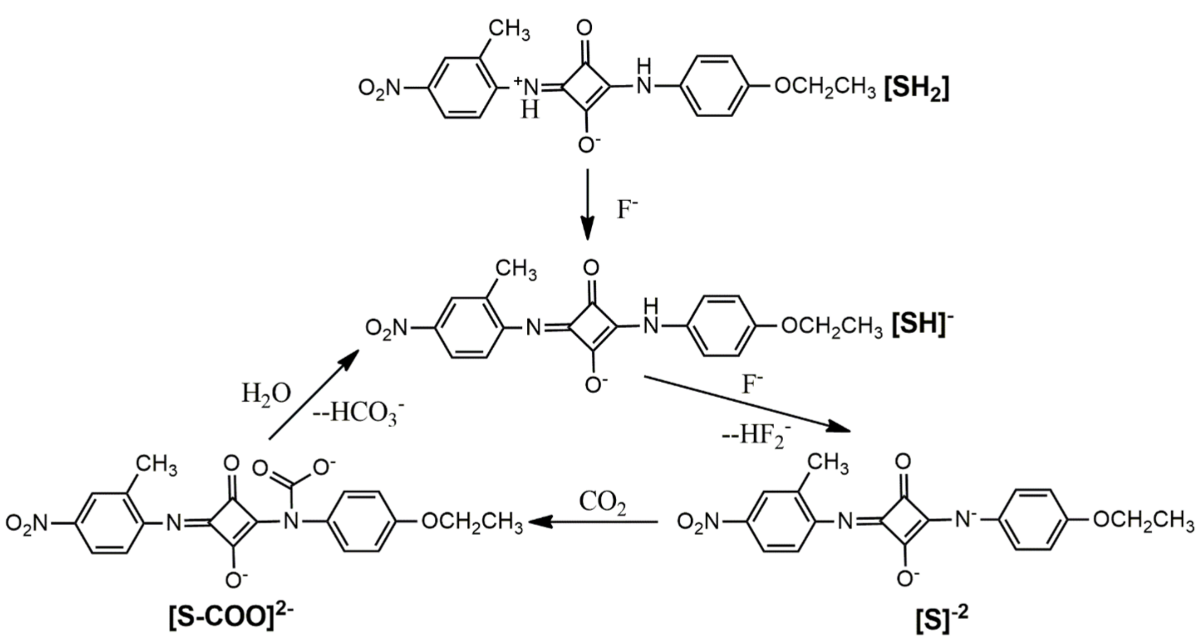
$SH_2 + F^- \leftrightarrows SH^- + HF$ (IX)

$SH^- + 2F^- \leftrightarrows S^{2-} + HF_2^-$ (X)

Green colored sulphide ions were highly unstable and reacts with carbon dioxide to form $S\text{-}COO^{2-}$ which immediately break down to SH^- ion and bicarbonate ions.

Another anion activated D-p-A type fluorophore was reported by Ali et al. (2016). It was prepared by connecting imidazole (donator D) with benzothiazole (Gainer A) by means of a phenyl (p) ring. It displays intramolecular charge transfer turn on fluorescent behavior. The photophysical responses of the fluorogen is studied in solvents of varying polarities and pH. The molecule displayed high selectivity towards F^- ions in presence of other ions in 20% DMSO water solvent system. Job's plot established 1: 1 bonding between the sensor and fluoride ion displaying notable binding stability and limit of detection (30 ppb). Fluoride bound sensor when exposed to carbon dioxide significant naked eye color variations are observed in which the initial color is retrieved along with corresponding revival of emission intensity. This behavior could be assigned to emergence of imidazolium hydrogen carbonate/ imidazolium ions/ salt originated due the reaction imidazolium ion with carbon dioxide gas. The studies revealed LOD as 100ppb;2.29mM).

Figure 7. Anion activated mechanistic pathway for carbon dioxide sensing by unsymmetrical 1,3-squaraine



[Indolo[3,2-b]carbazole(ICZ) derivatives consist of two N-H moieties, and it has been reported that N-H moiety can be deprotonated by anion and the deprotonated product can react with carbon dioxide to form the adduct N-COO$^-$. Based on these cognitions, the ICZ is functionalized with phenyl groups to improve the solubility and 6,12-Diphenyl-5,11-dihydroindolo[3,2-b]carbazole(DP-ICZ) derivative is obtained (Chen et al., 2017). On addition of fluoride ions the color of the solution changed to clay bank and the obvious color changes also reflected in photoluminescence behavior. It displayed blue fluorescence at 450 nm which changed to faintly yellow (562 nm) in the presence of fluoride ions with a concomitant decrease in fluorescent intensity from 972 to 40. In presence of other competitive ions this effect is found to be absent which establishes the selectivity of the probe towards fluoride ion. Previous reports established that nucleophilic N is one among the functional moieties that can use infirm electrophilic character of carbon dioxide gas for recognition application. The N-H fragment of DP-ICZ deprotonates on reaction with fluoride ions and on subjection to carbon dioxide gas showed disappearance of fluorescent peak at 562 nm along with appearance of new peak at 450 nm that appeared as retrieval of DP-ICZ. The LOD was determined as 1.07 μM. The mechanism of sensing may be attributed to transition from DP-2F to DP-ICZ. The assumption was further supported by ^{1}H NMR spectra of sensor, fluoride activated sensor (DP-2F) changes to DP-ICZ on exposure of CO_2. On adding four equivalents of F^- followed by exposure to excessive gas in deuterated chloroform, the NH peak located around 8.10 ppm diminishes first and reappeared afterwards. This event indicated that on exposure to the gas, the molecule transforms from fluorinated sensor to DP-ICZ. To investigate further, deuterated chloroform was changed to DMSO-d_6 to solubilize the precipitates that were present in chloroform resulted in appearance of signal at 8.45 ppm. Previous reports established the appeared peak for HCO^{3-} anion. Therefore, the mechanistic pathway can be proposed to proceed through the formation of DP-2F and CO_2 to DP-ICZ and $HCO^{3\,-}$.

Intramolecular Hydrogen Bond and Colorimetric Dye Based Fluorogens for Carbon Dioxide Sensing

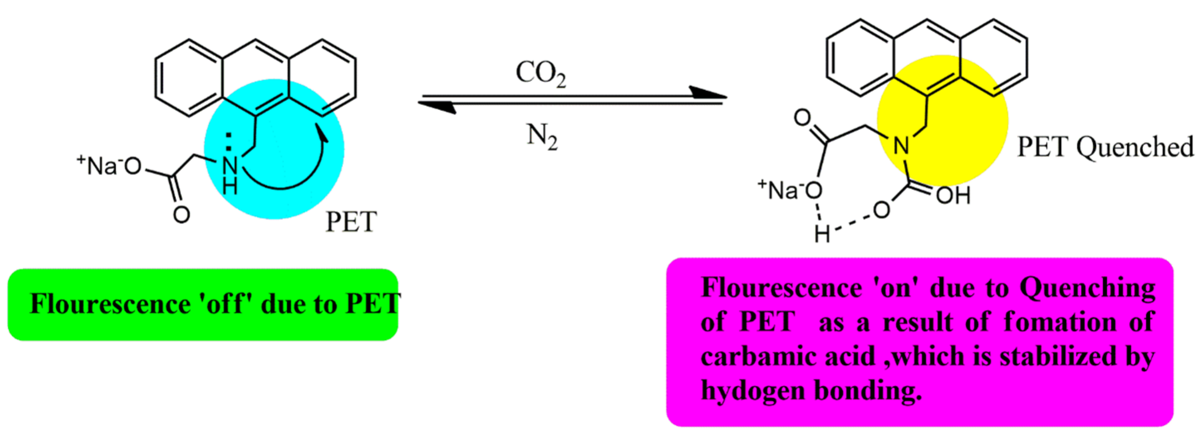
A hydrogen bond may be defined as intermolecular or intramolecular associative interactions between the two dipoles, when a highly electronegative atom containing lone pair of electrons is close to the hydrogen attached to an electronegative atom forming two dipoles. These bonds are as crucial as that of other forces like van der Waals interaction, non-covalent attractions and electrovalent bonding. These can be classified into two types: strong hydrogen bonds (energy is 12 kcal/mol) and standard hydrogen bonds (energy is 3-5 kcal/mol). Owing to their capability to stabilize the intermediates produced in the course of the reaction procedure, strong hydrogen bonds become imperative to many enzymatic and catalytic processes. To our interest, these interaction are also found to stabilize the intermediate formed on exposure to carbon dioxide and enable sensing of the analytical gas. Kang et al. (2015) reported a fluorophore for detection of carbon dioxide gas consisting of anthracene molecule appended to an amino acid. The probe is capable of stabilizing the carbamic acid formed during the formation of probe –CO_2 adduct via intramolecular hydrogen bonding. The amine moiety inherent in the chemical structures interact with carbon dioxide gas resulting in the formation of carbamic acid. The carbamic acid formed as mentioned above, act as proton contributor and carboxylate moiety of amino acid act as proton acceptor, thus resulting in the formation of hydrogen bonds. The emergence of these interactions leads to stabilization of carbamic acid thus making amino acid and functionalized amino acids a potential candidate for carbon dioxide gas sensing. The fluorescent emission for 1-aminomethylanthracenes moieties is diminished through photoinduced electron transfer by amine moiety towards anthracene.

But, on binding with metallic ions derivatized 1-aminomethylanthracene forms amide bond resulting in appreciation of fluorescent intensity, as result of blockage in the occurrence of PET. Taking these outcomes into cognizance, Kang et al. (2015), designed a fluorophore by appending anthracene moiety to sodium salt of amino acid as shown in the Figure 8. On exposure to carbon dioxide gas the fluoroprobe react to form carbamic acid bonded via hydrogen bonding with carboxylate ion, thus eventually blocking photoinduced electron transfer mechanism and induces fluorophoric increment of the adduct displayed in the Figure 8. The spectral information enables the researcher to estimate the detection limit of the probe for CO_2 to be ca. 2 ppm.

A series of effectual, solid-state probes for sensing carbon dioxide were prepared by Chatterji and Sen (2015), the probes consists of a gas receptive tertiary amino alcohol for example triethanol amine along with pH-indicator like cresol red, supported on aluminium oxide solid assistance. These probes demonstrated detectable visual signal even in the presence of minute quantity (ppm level) of environmental CO_2 and SO_2 without any interference from water molecules. The sensitivity possessed by the sensors was investigated with the signaling dyes bromothymol blue (BTB) or cresol red (CR), base (N,N'-dimethyl-2-methoxyethylamine, triethylamine, equimolar mixture of triethylamine and ethanol). These reaction mixture did not showed any change in color, demonstrating unequivocally that the formation of the alkylcarbonate moiety requires tertiary amino alcohol as skeleton. Keeping in view the observations, the researchers proposed the mechanism to be based on protonation-deprotonation equilibrium. Cresol red (CR) react with tertiary amino alcohol to interchange proton to form deprotonated anionic dye species which are purple in color. Amino alcohols when interact with carbon dioxide gas results in zwitterionic ammonium carbonate adduct. This hinders the proton removal from the signaler dye molecule by the amino alcohol, resulting yellow color of the protonated dye is visualized.

One more cresol based sensor, consisting of sensing mixture that comprise of the sensor sensitive to pH variations(cresol red) embedded on a gas-penetrable membrane, is synthesized by Kwanyoung et al. (2020). pH signaler when subjected to carbon dioxide demonstrated color variation, this variation is quantified by an RGB application. The shift in G and B values of the sensing mixture displayed noteworthy linear relationship with amount of carbon dioxide present in soil measured through non-dispersive infra-red (NDIR) probe enabling quantification of analyte concentration. Experiments through carbon

Figure 8. Mechanism of sensing of CO_2 by anthracence based fluorescent molecule via, stabilization of carbamic acid, formed by interaction of CO_2 with ligand, through hydrogen bonding



dioxide injection chamber revealed that the indicator has the ability to recognize soil carbon dioxide amount of 0.1 to 30% in a very short span of time. Real place investigation at a natural CO_2 opening and CO_2 leakage location revealed that this sensor can be utilized in measuring surficial CO_2 leakage and it offers a cost effective means of sensing along with the advantage of uncomplicated system installation.

Schutting et al. (2013) prepared Diketo-pyrrolo-pyrrole (DPP) based novel class of pH responsive sensors for carbon dioxide sensing and these were rendered dissolvable in organic solvents and in polymeric solvents through functionalizing dialkyl sulfonamide functional moieties. DPP and their derivatives are utilized in developing biophotonics and optoelectronics possessing less bandgap polymeric or copolymeric materials offering conjugation to be used in semiconductors. Qu et al. (2010) suggested a fluoride sensor that caused a shift to longer wavelength in wavelength of maximum absorption due to deprotonation of the lactam moiety of DPP chromophoric sensor. These observation suggested that DPP derivatives offers a promising potential for developing sensors for carbon dioxide as they are based on acid base equilibrium. The DPP based indicators synthesized by Schutting et al. (2013) display notably important absorption and emission spectral features in non-deprotonated or deprotonated forms that makes colorimetric and ratiometric measurements possible. The probe also offers modulatable sensitivity, appreciable optical variation even at less concentration of carbon dioxide and considerable photostability. The synthesized sensors coupled with tetraoctylammoniumhydroxide was planted on ethylcellulose to form plastic sensing entity for the gas under consideration. The probes sense CO_2 and showed color variation (blue when CO_2 is absent and pink when present) thus making colorimetric recognition possible. Noticeable shifts in the fluorescent intensity further support the color variation. For all the derivatives the fluorescent emissivity both in neutral and anionic form showed increment with increasing CO_2 amount. This increment of intensity for anionic form can be attributed to appreciable decrease in concentration of neutral form not the FRET. This may be because of spectral overlapping of emission spectra due to non-deprotonated species and absorption spectra due to anionic species formed by deprotonation.

Another diketo-pyrrolo-pyrrole (DPP) based sensor, 2-hydro-5-tert-butylbenzyl-3,6-bis(4-tert-butylphenyl)-pyrrolo[3,4-c]pyrrole-1,4-dione(DPPtBu^3) to sense carbon dioxide optically is synthesized following a facile one step synthetic route from ‘Pigment Orange 73’. Lactam nitrogen of ‘Pigment Orange 73’ is derivatized with tert-butylbenzyl group. The signaling dye molecule can be easily solubilized in organic/polymeric solvents and displays pH-dependent absorption. Both the species also demonstrate notable fluorescent quantum efficiency (φ_{prot}0.86;φ_{deprot}0.66). Thus, allowing the sensing of the carbon dioxide gas colorimetrically and ratiometrically (fluorescence intensity). The emission from the two species sensor corroborate well with the signals obtained from green/red routes for RGB photographic system. This makes possible the visualization of carbon dioxide dispersal through an uncomplicated and cost efficient optical set-up. This sensing system demonstrates exceptional sensitivity and is especially auspicious for tracking carbon dioxide levels in the atmosphere (Schutting et al., 2014).

It has been documented that certain amines other than primary amines interact with carbon dioxide and form carbonate ionic liquids when alcohols are present or form of carbamate ionic liquids with one another. Consequentially, physical characteristics, which include polarity and viscosity showed significant variation to larger values. These variation in physical parameters could be reversed to original standards by desorbing carbon dioxide by bubbling nitrogen gas. These amine/alcohol combinations are therefore sometimes called “smart solvent systems”. These variations in said physical parameters can be visualized by bare eyes with the assistance of indicator dyes. Charge transfer dyes (CT dye) assist in visualizing the variations in polarity. Fluorescent intensity decreases along with concomitant red shift with the increase in polarity. While, the viscosity variation can be seen using molecular rotor dyes (MR dye). Because of restriction of intramolecular rotation, the fluorescent emission caused by molecular rotor type pigments usually showed noticeable increment with the rise in solvent viscosity. Jin et al. (2016) dissolved both the dyes in amine/alcohol concoction. The fluorescence emission bands for the dyes do not overlap, the emission caused by CT dyes dominates in lower polarity and high viscosity solutions (the case before the interaction with carbon dioxide) however, on exposure to carbon dioxide the emission from CT dyes diminishes and emissions of MR dyes emerges and dominates in more polar and viscous solution (Figure 9). In particular, the group has taken combination of a Nile Red with allyl-2-cyano-3-(1,2,3,5,6,7-hexahydropyrido[3,2,1]quinolin-9-yl)acrylate(ACHQA) as the CT dye and MR dye, respectively. Equimolar combination of 1,8-diazabicyclo-[5.4.0]-undec-7-ene(DBU) with 1-propanol was the choice for smart solvent concoction. Nile Red and ACHQA in DBU/1-propanol medium emanated red light attributed to Nile Red, while the color subsequently moved towards green as the concentration of CO_2 is increased.

Aazaphthalocyanine dyes (AzaPc) have been demonstrated to exhibit favorable spectrum features, notable molar absorptivity (over 200 000 $L.mol^{-1}.cm^{-1}$) and appreciable quantum yields (up to 50%). These dyes are stable under the effect of radiant energy and easy derivatizable as per the requirement. Derivatizing with appropriate detection receptors these dyes can be made responsive to pH and metal ions.

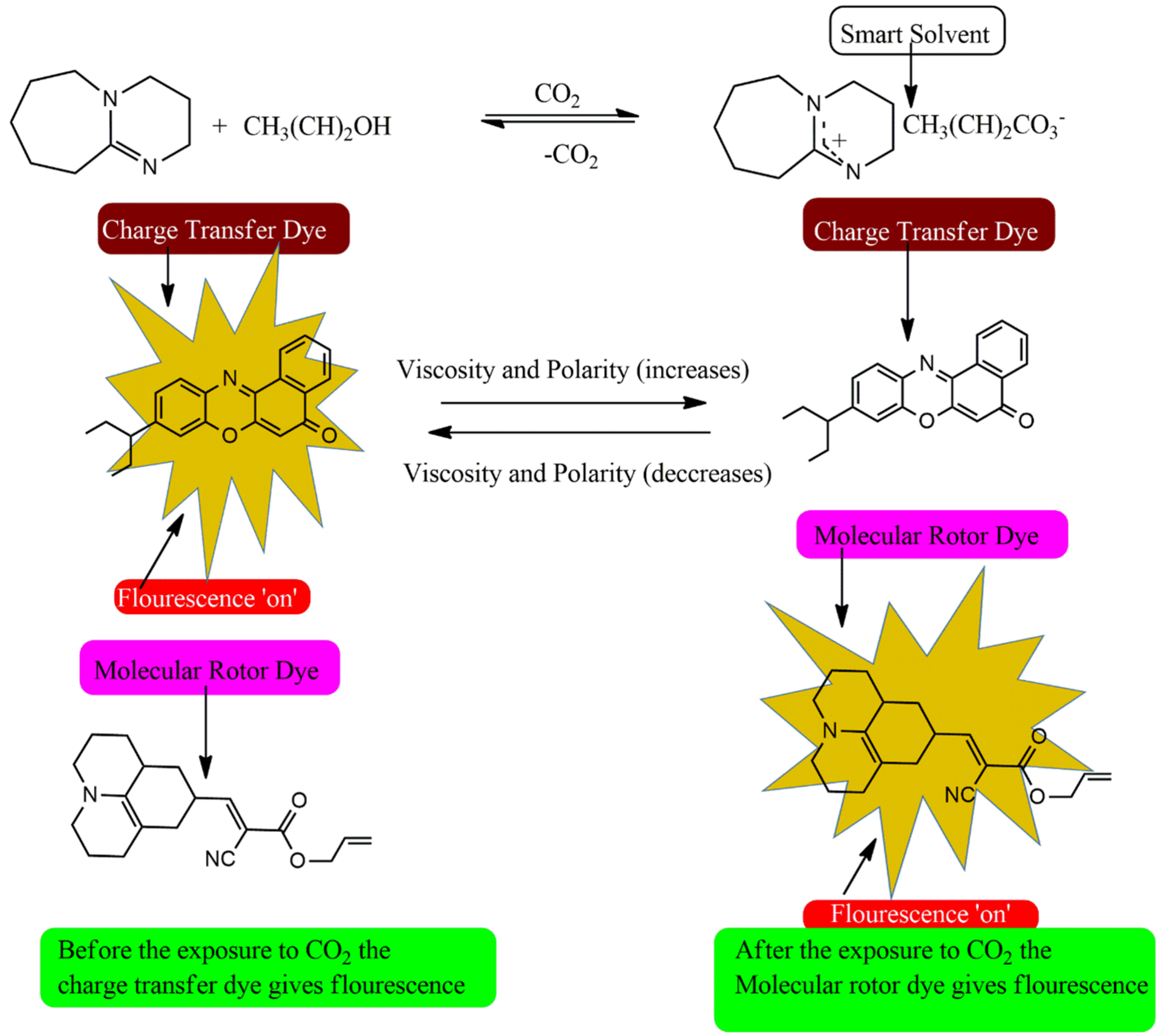
By controlling the intramolecular charge transfer mechanism the fluorescence switching to on and off state can be modulated. These novel pH indicators responsive in basic pH range offers the promising potentiality for use in optical CO_2 sensors. This could help these sensors overcome some of the shortcomings of the most advanced ones. Lochman et al. (2017) prepared CO_2 sensors reliant on zinc azaphthalocyanine (Zn-AzaPc) signalers implanted on polyurethane polymeric frameworks. All the four sensors displayed no fluorescence in their deprotonated form (when carbon dioxide is not present) and switch to ‘on’ mode when exposed the gas under analysis. The receptor carrying one phenolate receptor is found to be most appropriate because of the exceptional brightest emission. Hydrophillic Hydrothane is used as matrix in place of ethylcellulose matrix in case of hydrophobic Zn-AzaPc sensors. Hydrothane 25 displayed exceptional outcomes, increasing fluorescence intensity twelve folds in off/ on stages, notably effective quantum yield (0.071) and repeatable reaction towards carbon dioxide ranging in 0 - 95 kPa, along with little dependability on temperature ranging in 15-35 °C. Crucially, sensitiveness rose dramatically when a base’s alkyl chains were shortened, following the sequence TOAOH ˂ TBAOH ˂ TEAOH. This provides useful mechanism for extending the range of probes for variety of utilities.

Pfeifer et al. (2018) synthesized one more class of indicators based on derivatives of perylene molecule for optical recognition of pH and CO_2 gas. These molecular scaffolds showed appreciable luminescent features photostability and versatile chemical derivatization. The sensors can be prepared through a facile one step synthesis from Lumogen Orange. Distinguished fluorescence spectral profiles of these molecules for various forms made possible the colorimetric and ratiometric investigation of pH and carbon dioxide. The sensitivity towards carbon dioxide can be modified by varying the dye, amount of plasticizer and type of quaternary ammonium salt. The di-substituted perylene displays distinct features with two protonation/deprotonation equilibria capacitate recognition of analyte gas molecules in unprecedentedly broad dynamic range.

Nanomaterials Based Sensing Probes for Carbon Dioxide

The sensitivity of the sensing probe for the analyte is significantly influenced by the dimensions of the material. The unique and enhanced properties exhibited by materials with nanoscale dimensions may

Figure 9. Mechanism of sensing of CO_2 by the concoction of CT organic molecule and MR organic molecule



be ascribed to the enhancement of surface area at their disposal. The enhanced properties encompass size-dependent characteristics, increased catalytic activity, accelerated response and recovery, and surface energy. These attributes are pivotal in facilitating the enhanced sensing capabilities of sensors based on nanomaterials. As these materials own a larger surficial area per unit mass inevidently lead to increment in the surface energy. The enhanced surface energy improves cohesiveness of the material for the gas molecules and facilitates gas adsorption, thus enabling the sensing of the gas. Nano dimensions resulted in quantum confinement effect, which substantially influence the optical properties of material along with band structure and electronic features, thus increasing sensitivity towards environmental changes. Also, the larger surface and small dimensions accelerate gas diffusivity or adsorption, making the response and recovery times' quick.

Among the various forms of nanomaterial, burgeoning interest has been drawn towards carbon nanodots (CDs) on account of their extraordinary behavior in terms of ease of synthesis, chemically inert, unsusceptible to photobleaching, less toxic behavior, and satisfactory compatibility towards biotic system (Baker et al., 2010). Thus, enabling the carbon nanodots to act as sensors, catalysts, bioimaging entities and in drug delivery system (Zhao et al., 2011). Carbon nanodots normally have carboxylic acid or amine groups on the outer surficial area, which allows easy derivatization. Thus, functionalized carbon nanodots able to sense a particular entity can be formulated by derivatizing the surface with the receptors responsive towards analyte. Amino polymers like polyethyleneimine (PIE) are easily available and respond to carbon dioxide frequently. The amine-coated CDs produced by pyrolyzing a combination of carbon carrier and PEI are reportedly insensitive to CO_2, despite the fact that substituted PEI are coated as protecting layers on luminescent CDs. This insensitivity may be primarily because of the carbonization of carbon dots at elevated temperatures. Pei et al. (2017) prepared PEI coated carbon dots (PEI-CDs) by using three polymeric materials available in the market with molecular weight (Mn = 600, 1800, 10000 g/mol). The fluorescence spectral studies along with ^{13}C NMR studies were carried out to investigate CO_2-molecular switch 'on/off' type fluorescent behavior of the prepared PEI-CDs in water/DMSO solvent system, which were further employed to quantify the acidic gases like CO_2 and SO_2. The precipitates formed by the interaction of PEI-CD with carbon dioxide in dimethyl sulphoxide and water solution were gathered and ^{13}C NMR studies were performed. A peak located on 160.2 ppm appeared and attributed to HCO^{3-} anion, which evidenced the emergence of polyammonium bicarbonates precipitates. The pH of the solution showed decrement from 9.3 to 7.5 on attaining the equilibrium after the exposure to carbon dioxide gas. To further investigate the factors responsible for switching on/off of fluorescence, the variation caused by pH change on the fluorescence intensity of the system was investigated. To attain the purpose, hydrochloric acid was poured into the solution having PEI1.8K-CD (4 mg/ml) to maintain the pH value to 4.0, 5.0, 6.0, 7.0, 8.0 and 9.0 respectively, when the system is not exposed to carbon dioxide. Only a little change in fluorescence intensity was observed on varying pH from 7.5 to 9.0, which indicates that the pH change can only diminish/recover fluorescence intensity but not responsible for switching between the two modes. When carbon dioxide gas was exposed to the aqueous solution of PEI1.8K-CD and aqueous DMSO solution of PEI1.8K-CD at the same PEI-CD content of 4 mg/ml, no precipitates was observed for aqueous solution while for aqueous DMSO solution system polyammonium bicarbonate precipitates were formed. The formed precipitates were insoluble in the solution, it thus decreased the concentration of carbon dots and lead to switching off of the fluorescence. The results revealed that the emergence of precipitate of polyammoniumbicarbonates in water/DMSO medium engage in a vital role in switching the fluorescence modes on/off. Thus, the redox equilibrium between carbon dots and CO_2 followed by the production of precipitates (hydrophilic polyammoniumbicarbonates) are responsible for the fluorescence "on-off" outcomes. The reaction can be reversed on bubbling nitrogen gas.

Nemade & Wahguley (2014) fabricated chemically resistant carbon dioxide sensing probes comprised of graphene/aluminium oxide quantum dots. Composite material by varying percentage weight of graphene (20–80 wt%) and fixed one gram of aluminium oxide were prepared and sensing experiments were carried out. The outcomes of the investigations revealed that graphene/Al_2O_3-based sensors demonstrated notable identification which increases proportionally on incremental introduction of graphene.

The mechanistic pathway for recognition of gas is proportional to defect density caused by addition of grapheme onto the fixed amount of aluminium oxide. These defects offer vacancies for the atmospheric oxygen to be adsorbed. The adsorbed oxygen undergoes the reaction given below:

$O_2(g) \longrightarrow O_2$ (adsorbed) (XI)

O_2(adsorbed) + $e^- \longrightarrow O_2^-$ (adsorbed) (XII)

O_2^- (adsorbed) + $e^- \longrightarrow 2O^-$ (adsorbed) (XIII)

Recognition of carbon dioxide depends mainly upon the reaction of the surfacial molecules of probe and adsorbed oxide ions. Carbon dioxide is adsorbed by the bridging oxygens, resulting in emergence of surface carbonates, which eventually increases the resistivity of chemiresistor probe revealing the nature of probe to be n-type. 80 wt% graphene/Al_2O_3 composite found to have best among others in terms of sensor features like reaction time, temperature requirement and stability. The same research group also synthesized Graphene/Y_2O_3 (20 wt% graphene into 1 gram Y_2O_3) quantum dots composite chemiresistor type sensor for carbon dioxide gas. Graphene and the 20 weight percent graphene/Y_2O_3 composite exhibit good dependence on the CO_2 gas concentration (Nemade & Wahguley, 2013). The optimal sensing was calculated to be 1.08 for 20-wt% of graphene/ Y_2O_3 at 35 ppm of carbon dioxide amount. The mechanism for gas detection can be attributed to electron transfer reaction in which one of the reactant is oxidized while other is reduced. The existence of weak electrical attraction between the reactant entities (ions/ molecules) is the necessity for electron transfer process to proceed. The deviation of the reduction potential of donating and accepting reactants provides the driving free energy for the redox reaction. The detection pathway is similar to above composite that is the interaction of adsorbed oxygen ions and carbon dioxide. Due to the electron withdrawing nature of CO_2, it draw the electrons from the surface resulting in increment of electrical resistance, thus enabling the sensing.

The sensitivity of the sensor probe that works on the principle of interaction of surface molecules with entity to be analyzed, can be improved by the augmentation of the surface area. Electrospinning is one of the cost effective technique for preparing membranes with increased surface. In this method stronger static voltage is applied to generate an framework of short chained fibres (having diameter value from 10 to 1000 nm). Electrospun nanofibrous frameworks fabricated using this method are reported to possess 1 to 2 orders increased surface area as compared to regular thin films. This huge accessible surface area is anticipated to have the potential for exceptional sensitivity and quick reaction times. Aydogdu et al. (2011) and researchers prepared electrospun nanofibres using Poly(methyl methacrylate), ethyl cellulose, the plasticizer (dioctylphthalate, 8-hydroxypyrene-1,3,6-trisulfonicacidtrisodiumsalt and tetraoctylammoniumbromide. The probe displayed large sensitivity assigned to large surface area-to-volume ratio of the synthesized electrospun material. Stern-Volmer investigations revealed that these materials have 24 to 120 fold high sensitivities along with short response times and signal reversibility.

Fernández-Sánchez et al. (2007) described carbon dioxide responsive films by incorporating phenol dyes, α-naphtholphthalein (NAF), naphthol blue black (NBB) and calmagite (CMG), accompanied by phase-transfer agent, tetraoctylammonium hydroxide (TONOH), into metal-oxide nanoporous matrices (aluminum (AlOOH), silicon (SiO_2) and zirconium (ZrO_2) oxides.). The sensing films responded to CO_2 concentrations in the gas phase between 0.25% and 40% CO_2 (v/v) for NAF–TONOH, 4.1% and 30% CO_2 for NBB–TONOH and 0.6% and 40% CO2 for CMG–TONOH, with LOD of 0.25%, 4.1% and 0.6% CO2 (v/v) for NAF–TONOH, NBB–TONOH and CMG–TONOH, respectively. The film displayed appreciable dispersion and availability of signaler, resulting in fast response, reduced likelihood of agglomeration, the potential for gamma radiation sterilization, resistance towards chemicals and increased stability of the environment.

Nanoparticles based optical sensor consisting of 12-µm polystyrene (PS) film, upconverting nanoparticles (UCNPs; 40–100 nm in size) of the type $NaYF_4$:Yb,Er, and pH probe bromothymol blue (BTB) in its anionic (blue) form were synthesized by Ali et al. (2010). Selective permeability of the polystyrene for carbon dioxide over proton is the reason behind the choice. The UCNPs were exposed to 980-nm laser to result in green emission at 542 nm along with another red emission at 657 nm. The fluorescent intensity of the nanoparticles located at 542, 657 nm showed increment with the incremental exposure to carbon dioxide. The bromothymol blue (a sulfonate) and tetrabutylammonium cation (TBA) combines to result in an ion pair and tetraoctylammoniumhydroxide transforms BTB to phenoxide (blue) ionic species and forms buffer. This ensemble demonstrates a reaction time of ∼10 s on increasing carbon dioxide to 1% in pure argon medium, with the reversal of system within 180 s, and the LOD of 0.11% for carbon dioxide.

Another CO_2-responsive nanocomposite consisting of polymer, poly(N-(3-amidino)-aniline) (PNAAN), coated gold NPs (AuNPs) prepared by the reduction of $HAuCl_4$ using N-(3- amidino)-aniline (NAAN) (Ma et al., 2016). The amidine functional moiety of PNAAN is easily protonable to form a hydrophilic amidinium group due to the presence of dissolved carbon dioxide. This results in swelling of PNAAN and causes the detachment of the polymer from gold nanoparticles which consequently aggregates the nanopartilces to demonstrate the visible color variation. The optical measurement revealed LOD to be 0.0024 hPa.

In addition to above, layered double hydroxide-based nanocomposite HPTS/NiFe-LDH (8-hydroxypyrene-1,3,6-trisulfonicacid trisodium, HPTS) was prepared by simple one-step hydrothermal method (Li et al., 2016). The nanocomposite displays no fluorescence but when exposed to CO_2 gas the carbonate ions formed were then enter the interlayer of NiFe-LDH and result in the release of anionic dye, consequently recovering fluorescence. The fluorescence intensity increases proportionally to the amount of carbon dioxide.

Recently, colorimetric assay including silver nanoparticles was prepared by employing two capping agents: first is thiomalic acid and second is maltol (Sheini, 2020). The system's function depends on the hydrolytic cleavage of urea into NH_3 and CO_2. These products react with nanoparticles resulting in aggregation. Between the two capping agents, the maltol capped with silver nanoparticles selectively responds to carbon dioxide and easily visualized in color changes from yellow to red. The linear range was 0.08 $mg.dL^{-1}$-220.0 $mg.dL^{-1}$ for CO_2 and limits of detection was 0.06 $mg.dL^{-}$.

Li et al. (2021) synthesized a composite of tetraphenylethene (TPE) and gold nanoclusters (Au NCs) embedded onto disulfide functionalized hyperbranched poly(amidoamine) framework for recognition of dissolved CO_2 ($3.8 \times 10^{-4} – 1.9 \times 10^{-2}$ $mol{\cdot}L^{-1}$) with LOD 7.8 µM and the reaction is reversible by bubbling nitrogen gas.

Sol Gel Based Sensors for Carbon Dioxide

Sol gel based sensors employ silica sol-gel immobilized matrix which ensnare the analyte-responsive probe while permitting the analyte to permeate through the matrix. Sol-gel and polymer materials are the two types of immobilization matrices that are most frequently utilized. The sol gel method basically includes two steps: hydrolysis followed by condensation reaction with a suitable metal alkoxide. As a result, a porous glass matrix is formed that is responsible for the entrapping of analyte sensitive reagent, thus restricting its leaching, however it allows ingression of analytical entity. The sol gel preparation process offers many tailorable features like pH, starting material type and amount, amount of water, curing temperature, possibility of modification of physicochemical properties of the sol gel and available potentiality of designing hybrid matrixes containing both hydrophobic and hydrophilic moieties so as to improve the capability of sensor. However, this versatile nature is sometimes found to be disadvantageous as culminating sol gel morphology is highly depended upon the processing conditions. Particularly speaking, the final morphological structure of the matter significantly impacted by temperature. Thus, for high temperature application polymers are preferred as compared to sol gel.

A significant benefit of these materials in comparison to polymeric materials is their adaptability. Additionally, these materials are able to deposit on a variety of solid support without any tedious process, through various methods. As compared to conventional methods, this chemical procedure proceed via single step- moderate temperature pathway that was first utilized to fabricate an extensive variety of materials, including glasses or ceramics, with improved quality and uniformity. The significant property of sol gel method includes potential for the preparation of materials that combine inorganic and organic components even at the molecular level. The organic component of the above mentioned combination will stay unchanged during the sol-gel treatment owing to gentle processing at low temperatures, which is exceedingly challenging to do by traditional methods. The uniform mixing of inorganic /organic components to form a single phase offers excellent options for customizing the end attributes of the material which also includes optical. Therefore, the materials obtained from sol-gel present itself as a potential option for optochemical probe. The sol gel process includes sequence of consecutive (and typically overlapping) procedures: (a) hydrolytic cleavage of reactants (b) condensation, (c) gel formation (d) ageing and (e) drying. The whole procedure results the emergence of combined matrix of inorganic /organic components proceeds via origination of colloidal suspension (called sol) followed by formation of interconnected framework in a continual liquid form called as gel. Hydrolysis step involves the reaction of precursor's alkoxy functionality and water to generate silanol functional moieties (≡Si–OH) followed by condensation which includes the reaction of silanol with silanol /alkoxy groups to form siloxane (≡Si–O–Si≡) with concomitant removal of H_2O or alcohol. The end product of the reaction procedure is the generation of sol, a fluidic phase of high viscosity comprised of polymeric compounds, aggregated materials and medium used for reaction. The sol can be molded to form gel or may attached on the substrate. With the increase in siloxane bonds the molecules result in aggregation, thus linking sol molecules leading to gelation. On attaining the gelling point only the viscosity of the system increases without any chemical reaction. The speed of the reaction and variation in physical properties may decrease on attaining solid form but still, the system remains active and the conditions under which it ages significantly impact the ultimate structure of the material. Ageing process includes generation of crosslinking, shrinking and hardening of the gel.

Lo and Chu, (2009) reported sol gel based carbon dioxide probe which includes n-octyltriethoxysilane (Octyl-triEOS)/tetraethylorthosilane(TEOS) with dispersed form of 1-hydroxy-3,6,8-pyrenetrisulfonic acidtrisodiumsalt(HPTS, PTS-), granules of silica and tetraoctylammonium hydroxide (TOAOH). The flourometric studies revealed that the comparative fluorescence integration of indicator showed decrement on incremental exposure to carbon dioxide and found to have notable sensitivity of 26 (ratio I_{N2} / I_{CO2}, I_{N2} and I_{CO2} are the fluorescent integration in nitrogen medium and carbon dioxide environments, respectively) with a direct proportionality to carbon dioxide concentration in the span of 0-100%. The sensing system also exhibited significant response time of 9.8s (when system switches to carbon dioxide atmosphere from nitrogen) while on transition to reverse mode it is 195.4 s.

Another optical fluorescent sol-gel sensors was synthesized by Dansby-Sparks et al. (2010) using redesigned silica-doped framework with 1-hydroxy-pyrene-3,6,8-trisulfonate(HPTS) organic dye with

LOD 80 ppm accompanying limit of quantification as 200 ppm for carbon dioxide. On exposure to the target gas the fluorescent intensity due to dye molecule got diminished, because of the presence of the carbon dioxide gas which causes the protonation of its anionic form.

Other group ion paired 1-hydroxypyrene-3,6,8-trisulfonicacid and cetyltrimethylammonium bromide, trapped within a hybrid sol–gel-based three dimensional cage comprised of n-propyltriethoxysilane and liphophilic organic base (Wencel et al., 2010). This ensemble demonstrated two pH-dependent variations in optical signals, thus offering dual excitation ratiometric sensing to quantify dissolved carbon dioxide. This measuring method unresponsive to amount of indicator, percolation/photobleaching of the fluorescent responsive molecule and instrumental alterations. The experiments displayed high degree of reproducibility, reversing ability, stabilizing ability with LOD of 35 ppb.

An additional class of gel other than sol gel are polymer hydrogels (PHGs), these are a three-dimensional viscoelastic matrix prepared by the interlinking of polymeric chains through various chemical and physical entanglements. These hydrophilic polymers form a network that expand in biological liquids without dissolution followed by soaking up a significant quantity of them without dissolving in them. They can absorb more than 400 times their initial weight, which is over 20% of their original weight, and even more.

Wang et al. (2019) prepared a CO_2 sensitive hydrogel from Schiff's base reaction between polyethyleneimine with significant branching (BPEI) and moderately oxygenated dextran (PO-Dex) via stacking layer on layer. The swelling characteristics of the gel was investigated using Fabry Perot fringes. The films, similar to other hydrogels, exhibit swelling when exposed to water. Furthermore, the introduction of CO_2 leads to a more significant expansion of the particles, as a result of the chemical reaction of CO_2 and the $-NH_2$ belonging to BPEI. The expansion caused by gas can be detected through observation of the displacement of the Fabry–Perot fringes. Consequently, the film can serve as sensing probe towards dissolved CO_2 following optical mode. The signal produced by the probe towards CO_2 is linear/reversible and quick unlike most hydrogels.

Recently, Zhang et al. (2023) reported colorimetric carbon dioxide (CO_2) optical sensing ensemble having polypropylene framework placed onto a papery layer of thickness (30 μm) comprised of polyurethane. The polypropylene membrane facilitated the diffusion of CO_2, resulting in pH alterations within the hydrogel that contained an indicator (capable of dissolving in lipids), a cation exchange resin, and amine as cation. The sensitivity of the system is efficiently modulated by adjusting the proportion of the indicator molecule which is lipophilic in nature and the cation exchange resin. Slight excess amount of cation exchanger allow better sensing of carbon dioxide even at lower concentration. Color of the hydrogel ensemble corresponds well to the concentration of carbon dioxide gas and thus enable its quantification.

ELECTROCHEMICAL CARBON DIOXIDE SENSORS

The beginning of the electrochemistry dates back to late 18^{th} century with Galvani, Volta, and Nicholson. Since then the field of electrochemistry has found basic implications in various phenomena associated with regular life related processes such as corrosion, electroplating of metals, electrochemical treatment of drinking water, batteries, fuel cells, and electroanalytical sensors (Deng et al., 2008; Fu et al., 2008; Bergmann and Koparal, 2005; Laik et al., 2008; Robel et al., 2006; Xiang et al., 2007).

Electroanalytical chemistry has various applications which include environmental observation, quality control industrial sector, and biomedical investigation. Electroanalytical research has witnessed a mammoth uptrend in last few years with a range of development which include the fabrication of customized interfaces and monolayers of molecules (Braun et al., 1998; Wang et al., 2001), the linking of biological constituents with electrochemical transducer (Alfonta et al., 2001), and advancement in the basic understanding of voltammetric techniques. Electrochemical probes are attracting a significant attention for exploring chemical sensors.

Electroanalytical techniques are broadly classified as potentiometric and potentiostatic sensing. Current of electrochemical system is fixed at zero and potential established across the membrane is measured in potentiometry while in potentiostatic techniques electrode potential derives reactions involving electron-transfer and the current arising as a result is observed. The measured current is directly proportional to the rate of electrons across the interface of electrode and solution. Potentiostatic techniques are more popular due to their various distinct advantages.

Electroanalytical Techniques

Linear sweep voltammetry is simple electroanalytical technique where working electrode potential is changed with time in a linear manner in a particular direction (either from low positive potential to high positive potential or *vice versa*) at a constant scan rate and the resultant current is recorded with respect to applied potential or time.

Peak current obtained for a system which is reversible in linear sweep voltammetry is depicted by Randles-Sevčik equation:

$$i_p = [2.69 \times 10^5]\, n^{3/2} A D^{1/2} C \nu^{1/2}$$

here i_p is peak current in μA

n is the number of electrons

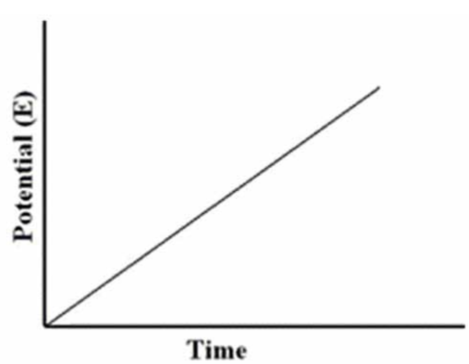
A is area of electrode surface in cm^2

D is diffusion coefficient of the species being oxidized or reduced in cm^2/s

C is concentration in mol/cm^3

ν is rate of scan in V/s

Figure 10. Potential-time waveform applied for linear scan voltammetry



Variations in voltammetric patterns of linear sweep voltammograms for different types of electrode reactions have been discussed comprehensively by Nicholson and Shain (1964). The outcome of their observations proved out as milestone in qualitative electrochemistry.

Cyclic voltammetry is another electroanalytical technique of prime importance and is based on linear variation of the working electrode potential. The technique is basically a different version of linear sweep voltammetry with provision of reverse potential scan and is carried out by switching the direction of the scan at a particular potential. In cyclic voltammetry, working electrode potential is varied from a potential (E_1) to another potential (E_2) at a predefined scan rate (v); but unlike linear sweep voltammetry, at potential E_2 the course of potential sweep is retreated instead of being concluded. On re-attaining the original potential, E_1, the sweep cycle may be ceased, again retreated, or continued to new value E_3. Single or a greater number of cycles are employed depending on the information sought.

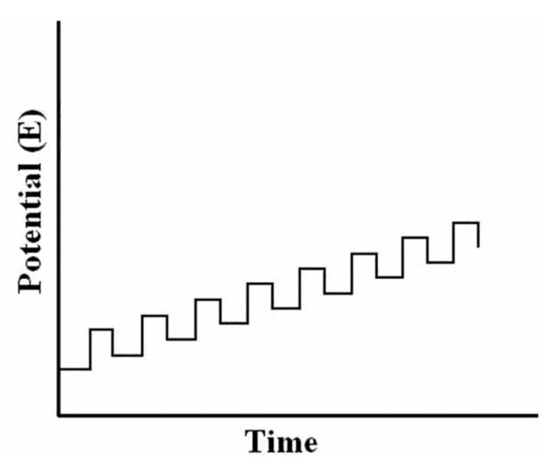
Cyclic voltammetry is considered as a powerful technique which gives important data about redox couple under investigation and allows simultaneous monitoring of oxidation as well as reduction processes. Hence, the technique is found to be very useful for investigating the redox behavior of biological molecules, organic or inorganic compounds with special emphasis on fundamental aspects of redox processes, electron transfer reactions, and understanding reaction intermediates. Application of cyclic voltammetry for analytical purposes is limited on account of the coupling of faradaic current with charging current.

Pulse voltammetry history accounts to the early work of Kemula which is centered on the concept of mechanical switch (Osteryoung and Wechter, 1989). In pulse technique, changes in potentials are discontinuous on the time scale of the experiment and sampling of the current is done only when the potential becomes constant for some-time. As a consequence, background current has been nullified, and reliable data can be collected at lower concentrations also. The credit for the basis of modern pulse voltammetric techniques goes to the early work of Barker and Jenkin (1952).

Differential pulse voltammetry is a very useful method for determination of organic as well as inorganic species. In differential pulse voltammetry, a pulse of constant height is superimposed on a linearly varying base potential applied on the working electrode.

The current is measured, just afore applying the pulse, and again just afore the pulse ends and the difference of the values are instrumentally recorded with respect to the potential. The height of resultant

Figure 11. Applied potential-time waveform for differential pulse voltammetry



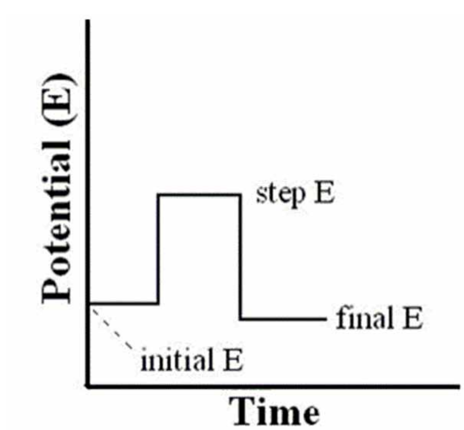
differential pulse voltammograms varies linearly with the concentration of the corresponding analytes. The technique is based on the fact that the charging and the faradaic currents declines with different rates after pulse application. The charging current decays quickly in comparison to faradaic current. Hence, recording current on conclusion of the pulse gives recording of the faradaic current, and charging current becomes negligible at this stage. Suppression of charging current helps in achieving lower detection limits (Bard and Faulkner, 2001). Differential pulse voltammetry gives better detection limits in comparison to linear sweep voltammetry and cyclic voltammetry. Due to its peak shaped nature, differential pulse voltammetry offers another advantage of well resolved peaks of closely spaced electrode processes. It makes possible to simultaneously monitor more than one electroactive species present in solution at a time.

Chronocoulometry employs square-wave voltage signal as an excitation signal and monitors charge as the function of time. The measured charge in a chronocoulometric experiment is assigned to contribution from (a) electrolysis of active specie, (b) electrolysis of active specie adsorbed on the surface of electrode, and (c) charging of the double-layer to new potential. Strength of the technique stems from the simple separation of adsorption and double-layer components from the diffusional component by plotting Q *versus* $t^{1/2}$, which makes it the most lucrative technique to determine surface excess of an electroactive species.

Modified Electrodes and Sensors

Electrochemical sensors include all those sensors which employ electrodes as detector device and detect the presence of an analyte by producing electrical signal which can be correlated to the concentration of an analyte. An electrochemical gas sensor specifies the gas molecules of interest and the information is converted into a suitable measurable property. Electrochemical sensors for gases comprise of gas sensing electrodes which are based on pH electrodes, and can detect gases which forms acidic or basic solutions. A gas sensor comprises of an ion-selective electrode which is engulfed by a thin film of an intermediate electrolyte solution and covered by a gas permeable membrane. Gas sensor for carbon dioxide was developed by Severinghaus and Bradley (1957). It is based on the principle that carbon dioxide gas decompose into bicarbonate and a proton which changes pH of the solution. However, in

Figure 12. Potential-time waveform for chronocoulmetry.



present methodology, CO_2 was not sensed directly and presence of other volatile compounds and gases can also impact the pH of the electrolyte. Possibilities of several types of electrochemical sensors using wide variety of materials have been explored. A screen printed electrode was developed by Ostrick et al. (2000) for CO_2 detection. A limitation of this electrode is its sensitivity to humidity. As far as sensitivity and selectivity is concerned; gold, silver or platinum electrodes are considered better while economical electrodes like vitreous carbon electrodes are capable of separating overlapping signals in blood gas analysis (Hrncˇı´rˇova et al., 2000). Zhou et al. (2001) have described working of multicomponent gas sensor based on transient electrochemistry principle. Schwandt et al. (2018) developed a solid state electrochemical sensor for CO_2 gas. Their work is unique as the individual sensor component can be prepared individually and can be assembled into the full sensor later. Atifi et al. (2018) reported conversion of CO_2 to CO at thin film Bi electrode which is accelerated by using suitable ionic liquid. Linear sweep voltammetry was the electrochemical technique employed for this purpose.

Struzik et al. (2018) reported potentiometric CO_2 sensors based on $Li_7La_3Zr_2O_{12}$ as conducting solid electrolytes, and the sensing activity is assigned to the cyclic redox process. The reported method has a distinct advantage of quick response time and sensing ability at relatively low temperature of 320 °C. Dorner et al. (2023) extensively studied the electrochemical reduction of CO_2 at silver electrodes using cyclic voltammetry. They found that selectivity for CO_2 consumption can be improved with increase in electrode rotation rate. A summary of electrochemical sensors for CO_2 detection has been tabulated in Table 1.

CONCLUSION

In this book chapter, the fluorescent and electrochemical sensing probes for sensing carbon dioxide have been systematically summarized. This chapter provides a methodical overview of sensors for the

Table 1. Electrochemical sensors for carbon dioxide sensing

Material used	Method	Electrolyte	Ref.
Glass electrode	Potentiometry	$NaHCO_3$-NaCl	Severinghaus and Bradley (1957)
$BaCO_3$	Potentiometry	--	Ostrick et al. (2000)
Reticulated vitreous carbon	Voltammetry	solid polymer electrolyte	Hrncˇı´rˇova et al., 2000
Teflon & acetylene black	Voltammetry	--	Zhou et al. (2001)
Na_2CO_3	Potentiometry	Na-β/β''-alumina and Na_2SO_4	Schwandt et al. (2018)
Bi/ILs having 1,8-diazabicyclo[5.4.0] undec-7-ene	Controlled-potential electrolysis	MeCN-based electrolytes	Atifi et al. (2018)
Li_2CO_3–Au	Potentiometry	($Li_{6.75}La_3Zr_{1.75}Ta_{0.25}O_{12}$)	Struzik et al. (2018)
Silver rotating disk electrode	Cyclic voltammetry	0.1M $KHCO_3$	Dorner et al. (2023)
nano-SnO_2/graphene on GC electrode	Voltammetry	0.1 M $NaHCO_3$	Jhang et al. (2014)
Cu modified boron doped diamond electrode	Linear Sweep voltammetry	0.5 MKOH	Jiwanti et al. (2018)
SnO_2/MWCNT on carbon paper	Linear Sweep Voltammetry and Chronoamperometry	0.5 M $NaHCO_3$	Bashir et al. (2016)
NiO on MWCNT with paper	Linear Sweep Voltammetry and Chronoamperometry	0.5 M $NaHCO_3$	Bashir et al. (2015)

recognition of carbon dioxide by highlighting the design concept, detection mechanistic pathway, characteristics, and sensing abilities in terms of limit of detection.

While much progress has been made in this area of study, we believe that two key factors should be taken into account when developing novel optical and electrochemical sensors in future. Firstly, to improve the applicability of the sensor for biotic systems, the sensors should be designed and synthesized offering stability, compatibility to biological arrangement, and dissolvability in aqueous medium. Secondly, the majority of the documented sensors just sense the analyte and do not adsorb/absorb the gas. Evidently, the adsorption/absorption of CO_2 is more required as compared to its mere detection. Therefore, it is especially important to develop the sensor that can detect, separate, and adsorb/ absorb carbon dioxide. In summary, the substantial roles that carbon dioxide plays in different fields, such as the chemical, environmental, therapeutic, and other industries, it is certain that the fluorescent and electrochemical sensors will receive a lot of recognition in future.

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Chapter 5
Water Pollutants, Sensor Types, and Their Advantages and Challenges

Sanjeevi Ramakrishnan
Nims Institute of Allied Medical Science and Technology, Nims University, Jaipur, India

Prashantkumar Sathvara
https://orcid.org/0000-0002-3548-5584
Nims Institute of Allied Medical Science and Technology, Nims University, Jaipur, India

Sandeep Tripathi
Nims Institute of Allied Medical Science and Technology, Nims University, Jaipur, India

Anuradha Jayaraman
Nims Institute of Allied Medical Science and Technology, Nims University, Jaipur, India

ABSTRACT

Water pollution is a global crisis impacting ecosystems, health, and economies. This chapter explores strategies to combat it, stressing advanced water quality sensors' vital role. It scrutinizes pollutants, emphasizing modern sensor tech's importance in ensuring water safety. Tackling pollution is crucial for biodiversity, human health, and clean water access. Pollutants include heavy metals, chemicals, pathogens, and sediments, requiring precise monitoring by sensors using various technologies. They offer real-time detection and response, covering chemical, biological, physical, remote sensing, and IoT-enabled sensors. Challenges like maintenance persist, requiring protocols and training. Collaboration and sensor tech are pivotal in ensuring cleaner water. This chapter highlights technology's role in managing water quality, emphasizing innovation for safeguarding this vital resource.

INTRODUCTION

Water pollution is indeed a critical global environmental challenge with far-reaching impacts on ecosystems, human health, and economies worldwide. Here's a breakdown of how water pollution affects

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each of these areas like in ecosystem Water pollution can have devastating effects on aquatic ecosystems. Contaminants such as heavy metals, pesticides, and industrial chemicals can accumulate in water bodies, harming aquatic plants, animals, and microorganisms (Lin et al., 2022a). Pollution can disrupt food chains, alter habitats, and lead to declines in biodiversity. Eutrophication, caused by excessive nutrient runoff, can result in oxygen depletion and the formation of harmful algal blooms, further degrading aquatic ecosystems (Anwar Abdelrahman Aly et al., 2016). Water pollution poses significant risks to human health. Contaminated water can transmit pathogens and cause waterborne diseases such as cholera, typhoid fever, and dysentery. Exposure to pollutants like heavy metals, pesticides, and industrial chemicals through contaminated water sources can lead to various health problems, including neurological disorders, cancer, and reproductive issues (Manoiu et al., 2022). Vulnerable populations, such as children, pregnant women, and communities lacking access to clean water and sanitation facilities, are particularly at risk. The economic consequences of water pollution are substantial. Contaminated water sources can render drinking water supplies unsafe, leading to increased healthcare costs due to waterborne illnesses and the need for water treatment infrastructure upgrades (Radu et al., 2022). Pollution-related damage to fisheries, aquaculture, and recreational water bodies can result in lost revenue and livelihoods for communities dependent on these resources. Additionally, industries may face regulatory fines and cleanup expenses for environmental contamination incidents, impacting their profitability and competitiveness (Sur et al., 2022).

Addressing water pollution requires coordinated efforts at local, national, and global levels to implement effective pollution prevention and control measures (Karunanidhi et al., 2021). This includes adopting pollution reduction strategies, investing in wastewater treatment infrastructure, promoting sustainable agricultural practices, and enforcing environmental regulations. Public awareness, education, and community engagement are also essential for fostering responsible water stewardship and ensuring the sustainable management of water resources for future generations.

VARIOUS CATEGORIES OF WATER POLLUTANTS

Water pollutants can be categorized into various groups based on their sources, characteristics, and impacts on aquatic ecosystems and human health. Heavy Metals including lead, mercury, cadmium, arsenic, and chromium, can accumulate in water bodies and bioaccumulate in aquatic organisms, posing risks to human health and ecosystems (Ahamad et al., 2020). Organic Compounds such as pesticides, herbicides, industrial chemicals, solvents, and pharmaceuticals, can leach into water sources from agricultural runoff, industrial discharges, and wastewater effluents, affecting water quality and aquatic organisms (Dwivedi, 2017). Nutrients such as nitrogen and phosphorus, can lead to eutrophication and harmful algal blooms when present in excessive amounts, degrading water quality, oxygen levels, and aquatic habitats (Fischer et al., 2012). Persistent Organic Pollutants including polychlorinated biphenyls, polycyclic aromatic hydrocarbons, and chlorinated pesticides, which are resistant to degradation, bioaccumulate in aquatic organisms and pose long-term risks to humans and environmental health (Gambhir et al., 2012). Chlorinated Compounds such as chlorine, chloramines, and chlorinated solvents, are used for disinfection and industrial processes but can form disinfection by-products when reacting with organic matter in water, some of which are carcinogenic or toxic (Kordbacheh & Heidari, 2023).

Some pathogens including bacteria, viruses, protozoa, and parasites, can contaminate water sources through sewage discharges, agricultural runoff, and animal waste, causing waterborne diseases such as cholera, typhoid fever, gastroenteritis, and hepatitis. Algal Toxins produced by harmful algal blooms and cyanobacteria, including microcystins, saxitoxins, and cylindrospermopsin, can contaminate drinking water sources, posing risks to human health, livestock, and aquatic organisms (Fischer et al., 2012).

Physical Pollutants like Suspended Solids including sediments, silt, and particulate matter, can cloud water, reduce water clarity, and smother benthic habitats when suspended in high concentrations, affecting aquatic ecosystems and habitat quality (Gambhir et al., 2012). Sedimentation resulting from soil erosion, construction activities, and land development, can degrade water quality, impair aquatic habitats, and increase turbidity, sedimentation, and nutrient loading in water bodies (Verma & Ratan, 2020). Thermal Pollution resulting from the discharge of heated water from industrial processes, power plants, and urban runoff, can raise water temperatures, disrupt aquatic ecosystems, and decrease dissolved oxygen levels, affecting fish populations and biodiversity. Radionuclides including isotopes of uranium, radium, cesium, and strontium, can enter water sources through natural processes, mining activities, nuclear accidents, and nuclear waste disposal, posing risks to human health and the environment due to their radioactive properties (Sanjeevi, 2011). These categories of water pollutants interact with each other and with natural environmental processes, influencing water quality, ecosystem health, and human well-being.

WATER POLLUTION EFFECTS IN ECOSYSTEM

Water pollution can have profound and multifaceted impacts on ecosystems, affecting various components and processes within aquatic environments: Pollutants introduced into water bodies can alter their chemical composition, leading to changes in pH levels, nutrient concentrations, and dissolved oxygen levels (Arenas-Sánchez et al., 2016). For example, industrial effluents containing acids or bases can disrupt the natural pH balance of water, affecting the survival and reproduction of aquatic organisms adapted to specific pH ranges (Bourdeau & Treshow, 1978). Excessive nutrient runoff from agricultural activities or sewage discharges can result in eutrophication, causing algae to bloom and consume oxygen upon decomposition, leading to hypoxic or anoxic conditions harmful to aquatic life. Many pollutants, such as heavy metals, pesticides, and persistent organic pollutants (POPs), have the potential to bio-accumulate in aquatic organisms (Chen et al., 2019). Bioaccumulation occurs when organisms absorb pollutants from their environment at a rate faster than they can excrete or metabolize them, leading to the accumulation of toxins in their tissues. Bio-magnification refers to the increase in pollutant concentrations at higher trophic levels of the food chain, as predators consume contaminated prey (Chen et al., 2019). This can result in high levels of pollutants in apex predators, posing risks to their health and reproductive success. Water pollution can degrade aquatic habitats essential for the survival of many species. Sedimentation, resulting from soil erosion due to deforestation or land development, can smother benthic habitats like coral reefs, sea-grass beds, and spawning grounds, reducing their productivity and biodiversity. Toxic pollutants can also directly damage habitat structures, such as coral skeletons or aquatic vegetation, affecting the availability of shelter, food, and breeding sites for aquatic organisms (Fatima et al., 2020). Pollution-induced changes in water quality and habitat conditions can disrupt aquatic food webs, altering species interactions and community dynamics. For example, declines in primary producers like phytoplankton due to eutrophication can affect the abundance and distribution of herbivores and primary consumers. This ripple effect can propagate through the food chain, impacting higher trophic levels and ultimately leading to shifts in species composition and biodiversity (Håkanson & Bryhn, 1999). The cumulative impacts of water pollution on water quality, habitats, and food webs can lead to the loss of biodiversity in aquatic ecosystems. Species adapted to specific environmental conditions may decline or disappear due to pollution-induced stressors, habitat degradation, or competition with invasive species. Biodiversity loss can weaken ecosystem resilience, making ecosystems more vulnerable to further environmental disturbances and reducing their ability to provide valuable ecosystem services, such as water purification, nutrient cycling, and climate regulation.

WATER POLLUTION EFFECT ON HUMAN HEALTH

Water pollution poses significant risks to human health through various pathways of exposure. Contaminated water sources can harbor a wide range of pathogens, including bacteria, viruses, protozoa, and parasites, which can cause waterborne diseases. Examples include cholera, typhoid fever, dysentery, giardiasis, and cryptosporidiosis (Malik et al., 2020). These diseases are typically spread through the ingestion of contaminated water or food prepared with contaminated water. Symptoms can range from mild gastrointestinal discomfort to severe illness and, in some cases, death, particularly among vulnerable populations such as children, the elderly, and individuals with weakened immune systems. Water pollution can introduce various chemical contaminants into drinking water sources, posing health risks to human populations (Halder & Islam, 2015). Heavy metals such as lead, mercury, arsenic, and cadmium can leach into water sources from industrial discharges, mining activities, and natural geological processes. Pesticides, herbicides, and industrial chemicals can also contaminate water supplies through agricultural runoff, urban runoff, and industrial effluents (Haseena et al., 2017; Ramakrishnan & Jayaraman, 2019). Chronic exposure to these chemical contaminants through drinking water consumption can lead to adverse health effects, including neurological disorders, developmental delays, cancer, reproductive problems, and organ damage. Some pollutants present in water bodies have the potential to bioaccumulate in aquatic organisms and biomagnify through the food chain, increasing human exposure risks. For example, methylmercury, a highly toxic form of mercury, bioaccumulates in fish tissue and can reach high concentrations in predatory fish species commonly consumed by humans (Inyinbor Adejumoke et al., 2018). Chronic consumption of contaminated fish can result in mercury poisoning, leading to neurological impairments, cardiovascular problems, and developmental disorders, particularly in fetuses and young children. Excessive nutrient runoff from agricultural activities and wastewater discharges can promote the growth of harmful algal blooms (HABs) in water bodies. Some species of algae produce toxins known as cyanotoxins, which can contaminate drinking water supplies and pose health risks to humans and animals. Exposure to cyanotoxins through ingestion, inhalation, or skin contact can cause a range of health effects, including gastrointestinal illness, liver damage, respiratory problems, and neurological symptoms (Lin et al., 2022b). Water pollution incidents, such as chemical spills or contamination of water treatment plants, can disrupt water and sanitation services, compromising access to safe drinking water and sanitation facilities. Communities affected by such incidents may experience shortages of clean water for drinking, cooking, and hygiene, increasing the risk of waterborne diseases and sanitation-related health problems (R. Qadri & Faiq, 2020; Ranjan et al., n.d.). Vulnerable populations, including those living in low-income areas or disaster-prone regions, are particularly susceptible to the health impacts of disrupted water and sanitation services. Addressing water pollution and protecting human health requires comprehensive strategies that focus on pollution prevention, source control, water quality monitoring, and effective water treatment and sanitation infrastructure (Sanjeevi, 2011; Sanjeevi et al., 2017). Public awareness, education, and community engagement are also essential for promoting water stewardship practices and ensuring access to clean water for all.

WATER POLLUTION IMPACT ON ECONOMIC GROWTH

The economic impacts of water pollution can be substantial and wide-ranging, affecting various sectors and aspects of economic activity. Water pollution-related illnesses can impose significant healthcare costs on individuals, communities, and healthcare systems (Zhang et al., 2017). Treating waterborne diseases, such as cholera, typhoid fever, and gastrointestinal infections, requires medical attention, medications, hospitalization, and sometimes long-term care. These healthcare expenses can strain household budgets, burden public health systems, and reduce productivity due to illness-related absenteeism from work or school. Contaminated water sources require treatment to meet safe drinking water standards, which can incur substantial costs for water utilities and municipalities (Reddy & Behera, 2006). Water treatment processes such as filtration, disinfection, and chemical treatment are necessary to remove or neutralize pollutants and pathogens from drinking water supplies. Investing in water treatment infrastructure upgrades, maintenance, and operational costs can impose financial burdens on water providers and may lead to increased water tariffs for consumers (Orubu & Omotor, 2011). Water pollution can degrade the quality of recreational water bodies, such as beaches, lakes, and rivers, reducing their attractiveness to tourists and outdoor enthusiasts. Polluted water bodies may be subject to swim advisories, beach closures, or fishing bans due to health concerns, resulting in lost revenue for tourism-dependent businesses, including hotels, restaurants, marinas, and recreational outfitters (Muyibi et al., 2008). Declines in tourism and recreational activities can harm local economies and employment opportunities in coastal and inland communities. Water pollution can have detrimental effects on fisheries and aquaculture operations, leading to declines in fish stocks, shellfish harvests, and aquaculture yields (Cai et al., 2020). Contaminants such as heavy metals, pesticides, and toxins from harmful algal blooms can accumulate in aquatic organisms, rendering them unsafe for human consumption and damaging commercial fisheries and aquaculture enterprises (Li & Li, 2021; R. Sanjeevi et al., 2022). Economic losses from reduced fishery yields, fishery closures, and market disruptions can affect livelihoods and income for fishermen, fish farmers, and seafood processors. Water pollution can diminish the value of waterfront properties and real estate investments in areas with polluted water bodies. Contaminated water sources can detract from the aesthetic appeal and recreational appeal of waterfront properties, leading to decreased demand and lower property values (Juma et al., 2014). Homeowners, businesses, and developers may experience financial losses and reduced returns on investment in polluted waterfront areas, affecting property tax revenues and municipal budgets. Water pollution can impair agricultural productivity and soil fertility through contamination of irrigation water sources and agricultural runoff. Excessive nutrient runoff, pesticides, and industrial chemicals can accumulate in soil and water, affecting crop yields, quality, and marketability. Farmers may incur additional costs for water treatment, soil remediation, and crop loss mitigation measures, impacting farm profitability and agricultural competitiveness (Juma et al., 2014; Sathvara et al., 2023). Water pollution-related restrictions on irrigation water use can exacerbate water scarcity issues in agricultural regions, affecting food production and rural economies (Choi et al., 2015).

ADVANCED WATER QUALITY IN MONITORING AND ADDRESSING

Advanced water quality monitoring and addressing techniques encompass a range of innovative technologies and approaches aimed at enhancing the effectiveness, efficiency, and timeliness of water quality assessment and management (Park et al., 2020). Remote sensing technologies, including satellite imagery, aerial drones, and unmanned aerial vehicles (UAVs), are increasingly used for monitoring water quality over large spatial scales. These technologies can provide real-time or near real-time data on parameters such as water clarity, chlorophyll concentration, turbidity, and algal blooms, allowing for the timely detection of pollution events and environmental changes. Deploying networks of sensors and monitoring devices in water bodies enables continuous, high-resolution monitoring of water quality parameters (Mishra et al., 2016; Olatinwo & Joubert, 2019). These sensors can measure various physical, chemical, and biological indicators, such as temperature, pH, dissolved oxygen, nutrients, pollutants, and microbial contaminants. Advanced sensor networks can provide comprehensive datasets for analyzing spatial and temporal variations in water quality and identifying pollution sources and trends (Olatinwo & Joubert, 2018). Advanced data analytics techniques, including machine learning algorithms, statistical analyses, and numerical modeling, are used to process and interpret large volumes of water quality data. These tools can identify patterns, correlations, and anomalies in water quality datasets, predict future water quality conditions, and simulate the impacts of pollution sources and management strategies (Abbasi et al., 2013; O'Grady et al., 2021). Data-driven approaches enhance decision-making for water quality management and facilitate targeted interventions to address pollution hotspots. Real-time monitoring systems enable the continuous surveillance of water quality parameters and the rapid detection of pollution events. Citizen science initiatives engage the public in monitoring and addressing water quality issues, leveraging the collective efforts of volunteers, community groups, and citizen scientists (Kumar et al., 2022; Prashantkumar B. Sathvara et al., 2023). Crowdsourcing platforms and mobile applications enable citizens to collect water quality data, report pollution sightings, and participate in environmental monitoring efforts. Citizen-generated data supplements traditional monitoring programs, enhances spatial coverage, and fosters community awareness and stewardship of water resources. Ongoing advancements in sensor technology, nanotechnology, microfluidics, and biosensors are driving the development of novel water quality monitoring tools and techniques. Miniaturized, low-cost sensors, wearable devices, and smartphone-based technologies are expanding access to water quality monitoring capabilities, particularly in resource-constrained or remote regions (El-Shafeiy et al., 2023). Emerging technologies hold promise for improving the affordability, portability, and accessibility of water quality monitoring solutions, democratizing access to environmental data, and empowering communities to address water pollution challenges. By harnessing advanced monitoring technologies, data analytics, and collaborative approaches, stakeholders can enhance their capacity to monitor, assess, and respond to water quality issues effectively, ultimately contributing to the sustainable management and protection of freshwater resources and ecosystems.

ADVANCED WATER QUALITY SENSORS

Advanced water quality sensors encompass a variety of cutting-edge technologies designed to detect and measure a wide range of parameters with high accuracy, sensitivity, and efficiency. These sensors play a crucial role in environmental monitoring, water resource management, and pollution control efforts.

1. **Optical Sensors:** Optical sensors utilize light-based techniques to measure various water quality parameters. Fluorescence sensors can detect organic matter, chlorophyll-a, and other fluorophores, providing insights into nutrient levels and algal biomass. Turbidity sensors use light scattering to quantify suspended solids and particulate matter in water, indicating water clarity and sediment levels. Additionally, optical sensors can measure parameters such as dissolved oxygen, pH, and chemical contaminants through spectroscopic methods. It plays a crucial role in water quality monitoring. These sensors convert light into electronic signals, measuring incident light intensity and transforming it into readable data (Ankitkumar B Rathod et al., 2023; Parambil et al., 2022). In water quality assessment, optical sensors detect interactions of light with particles or dissolved constituents. For instance, dissolved constituents like nitrate and organic matter convert absorbed light into other forms of energy. UV/Vis and fluorescence spectroscopy are common optical methods for in situ monitoring. Glass-fiber-optic turbidity sensors use optical fibers to detect changes in turbidity caused by suspended particles in water. Overall, optical sensors contribute to real-time monitoring and environmental protection by assessing water quality.
2. **Electrochemical Sensors:** Electrochemical sensors play a significant role in detecting chemical ions, molecules, and pathogens in water and other applications. These sensors offer several advantages, including sensitivity, portability, speed, affordability, and suitability for online and in-situ measurements compared to other methods. They can detect compounds that undergo specific transformations within a potential window, making them versatile for multiple ion detections (Kanoun et al., 2021). Electrochemical sensors rely on electrochemical reactions to detect and quantify specific ions, gases, and pollutants in water. Ion-selective electrodes (ISEs) are commonly used to measure concentrations of ions such as chloride, nitrate, ammonia, and heavy metals. pH sensors utilize glass or membrane electrodes to measure hydrogen ion activity in water, providing insights into water acidity or alkalinity. Electrochemical sensors are known for their rapid response times, high sensitivity, and suitability for in-situ monitoring applications.
3. **Biosensors:** Biosensors play a pivotal role in water quality detection, offering simple and accessible solutions for water management. Unlike traditional sensors, biosensors utilize natural microbes and enzymes engineered to respond to specific toxins. When exposed to contaminants, these biosensors produce chemical reactions, emit light, or even sound. Biosensors utilize biological components such as enzymes, antibodies, or microorganisms to detect target analyses in water samples. Enzyme-based biosensors can detect specific pollutants or contaminants through enzymatic reactions, offering high selectivity and specificity. Immune-sensors utilize antigen-antibody interactions to detect pathogens, toxins, or chemical contaminants in water. Microbial biosensors employ living

Figure 1. Optical sensors working principal

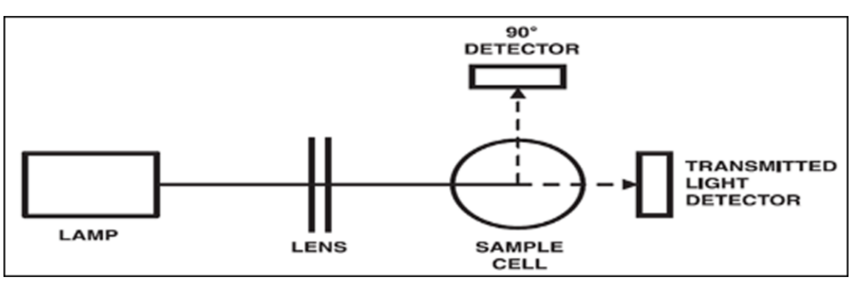
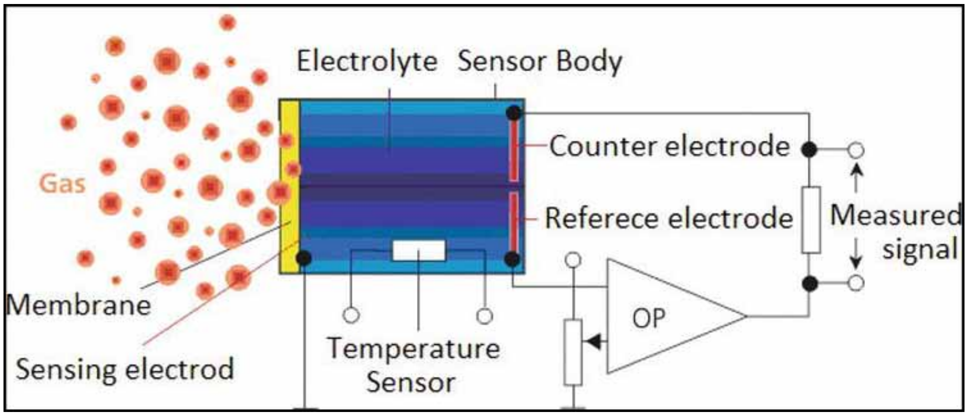


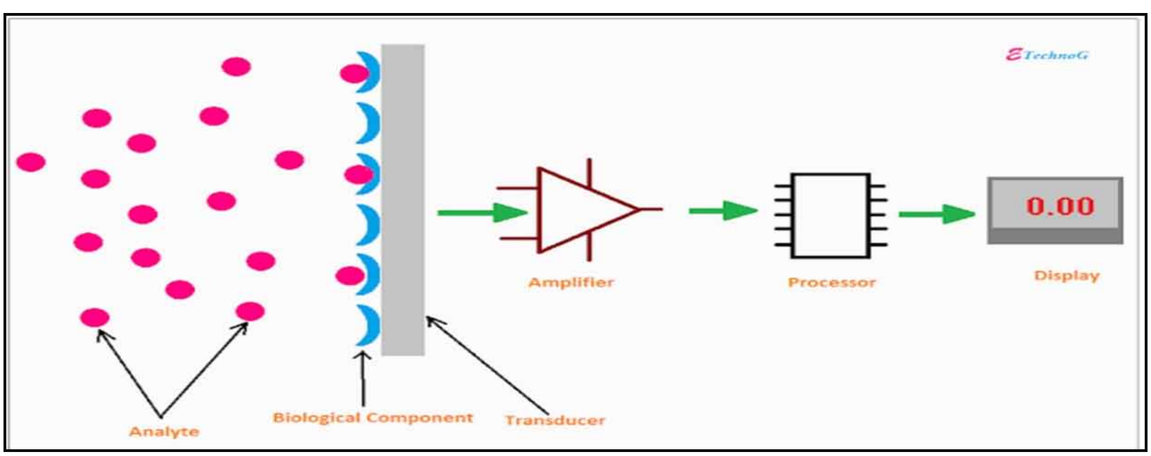
Figure 2. Electrochemical sensor working principal



microorganisms to assess water quality based on metabolic activity or inhibition responses (Mustafa et al., 2017). Biosensors offer the advantage of biological recognition elements, enabling sensitive and selective detection of target analytes in complex environmental samples.

4. **Acoustic Sensors**: Acoustic sensors are essential tools for water quality analysis. These sensors utilize sound waves to determine various water properties. Sonar-based acoustic sensors accurately measure water depth, playing a crucial role in hydrographic surveys, underwater mapping, and managing water resources. Additionally, they are permanently installed in water distribution networks for leak detection, automatically recording noise samples from water flow within pipes. By analyzing these samples, leaks, and anomalies can be detected promptly, minimizing water loss. Acoustic sensors also contribute to environmental monitoring by assessing underwater noise levels, which impact marine ecosystems. Understanding noise pollution helps protect aquatic life and maintain ecological balance. Furthermore, acoustic sensors provide valuable data for mapping underwater terrain, identifying submerged objects, and assessing seafloor conditions, crucial for navigation safety and environmental studies. Acoustic sensors use sound waves or ultrasonic waves

Figure 3. Biosensor working principal



to characterize water properties and detect changes in water quality. Acoustic Doppler sensors can measure water velocity, flow rates, and sediment transport in rivers, streams, and estuaries, providing insights into hydrodynamic processes and sedimentation dynamics (An et al., 2021). Acoustic spectroscopy techniques can assess water quality parameters such as suspended solids, particle size distribution, and bubble concentration based on acoustic backscatter or attenuation measurements.

5. **Nanotechnology-based Sensors:** Nanotechnology-based sensors hold immense promise for water quality monitoring. These sensors, designed with nanomaterials, offer high efficiency, multiplex functionality, and flexibility. While many Nano sensors can achieve these goals, further development is needed to create user-friendly tools capable of detecting analyses in previously inaccessible locations. Water quality monitoring faces challenges due to matrix variability, complex compositions, and low pollutant concentrations. Nanomaterial-enabled sensor platforms promise ultralow multiplex detection and rapid analysis times. Although excitement surrounds nano-enabled sensors, only a few have made it to the market. Nevertheless, their potential impact remains significant, providing widespread and potentially low-cost monitoring of chemicals, microbes, and other analyses in drinking water. Addressing global water challenges requires harnessing the full potential of nanotechnology-enabled sensors (Sanjeevi et al., 2017; Vikesland, 2018). Nanotechnology-based sensors leverage nanomaterials and nanostructures to enhance sensitivity, selectivity, and performance in water quality monitoring applications. Nanomaterials such as carbon nanotubes, graphene, and metal nanoparticles exhibit unique properties that can be exploited for sensing purposes (Nasture et al., 2022). Nano-scale sensors can detect trace levels of contaminants, pathogens, and pollutants in water with high sensitivity and specificity, offering potential for miniaturization, portability, and integration into autonomous monitoring platforms.
6. **Smart Sensors and IoT Integration:** Smart sensors integrated with the Internet of Things (IoT) play a pivotal role in advancing water quality monitoring. These intelligent devices enhance our ability to assess and manage crucial components of daily human needs, especially in agriculture and daily life. Researchers propose IoT-based systems equipped with wireless sensor networks and water quality sensors. These sensors include turbidity, conductivity, temperature, pH, and oxidation-reduction potential sensors. Fuzzy logic models are implemented to predict local water contamination risks. Such systems enable real-time monitoring and management of water quality. While smart sensors offer immense potential, challenges remain. These include ensuring sensor accuracy, addressing data privacy concerns, and developing user-friendly interfaces. However, the benefits of real-time monitoring, early detection of anomalies, and efficient resource utilization make IoT-based water quality systems indispensable (Anwar Abdelrahman Aly et al., 2016; Zulkifli et al., 2022). Smart sensors equipped with data logging, wireless communication, and Internet of Things (IoT) connectivity capabilities enable real-time monitoring and remote data transmission from field locations to central databases or cloud-based platforms. Integrated sensor networks and IoT systems facilitate continuous monitoring of multiple water quality parameters across large spatial scales, enabling data-driven decision-making, early warning systems, and adaptive management strategies for water resource management and pollution control (Bhardwaj et al., 2022).

These advanced water quality sensors contribute to an enhanced understanding of aquatic ecosystems, early detection of pollution events, and informed decision-making for sustainable water management and environmental protection efforts. Continued innovation and technological advancements in sensor

Table 1. Water quality parameter, sensor, advantages, and disadvantages

Water Quality Parameter	Sensor Type	Advantages	Disadvantages	References
Colored Dissolved Organic Matter (CDOM)	Spectrophotometry	- Rapid measurements. - Non-destructive.	- Influenced by water turbidity. - Limited depth penetration.	
Secchi Disk Depth (SDD)	Visual observation	- Simple and low-cost. - Provides a quick estimate of water Clarity.	- Subjective interpretation. - Limited precision.	
Turbidity	Turbidity sensors	- Continuous monitoring. - Reflects suspended solids levels.	- Calibration needed. - Affected by sensor fouling.	
Total Suspended Sediments (TSS)	Turbidity sensors	- Quantifies sediment load. - Real-time data.	- Limited accuracy in high turbidity conditions.	
Water Temperature (WT)	Temperature sensors	- Easy to deploy. - Real-time monitoring.	- Prone to drift. - Affected by solar radiation.	
Total Phosphorus (TP)	Spectrophotometry	- Measures nutrient levels. - Non-destructive.	- Requires reagents for analysis. - Interference from other compounds.	
Sea Surface Salinity (SSS)	Conductivity sensors	- Reflects salinity variations. - Real-time data.	- Calibration needed. - Affected by fouling.	
Dissolved Oxygen (DO)	Optical sensors	- Vital for aquatic life. - Continuous monitoring.	- Affected by temperature and pressure. - Requires calibration.	
Biochemical Oxygen Demand (BOD)	BOD sensors	- Indicates organic pollution. - Real-time assessment.	- Requires incubation period. - Interference from other substances.	
Chemical Oxygen Demand (COD)	COD sensors	- Measures organic and inorganic pollutants. - Quick results.	- Requires reagents. - Interference from other compounds.	

design, fabrication, and deployment will further advance capabilities for water quality monitoring and address emerging challenges in water resource sustainability and pollution mitigation.

The Capabilities of Modern Sensors and Their Significance in Achieving the Mission of Cleaner and Safer Waters

Modern sensors possess advanced capabilities that play a pivotal role in achieving the mission of cleaner and safer waters by enabling efficient, accurate, and timely monitoring of water quality parameters.

1. High Sensitivity: Modern sensors exhibit high sensitivity, allowing them to detect low concentrations of contaminants and pollutants in water. This capability is essential for early detection of pollution events and monitoring compliance with water quality standards, enabling prompt intervention and corrective actions to prevent or mitigate adverse impacts on aquatic ecosystems and human health.
2. Real-time Monitoring: Many modern sensors enable real-time or near real-time monitoring of water quality parameters, providing continuous data streams that capture temporal variations and dynamics in water quality. Real-time monitoring facilitates rapid detection of pollution incidents, timely response to changing environmental conditions, and adaptive management strategies for maintaining water quality within acceptable limits.

3. Multi-parameter Measurement: Advanced sensors are capable of measuring multiple water quality parameters simultaneously, offering comprehensive insights into the chemical, physical, and biological characteristics of water bodies. Multi-parameter sensors streamline monitoring efforts, reduce the need for multiple instruments or sampling campaigns, and provide integrated datasets for holistic assessments of water quality and ecosystem health.
4. Remote Monitoring: Modern sensors are equipped with wireless communication capabilities, enabling remote monitoring of water quality in remote or inaccessible locations. Remote monitoring systems transmit data to centralized databases or cloud-based platforms, allowing stakeholders to access real-time monitoring data, receive alerts and notifications, and make informed decisions regarding water quality management and pollution control measures.
5. Accuracy and Precision: Advanced sensor technologies offer high accuracy and precision in measuring water quality parameters, minimizing measurement errors and uncertainties. Accurate sensor data enhance the reliability and credibility of monitoring results, supporting evidence-based decision-making and regulatory compliance efforts to protect water resources and public health.
6. Autonomous Operation: Some modern sensors are designed for autonomous or unmanned operation, capable of self-calibration, self-diagnosis, and long-term deployment in field environments. Autonomous sensors reduce the need for manual intervention, maintenance, and data collection, optimizing resources and personnel allocation for water quality monitoring programs.
7. Cost-effectiveness: Advances in sensor technology have led to the development of cost-effective monitoring solutions, including low-cost sensors, miniaturized devices, and scalable sensor networks. Cost-effective sensors increase accessibility to water quality monitoring capabilities, particularly in resource-constrained or underserved regions, and facilitate community-based monitoring initiatives and citizen science programs.
8. Data Integration and Analysis: Modern sensors are often integrated with data logging, storage, and analysis functionalities, facilitating the processing, interpretation, and visualization of monitoring data. Integrated sensor networks and data management systems enable seamless data integration, trend analysis, and spatial mapping of water quality parameters, supporting evidence-based decision-making and long-term planning for water resource management and pollution control.

MISSION TO COMBAT WATER POLLUTION

A mission to combat water pollution involves a multifaceted approach aimed at reducing, mitigating, and preventing the introduction of pollutants into water bodies, restoring degraded ecosystems, and promoting sustainable water management practices (Wang et al., 2016). In water pollution prevention implementing measures to prevent pollution at the source is crucial for reducing the influx of contaminants into water bodies. This includes regulatory measures to control industrial discharges, agricultural runoff, and urban storm water runoff, as well as promoting pollution prevention practices among businesses, industries, and individuals. Establishing comprehensive water quality monitoring programs to assess the status and trends of water quality parameters in rivers, lakes, estuaries, and coastal waters is essential. Continuous monitoring using advanced sensor technologies enables early detection of pollution events, identification of pollution sources, and data-driven decision-making for water quality management (Rene et al., 2019). Enacting and enforcing robust regulatory frameworks and water quality standards is necessary to protect water resources and ensure compliance with pollution control measures. Regulatory agencies play a critical role in monitoring compliance, issuing permits, enforcing environmental regulations, and imposing penalties for violations of water quality standards. Investing in wastewater treatment infrastructure and technologies to treat domestic, industrial, and agricultural effluents is essential for removing pollutants before they are discharged into water bodies. Upgrading and expanding wastewater treatment plants, implementing advanced treatment processes, and promoting water reuse and recycling initiatives contribute to reducing pollution and conserving freshwater resources. Restoring degraded aquatic ecosystems, such as wetlands, riparian zones, and mangrove forests, helps improve water quality, enhance biodiversity, and provide habitat for aquatic flora and fauna. Ecosystem restoration projects involve habitat rehabilitation, reforestation, sediment remediation, and reintroduction of native species to restore ecological functions and services. Increasing public awareness and fostering community engagement are essential for promoting responsible water stewardship practices and behavior change. Educational campaigns, outreach initiatives, and citizen science programs empower individuals, communities, and stakeholders to take proactive measures to prevent pollution, conserve water resources, and protect aquatic ecosystems (Anwar Abdelrahman Aly et al., 2016; Lees, 1994). Addressing trans-boundary water pollution requires international cooperation and collaboration among neighboring countries sharing water resources. Bilateral and multilateral agreements, joint monitoring programs, and collaborative initiatives facilitate data sharing, coordinated management, and mutual support for addressing shared water pollution challenges. Harnessing innovation and technology, including advanced sensor technologies, data analytics, remote sensing, and artificial intelligence, enhances the effectiveness and efficiency of water pollution monitoring, management, and remediation efforts. Investing in research and development, fostering partnerships between academia, industry, and government, and promoting technology transfer facilitate the adoption of innovative solutions for combating water pollution.

By implementing a comprehensive and coordinated approach encompassing these components, a mission to combat water pollution can achieve significant progress in safeguarding water resources, protecting aquatic ecosystems, and ensuring access to clean and safe water for all. Such efforts contribute to sustainable development, environmental conservation, and the well-being of present and future generations.

To Preserve Aquatic Ecosystems and Protect Biodiversity by Reducing Water Pollution

Preserving aquatic ecosystems and protecting biodiversity by reducing water pollution requires concerted efforts across multiple fronts.

1. Source Reduction and Pollution Prevention:
    - Implement pollution prevention measures to reduce the release of pollutants into water bodies.
    - Enforce regulations and incentivize industries to adopt cleaner production practices and technologies.
    - Promote sustainable agriculture practices, such as precision farming, integrated pest management, and soil conservation, to minimize nutrient runoff and pesticide contamination.
    - Encourage the use of eco-friendly products and materials to reduce the generation of pollutants in households and businesses.

2. Wastewater Treatment and Management:
   - Upgrade and expand wastewater treatment infrastructure to improve the quality of treated effluents.
   - Implement advanced treatment processes, such as tertiary treatment and disinfection, to remove contaminants like nutrients, pathogens, and emerging pollutants.
   - Implement decentralized wastewater treatment systems and constructed wetlands to treat sewage and storm water runoff at the source.
   - Promote water reuse and recycling initiatives to reduce the discharge of treated effluents into water bodies and alleviate pressure on freshwater resources.
3. Ecosystem Restoration and Conservation:
   - Restore and rehabilitate degraded aquatic ecosystems, including wetlands, riparian zones, coral reefs, and estuaries, to enhance biodiversity and ecosystem services.
   - Implement habitat conservation measures to protect critical habitats for aquatic flora and fauna, including endangered species.
   - Establish marine protected areas (MPAs) and biodiversity conservation zones to safeguard vulnerable ecosystems and promote sustainable fisheries management.
   - Implement sustainable aquaculture practices to minimize environmental impacts and preserve wild fish stocks.
4. Integrated Water Resources Management:
   - Adopt integrated water resources management (IWRM) approaches to balance competing water demands and optimize water allocation for ecological, economic, and social needs.
   - Promote watershed management initiatives to address non-point source pollution and land-use impacts on water quality.
   - Foster collaboration among stakeholders, including government agencies, local communities, NGOs, and private sectors, to develop and implement holistic water management plans.
   - Incorporate ecosystem-based approaches into water resource planning and decision-making processes to maintain the health and resilience of aquatic ecosystems.
5. Public Awareness and Education:
   - Raise public awareness about the importance of preserving aquatic ecosystems and protecting biodiversity.
   - Educate communities about the impacts of water pollution on human health, ecosystems, and the economy.
   - Engage stakeholders through outreach programs, educational campaigns, and citizen science initiatives to promote participation in water conservation and pollution prevention efforts.
   - Foster environmental literacy and empower individuals to take action to protect water resources through sustainable behaviors and practices.
6. Research and Innovation:
   - Invest in research and development to advance knowledge and technologies for water pollution monitoring, management, and remediation.
   - Support interdisciplinary research collaborations to address complex water pollution challenges and develop innovative solutions.
   - Foster technology transfer and knowledge exchange to facilitate the adoption of best practices and technologies for water quality improvement.

  - Promote the development of green technologies and nature-based solutions for water pollution control, such as phytoremediation, bio-filtration, and ecological engineering.

By implementing these strategies in a coordinated and collaborative manner, it is possible to reduce water pollution effectively, preserve aquatic ecosystems, and protect biodiversity for the benefit of present and future generations.

WATER POLLUTION HAS DETRIMENTAL EFFECTS ON AQUATIC LIFE, ENDANGERING SPECIES AND ECOSYSTEMS

Pollutants such as heavy metals, pesticides, industrial chemicals, and oil spills can be highly toxic to aquatic organisms. These pollutants disrupt biological processes, impair vital functions, and cause physiological damage, leading to illness, deformities, reproductive impairments, and mortality among aquatic species (Ogidi & Akpan, 2022). Certain pollutants can bioaccumulate in the tissues of aquatic organisms, meaning they accumulate in higher concentrations as they move up the food chain. Predatory species at the top of the food chain, such as large fish or marine mammals, can accumulate high levels of pollutants through biomagnification, increasing their susceptibility to adverse health effects and reproductive issues. Water pollution can degrade aquatic habitats critical for the survival and reproduction of many species (Moyle & Leidy, 1992). Sedimentation, nutrient runoff, and chemical contamination can smother benthic habitats, destroy coral reefs, degrade wetlands, and eliminate spawning grounds, reducing available habitat and altering ecosystem structure and function. Excessive nutrient runoff from agricultural activities and sewage discharges can lead to eutrophication, a condition characterized by nutrient enrichment and algal overgrowth in water bodies. Harmful algal blooms (HABs) can form, releasing toxins that poison aquatic organisms, deplete oxygen levels, and disrupt food webs, leading to mass mortality events and ecosystem degradation. Water pollution can interfere with the reproductive success and development of aquatic species. Endocrine-disrupting chemicals (EDCs) can disrupt hormonal balance, causing reproductive abnormalities, feminization of male organisms, and decreased fertility rates. Pollutants can also interfere with embryo development, larval growth, and juvenile survival, impairing population recruitment and resilience. Chronic exposure to water pollution can lead to declines in species richness, abundance, and genetic diversity in aquatic ecosystems. Pollution-sensitive species may disappear from contaminated habitats, leading to shifts in species composition and ecosystem structure (Malmqvist & Rundle, 2002). Biodiversity loss weakens ecosystem resilience, making ecosystems more vulnerable to additional stressors and less capable of providing essential ecosystem services. Acid rain and acid mine drainage can lower pH levels in freshwater ecosystems, causing acidification and impairing the ability of aquatic organisms to regulate their internal pH. Acidification can harm fish, amphibians, mollusks, and other aquatic organisms, affecting their survival, growth, reproduction, and physiological functions. Elevated carbon dioxide levels in the atmosphere lead to increased absorption of carbon dioxide by oceans, resulting in ocean acidification (Häder et al., 2020). Water pollution damages aquatic life, particularly species with calcium carbonate shells, like corals and mollusks, imperiling their survival. Urgent action is vital for ecosystem restoration and pollution control.

IMPACT OF POLLUTED WATER ON HUMAN HEALTH AND THE FUNDAMENTAL NEED FOR ACCESS TO CLEAN AND SAFE DRINKING WATER

Polluted water poses significant risks to human health, emphasizing the fundamental need for access to clean and safe drinking water.

Contaminated water sources can harbor a variety of pathogens, including bacteria, viruses, protozoa, and parasites, which can cause waterborne diseases such as cholera, typhoid fever, dysentery, giardiasis, and cryptosporidiosis. Ingestion of contaminated water or food prepared with contaminated water can lead to gastrointestinal illnesses ranging from mild diarrhea to severe dehydration and death, particularly among vulnerable populations such as children, the elderly, and individuals with weakened immune systems (Schwarzenbach et al., 2010). Water pollution introduces chemicals like heavy metals, pesticides, and industrial substances into drinking water, causing health issues like neurological disorders, cancer, and reproductive problems. Agricultural runoff can also spur harmful algal blooms (Khan et al., 2013). Cyanotoxins from algae can contaminate water, causing gastrointestinal illness, liver damage, respiratory issues, and neurological symptoms. Polluted water breeds disease vectors, spreading malaria, dengue, Zika, and schistosomiasis (Fawell & Nieuwenhuijsen, 2003). Water pollution threatens food security by tainting freshwater used in agriculture and fishing, leading to foodborne illnesses and nutritional deficiencies. Reduced fish yields and biodiversity hinder nutrient access, affecting physical and cognitive development, especially in children. Waterborne diseases incur social and economic costs, perpetuating poverty and inequality. Universal access to clean water is crucial for human health and sustainable development.

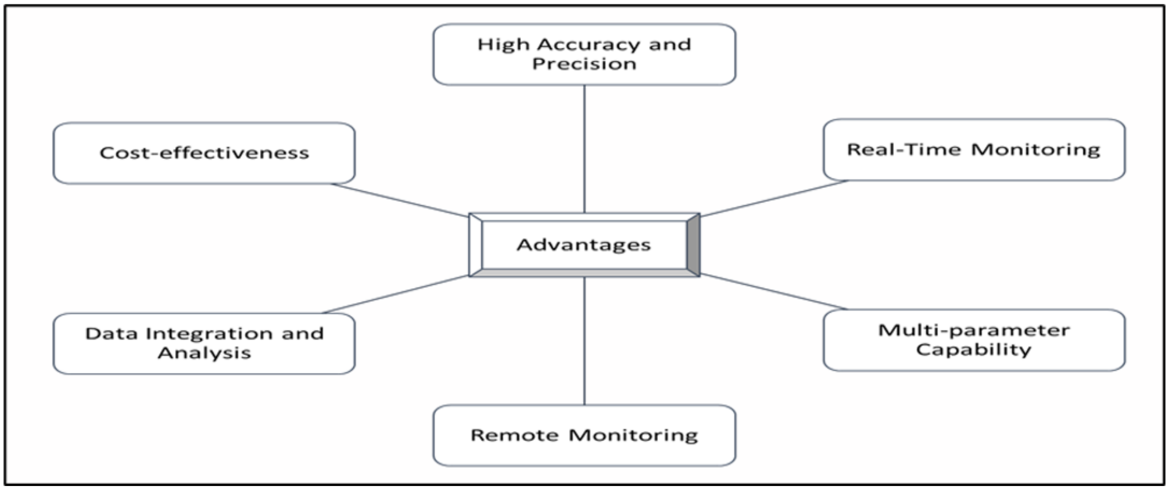
Advantages and Challenges of Advanced Water Quality Sensors

Advanced water quality sensors offer several advantages for monitoring and managing water resources effectively, but they also come with certain challenges (Kruse, 2018).

Advantages:

1. High Accuracy and Precision: Advanced sensors can provide highly accurate and precise measurements of various water quality parameters, enabling reliable monitoring of changes in water quality over time and across different locations.
2. Real-Time Monitoring: Many advanced sensors offer real-time or near real-time monitoring capabilities, allowing for rapid detection of pollution events, timely response to water quality fluctuations, and proactive management of water resources.
3. Multi-parameter Capability: Some advanced sensors are capable of measuring multiple water quality parameters simultaneously, providing comprehensive insights into the chemical, physical, and biological characteristics of water bodies with a single device.
4. Remote Monitoring: Advanced sensors equipped with wireless communication capabilities enable remote monitoring of water quality in remote or inaccessible locations, facilitating data collection and analysis across large spatial scales.
5. Data Integration and Analysis: Advanced sensors are often integrated with data logging, storage, and analysis functionalities, enabling seamless integration of monitoring data, trend analysis, and visualization of water quality parameters for informed decision-making.

Figure 4. Advantage of water quality sensors



6. Cost-effectiveness: Advances in sensor technology have led to the development of cost-effective monitoring solutions, including low-cost sensors and scalable sensor networks, which increase accessibility to water quality monitoring capabilities, particularly in resource-constrained or underserved regions.

CHALLENGES

Advanced sensors require regular calibration and maintenance to ensure accurate and reliable measurements. Calibration drift, fouling, and sensor degradation over time can affect sensor performance and data quality, necessitating ongoing attention and resources for maintenance. Some advanced sensors may be complex to operate and require technical expertise for installation, calibration, and troubleshooting. Limited technical capacity and expertise among end-users can pose challenges to the widespread adoption and effective use of advanced sensor technologies. Environmental factors such as temperature variations, fouling, biofouling, and turbidity can affect sensor performance and data accuracy (Jan et al., 2021). Managing sensor interference and environmental impacts on measurements entails careful calibration adjustments. Handling large sensor data volumes and interpreting complex datasets poses challenges, especially for non-specialists. Effective data management and analysis are vital for informed decision-making. Standardization efforts are crucial for data reliability and interoperability, while privacy and security concerns must be addressed in deploying advanced sensor networks for water quality monitoring. Despite challenges, advanced sensors offer significant benefits, requiring continued innovation and collaboration for maximizing their potential in safeguarding water resources and public health.

CRITICAL ENVIRONMENTAL ISSUE

Indeed, understanding the broader context of water quality is crucial for addressing this critical environmental issue effectively. Water quality encompasses a complex interplay of physical, chemical, and biological factors that influence the health and integrity of aquatic ecosystems, as well as human well-being. Here are some key aspects of the broader context of water quality and the technological solutions available to address this issue:

Water quality is influenced by both natural processes and human activities. Natural factors such as weathering, erosion, and biological processes interact with anthropogenic sources of pollution, including industrial discharges, agricultural runoff, urbanization, and wastewater effluents. Understanding the sources, pathways, and impacts of pollutants on water quality is essential for developing effective management strategies (Shoushtarian & Negahban-Azar, 2020). Water quality plays a critical role in supporting healthy aquatic ecosystems and biodiversity. Clean and healthy water bodies provide essential habitats for a diverse range of aquatic species, including fish, invertebrates, plants, and microorganisms (Prăvălie, 2016). Maintaining water quality is essential for preserving ecosystem services such as water purification, nutrient cycling, flood regulation, and habitat provision. Access to clean and safe drinking water is essential for human health and well-being. Contaminated water sources can pose risks to human health through waterborne diseases, chemical exposures, and other health impacts. Ensuring access to clean water for drinking, sanitation, and hygiene is fundamental for preventing water-related illnesses and promoting public health.

Regulatory frameworks and water quality standards play a crucial role in protecting water resources and public health. Governments and regulatory agencies establish standards and guidelines for water quality parameters such as drinking water quality, recreational water quality, and environmental quality. Compliance with regulatory requirements helps mitigate pollution and ensure the safety of water supplies for human consumption and ecosystem health. Technological innovations offer valuable tools and solutions for monitoring, assessing, and managing water quality. Advanced sensor technologies, remote sensing platforms, data analytics, and modeling tools enable real-time monitoring of water quality parameters, early detection of pollution events, and informed decision-making for pollution control measures (Pimentel et al., 2004). Nature-based solutions, such as constructed wetlands, riparian buffers, and green infrastructure, offer cost-effective approaches to improving water quality and enhancing ecosystem resilience. Adopting integrated water management approaches is essential for addressing water quality challenges comprehensively. Integrated water management considers the interconnectedness of water resources, land use, ecosystems, and human activities, taking into account social, economic, and environmental factors. Collaborative governance, stakeholder engagement, and adaptive management strategies are key elements of integrated water management approaches (Alcamo & Henrichs, 2002). By gaining insights into the broader context of water quality and leveraging technological solutions, stakeholders can work together to address this critical environmental issue effectively. By protecting and restoring water quality, we can ensure the sustainability of water resources for current and future generations, safeguarding both ecosystems and human well-being.

CONCLUSION

In conclusion, addressing water quality is a multifaceted challenge that requires a comprehensive understanding of its broader context, including ecological, social, economic, and technological dimensions. Water quality is intricately linked to the health of aquatic ecosystems, biodiversity, human well-being, and sustainable development. Pollution from both natural and anthropogenic sources poses significant threats to water quality, leading to adverse impacts on ecosystems, public health, and socio-economic activities.

However, technological solutions offer valuable tools and approaches for monitoring, assessing, and managing water quality effectively. Advanced sensor technologies, remote sensing platforms, data analytics, and modeling tools enable real-time monitoring, early detection of pollution events, and informed decision-making for pollution control measures. Additionally, nature-based solutions and integrated water management approaches provide cost-effective strategies for improving water quality, enhancing ecosystem resilience, and promoting sustainable water use.

To address water quality challenges successfully, collaboration and cooperation among stakeholders are essential. Governments, regulatory agencies, communities, industries, academia, and non-governmental organizations must work together to implement robust regulatory frameworks, promote pollution prevention measures, and invest in sustainable water management practices. By safeguarding water quality, we can protect aquatic ecosystems, preserve biodiversity, ensure access to clean and safe drinking water, and promote the well-being of present and future generations.

In summary, addressing water quality is not only a matter of environmental conservation but also a fundamental requirement for sustainable development and human prosperity. By recognizing the importance of water quality within its broader context and adopting holistic approaches and technological solutions, we can achieve cleaner and safer waters for the benefit of both ecosystems and societies worldwide.

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Chapter 6
Sensors for Monitoring Water Pollutants

Surjit Singha
https://orcid.org/0000-0002-5730-8677
Kristu Jayanti College (Autonomous), India

ABSTRACT

This chapter presents an overview of water pollutants and sensor technologies for monitoring them. The chapter emphasizes detection and quantification techniques while discussing chemical, physical, and biological contaminants in surface and groundwater. In addition to examining real-time monitoring advancements, this study delves into critical sensors, including spectroscopic, electrochemical, biosensor, and remote sensing technologies that are emerging, lab-on-a-chip, and nanomaterials. An analysis is conducted on the prospects of water pollutant sensors that progressively improve sensitivity, selectivity, and cost-effectiveness. This extensive evaluation enhances comprehension and resolution of water pollution issues while advocating for sustainable water management strategies that benefit ecosystems and human health.

INTRODUCTION

Water pollution is a substantial peril to ecosystems and human health on a global scale. The detrimental consequences of water body contamination extend to the equilibrium of aquatic ecosystems and the purity of potable water, ultimately resulting in extensive environmental deterioration. The surveillance of water contaminants is of the utmost importance to guarantee adherence to regulations, enable practical remediation endeavours, and protect valuable water resources (Liu et al., 2022).

Researchers and engineers have developed and implemented various sensor technologies that detect and quantify contaminants in water sources to meet this urgent demand. The capabilities of these sensors are extensive, ranging from the detection of chemical pollutants to the evaluation of physical parameters and the monitoring of biological indicators. Using these cutting-edge sensors, scholars and practitioners in the environmental field can acquire significant knowledge concerning the condition of

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aquatic ecosystems and formulate well-informed choices concerning approaches to alleviate pollution (Shahra & Wu, 2020).

This chapter aims to thoroughly examine the significant categories of water pollutants encountered in diverse settings and investigate the state-of-the-art sensor technologies used to detect and monitor these pollutants. By reviewing the most recent developments in sensor technology and their implementations in water quality evaluation, this chapter aims to make a scholarly contribution to the ongoing dialogue surrounding water pollution and the promotion of sustainable water resource management.

Water pollution is an urgent ecological concern with wide-ranging consequences for biodiversity, ecosystems, and human health. The presence of diverse pollutants—chemicals, pathogens, and physical debris—in water bodies poses a significant risk to providing potable water and causes disturbances in aquatic ecosystems. To address water pollution, it is necessary to conduct exhaustive monitoring to identify sources, evaluate hazards, and implement effective mitigation strategies. Sophisticated sensor technologies are paramount in these surveillance endeavours as they facilitate instantaneously identifying and measuring contaminants within water systems (Ma et al., 2023).

Water pollutant sensors are rooted in engineering, chemistry, environmental science, and physics. The subject matter encompasses comprehension of the conduct of contaminants within aquatic ecosystems, such as their origins, methods of transport, and interactions with both biotic and abiotic elements. Furthermore, sensor technologies employ spectroscopy, electrochemistry, biology, and remote sensing principles to identify and assess water samples' impurities. Theoretical models and concepts guide the design, development, and deployment of sensor systems used in water quality monitoring. These frameworks enable the precise measurement and interpretation of data.

The framework for water pollutant sensors incorporates the conceptualization of sensor technologies in environmental monitoring and management. Identification of critical elements, including sensor types, detection mechanisms, data processing algorithms, and decision support systems, is required. The conceptual framework incorporates additional elements that impact sensor performance, such as environmental conditions, sensor calibration, and data validation. By harmonizing these elements within a unified structure, scholars and professionals alike can proficiently devise and execute sensor-driven surveillance approaches to tackle the complexities of water pollution.

This study's objective is a comprehensive overview of sensor technologies for monitoring water pollutants. The objective is to investigate the advancements, applications, and underlying principles of spectroscopic, electrochemical, biosensors, and remote sensing technologies for water quality evaluation. New developments in microfluidics, nanomaterials, and real-time monitoring networks are being examined as part of the research. It will help researchers understand what is coming next in water pollutant sensing.

This research includes various sensor technologies that surveil chemical, physical, and biological contaminants in water systems. The subject encompasses substantial water contaminants, such as thermal pollution, heavy metals, pesticides, pathogens, and sediment. In addition, the study examines the applications of sensor technology in surface water, groundwater, and effluent treatment systems. The study not only examines well-established sensor technologies but also investigates emergent advancements and potential improvements to the capabilities of monitoring water quality.

MAJOR TYPES OF WATER POLLUTANTS

Water pollution is an intricate and widespread menace that jeopardizes the health of humans and ecosystems. It comprises a multitude of contaminants that may originate from diverse pathways and sources. Chemical contaminants from metropolitan development, agricultural operations, and industrial processes collectively contribute significantly to water pollution. Heavy metals, including lead, mercury, cadmium, and arsenic, are released into aquatic environments via atmospheric deposition, mining, and industrial effluents. These substances accumulate in the environment and persist for extended periods, presenting significant health hazards. Commonly employed in agriculture to augment crop productivity, pesticides and herbicides have the potential to seep into surface and groundwater via discharge and leaching processes. It can harm aquatic organisms and expose humans to health hazards if they consume contaminated water or marine food sources. Moreover, pharmaceutical substances such as analgesics, hormones, and antibiotics enter water systems via effluent discharges. The compounds mentioned above present challenges due to their extensive application, prolonged persistence, potential environmental harm, and contribution to the proliferation of antibiotic resistance (Akhtar et al., 2021; Herath et al., 2022).

Physical pollutants also play a role in the deterioration of water quality, alongside chemical contaminants. These pollutants modify the physical attributes of aquatic ecosystems and worsen ecological pressures. Sedimentation caused by construction activities, deforestation, and soil erosion can disrupt marine habitats, suffocate benthic organisms, and impair water clarity, thereby endangering the health and biodiversity of an ecosystem. In addition, urban areas, power plants, and factories can contribute to thermal pollution, which can increase water temperatures, decrease dissolved oxygen levels, and disrupt thermal stratification patterns. This phenomenon may induce detrimental consequences for aquatic organisms, including alterations in their metabolic rates, reproductive difficulties, and increased susceptibility to diseases and parasites (Gonzalez et al., 2023).

Biological pollutants, including microorganisms and pathogens, present supplementary obstacles to water quality and human health. Bacterial pathogens such as Escherichia coli and Salmonella, which frequently arise from human and animal faecal contamination, can potentially induce waterborne diseases and present substantial hazards to public health, especially in regions where sanitation and hygiene standards are insufficient. Parasites such as Giardia and Cryptosporidium, in addition to waterborne viruses including norovirus, hepatitis A virus, and rotavirus, can cause gastrointestinal infections and other health complications. These are particularly hazardous for infants, older people, and individuals with compromised immune systems (Gall et al., 2015). A comprehensive strategy is required to address the myriad issues arising from water pollution. This strategy should incorporate cutting-edge sensor technologies that enable real-time monitoring and early detection of contaminants, stringent regulations ensuring adherence to pollution control protocols and compliance with water quality standards, and active engagement and participation of the community to foster consciousness, promote accountability, and mobilize collective efforts towards sustainable water management practices. By embracing this comprehensive methodology, stakeholders can engage in cooperative efforts to alleviate the consequences of water pollution, maintain the ecological soundness of aquatic ecosystems, and ensure the general public's well-being for current and future cohorts.

SENSOR TECHNOLOGIES FOR WATER POLLUTANTS

Ensuring the health of ecosystems and taking preventative measures against water pollutants requires the implementation of sophisticated sensor technologies that can precisely identify contaminants in various environmental settings. Spectroscopic sensors use spectroscopy techniques, such as UV-Vis, infrared (FTIR), and fluorescence spectroscopy, to study how matter and electromagnetic radiation interact. These sensors' outstanding sensitivity and specificity facilitate identifying a wide range of contaminants, such as dissolved gases, organic compounds, and heavy metals. According to Naimaee et al. (2024), spectroscopic sensors give environmental scientists and analysts detailed chemical profiles that let them know exactly how much certain pollutants are in water samples. The ability of electrochemical sensors to detect alterations in electrical characteristics caused by chemical reactions occurring at the surfaces of electrodes is vital. In water samples, electrochemical sensors are proficient at detecting ions, redox-active species, and gases. Due to their portability, swift response times, and low detection limits, these devices are indispensable for field-based monitoring applications. Their adaptability and dependability enable prompt intervention and remediation initiatives in the event of contamination incidents, making real-time monitoring of critical water quality parameters possible (Kanoun et al., 2021).

Biosensors are an innovative method for detecting pollutants that utilize biological recognition elements in conjunction with transducer technologies, such as antibodies or enzymes. With minimized interference from matrix components, these sensors provide specificity and selectivity in detecting target pollutants beyond all comparisons. Putting biosensors into portable devices makes on-site monitoring easier. It gives us helpful information about water quality so we can act and use proactive management strategies to lower the risk of contamination (Gavrilaș et al., 2022). Remote sensing technologies, which include aerial and satellite platforms, bring about a significant paradigm shift in the surveillance and evaluation of water quality on a large scale. Remote sensing techniques employ multispectral, thermal infrared, and LiDAR to produce maps that accurately depict critical water quality indicators, including turbidity, chlorophyll concentration, and temperature gradients. According to Yang et al. (2022), these technologies provide decision-makers with crucial knowledge regarding temporal and spatial trends in water quality. It enables them to allocate resources and make well-informed decisions supporting sustainable water management practices.

Using remote sensing technologies, spectroscopic sensors, electrochemical sensors, biosensors, and biosensors, environmental scientists and water resource managers can improve their ability to track water pollutants effectively, find where the pollution comes from, and implement targeted plans to clean it up. Sensor technologies of this nature are essential in promoting sustainable water management, preserving the vitality of aquatic ecosystems, and shielding the general public from the detrimental consequences of water pollution.

EMERGING SENSING TECHNOLOGIES

Emerging sensing technologies are revolutionizing environmental monitoring, offering innovative solutions to enhance pollution detection efforts' efficiency, accuracy, and timeliness. Nanomaterials-based sensors can find contaminants even at deficient concentrations with unmatched sensitivity and selectivity using the unique properties of materials like carbon nanotubes, graphene, and metal nanoparticles. This capability detects various pollutants, from heavy metals to organic compounds, making them indispensable for water quality monitoring. Additionally, their compact size and portability enable their deployment in diverse environmental settings, including remote or inaccessible locations, thereby extending the reach of monitoring efforts (Willner & Vikesland, 2018).

Microfluidic and lab-on-a-chip sensors represent another promising avenue in environmental sensing. These sensors integrate multiple analytical functions onto compact platforms, allowing for rapid and efficient detection of water pollutants in real-time. With reduced sample volume requirements and fast analysis times, these sensors are well-suited for on-site monitoring applications, providing high precision and enabling timely intervention measures. Their versatility and efficiency make them invaluable tools for monitoring water quality parameters in various environmental contexts (Kapoor et al., 2020). Real-time monitoring networks, powered by advancements in sensor technology and data analytics, offer continuous surveillance of water quality parameters across large spatial scales. By collecting real-time data on critical indicators such as pH, dissolved oxygen, temperature, and nutrient concentrations, these networks enable prompt responses to emerging threats, supporting proactive management strategies for sustainable water resource management. Integrating remote sensing technologies, IoT devices, and machine learning algorithms further enhances the capabilities of these networks, enabling predictive modelling and adaptive management strategies to anticipate and address potential issues before they escalate (Sejdiu et al., 2022). Emerging sensing technologies offer promising opportunities to revolutionize water quality monitoring and pollution detection efforts. By providing enhanced detection, analysis, and response capabilities, these technologies protect and conserve water resources, ensuring their availability and quality for current and future generations.

FUTURE OUTLOOK FOR WATER POLLUTANT SENSORS

Water pollutant sensors will undergo significant advancements shortly, transforming environmental monitoring. Enhanced sensitivity and selectivity will facilitate the identification of a broader range of contaminants at lower concentrations as materials science, nanotechnology, and signal processing techniques continue to advance. It will contribute to an enhanced comprehension of the dynamics of water quality and facilitate the timely identification of pollution.

Portability and field testing will be of the utmost importance to meet the growing need for platforms that are simple to implement and can be utilized by individuals without specialized knowledge in diverse environmental conditions. A strong emphasis on accessibility will facilitate prompt responses to pollution incidents, enable expedited on-site monitoring, and support the development of proactive management strategies.

The democratization of access to sophisticated sensor technologies will benefit resource-constrained communities and developing regions through reduced costs and maintenance obligations. Incorporating self-calibration and self-cleaning mechanisms into these sensors will reduce the burden of upkeep and maintenance while ensuring their long-term performance and dependability.

In addition, integrating AI algorithms and networked systems with water pollutant sensors will revolutionize water quality monitoring. The integration of these components will facilitate autonomous operation, real-time data analysis, and well-informed decision-making, ultimately resulting in enhanced strategies for detecting and mitigating pollution. By promoting adaptive management approaches, these developments will contribute to preserving freshwater ecosystems for present and future generations and aid in the sustainable management of water resources.

Incorporating artificial intelligence (AI), selectivity, sensitivity, portability, and cost-effectiveness presents significant potential in augmenting our capacity to protect freshwater resources. These advancements will be instrumental in tackling the issue of water pollution and guaranteeing the long-term viability of water management methodologies. Ensuring the health of ecosystems and preventative measures against water pollutants requires the implementation of sophisticated sensor technologies that can precisely identify contaminants in various environmental settings. Spectroscopic sensors employ spectroscopy principles, including UV-Vis, infrared (FTIR), and fluorescence spectroscopy, to analyze the interactions between matter and electromagnetic radiation. These sensors' outstanding sensitivity and specificity facilitate identifying a wide range of contaminants, such as dissolved gases, organic compounds, and heavy metals. Spectroscopic sensors enable analysts and environmental experts to precisely determine the concentrations of particular pollutants in water samples through comprehensive chemical profiles (Naimaee et al., 2024). The ability of electrochemical sensors to detect alterations in electrical characteristics caused by chemical reactions occurring at the surfaces of electrodes is vital. In water samples, electrochemical sensors are proficient at detecting ions, redox-active species, and gases. Due to their portability, swift response times, and low detection limits, these devices are indispensable for field-based monitoring applications. Real-time monitoring of critical water quality parameters is made possible by their adaptability and dependability; this enables prompt intervention and remediation initiatives in the event of contamination incidents (Kanoun et al., 2021).

Biosensors are an innovative method for detecting pollutants that utilize biological recognition elements in conjunction with transducer technologies, such as antibodies or enzymes. With minimized interference from matrix components, these sensors provide specificity and selectivity in detecting target pollutants beyond all comparisons. The integration of biosensors into portable devices facilitates on-site monitoring, allowing for the provision of actionable insights into water quality conditions and the implementation of proactive management strategies aimed at mitigating contamination risks (Gavrilaș et al., 2022). Remote sensing technologies, which include aerial and satellite platforms, bring about a significant paradigm shift in the surveillance and evaluation of water quality on a large scale. Remote sensing techniques employ multispectral, thermal infrared, and LiDAR to produce maps that accurately depict critical water quality indicators, including turbidity, chlorophyll concentration, and temperature gradients. According to Yang et al. (2022), these technologies provide decision-makers with crucial knowledge regarding temporal and spatial trends in water quality. It enables them to allocate resources and make well-informed decisions supporting sustainable water management practices.

By utilizing remote sensing technologies, spectroscopic sensors, electrochemical sensors, biosensors, and biosensors, environmental scientists and water resource managers can augment their capacity to monitor water pollutants efficiently, detect the origins of contamination, and execute focused mitigation strategies. Sensor technologies of this nature are essential in promoting sustainable water management, preserving the vitality of aquatic ecosystems, and shielding the general public from the detrimental consequences of water pollution.

DISCUSSION

The discourse on water pollutant monitoring sensors incorporates many critical facets essential for comprehending the present state of affairs and the potential of environmental monitoring. This segment examines the implications of the previously discussed sensor technologies, including their practical implementations, obstacles, and potential directions for future progress. Implementing sophisticated sensor technologies, such as electrochemical, spectroscopic, biosensor, and remote sensing systems, signifies a substantial progression in water quality monitoring. These sensors provide improved functionalities for detecting contaminants with exceptional sensitivity, specificity, and efficacy. Real-time data on critical water quality parameters enables policymakers, environmental experts, and researchers to make well-informed judgments concerning strategies to mitigate pollution and manage resources. Spectroscopic sensors use spectroscopy principles to make finding and measuring chemical compounds in water samples easier by looking at their unique spectral signatures. This technological advancement provides a swift and destructive approach to water sample analysis, enabling the identification of dissolved gases, heavy metals, and organic compounds. Researchers must overcome obstacles such as interference from matrix components and calibration requirements to ensure precise and dependable measurements. The ability of electrochemical sensors to detect alterations in electrical properties caused by chemical reactions occurring at electrode surfaces is crucial. These sensors' portability, quick response times, and low detection limits make them ideal for field-based monitoring applications. Notwithstanding their extensive implementation, sensor drift, corrosion, and calibration variability continue to be subjects of ongoing investigation and advancement.

Biosensors can find pollutants accurately and selectively using biological recognition elements and transducer technologies. The prospective applications of these sensors in portable devices for on-site monitoring include the detection of waterborne pathogens and contaminants in real time. Before their full potential in environmental monitoring applications can be realized, it is necessary to resolve sensor stability, storage life, and reproducibility challenges. Remote sensing technologies, which encompass aerial and satellite platforms, bring about a paradigm shift in the surveillance and evaluation of water quality on a large scale. These technologies facilitate the creation of maps that accurately represent water quality indicators spatially precisely. It aids in making well-informed decisions and allocating resources supporting sustainable water management practices. However, obstacles, including data processing, interpretation complexity, and spatial and temporal resolution limitations, necessitate additional development and research.

Water pollutant sensors are expected to progress in portability, cost-effectiveness, selectivity, and sensitivity with an eye toward the future. Real-time monitoring networks, microfluidic and lab-on-a-chip sensors, and nanomaterial-based sensors are all examples of emerging technologies that can potentially significantly transform environmental monitoring endeavours. By resolving obstacles, including sensor drift, calibration variability, and the intricacy of data interpretation, these technologies can augment our capacity to oversee, identify, and alleviate water pollution. In doing so, they will ultimately aid in conserving freshwater resources and safeguarding human health and ecosystems.

The discourse underscores the significance of sensor technologies in effectively tackling the complex issues associated with water contamination. By capitalizing on progress in sensor technology, materials science, and data analytics, interested parties can augment their ability to monitor and manage the environment efficiently. Academia, industry, government agencies, and communities must work together to foster innovation, overcome technological barriers, and encourage the broad implementation of sensor technologies in sustainable water resource management.

CONCLUSION

The surveillance and evaluation of water contaminants are critical to protect human well-being, maintain ecological integrity, and guarantee the long-term viability of water supplies. This chapter has comprehensively examined notable water pollutants and the sensor technologies employed for their detection and monitoring. The overview includes chemical, physical, and biological contaminants in both surface and groundwater. In addition to remote sensing technologies, spectroscopic, electrochemical, and biosensors, we have examined emerging trends in lab-on-a-chip, real-time monitoring, and nanomaterials. Upon contemplation of the future, it becomes evident that water contaminant sensors that are progressively more sensitive, cost-effective, portable, and selective could be enhanced by incorporating artificial intelligence. By capitalizing on these developments, interested parties can improve their capacity to oversee, identify, and alleviate water pollution, thereby fostering sustainable water management methodologies and guaranteeing the ongoing accessibility and excellence of water resources for present and future cohorts.

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KEYWORDS AND DEFINITIONS

Biosensors: Sensors incorporating biological recognition elements and transducer technologies to detect target analytes, offering high specificity and selectivity.

Electrochemical Sensors: Devices that detect changes in electrical properties resulting from chemical reactions, commonly used to measure ions or redox-active species in water.

Nanomaterials: Materials with dimensions on the nanoscale, such as carbon nanotubes or metal nanoparticles, are utilized for their unique properties in sensor development.

Real-Time Monitoring: Continuous environmental parameter monitoring provides instantaneous data collection and analysis for timely decision-making and intervention.

Remote Sensing: Techniques employing satellite or aerial platforms to collect data on Earth's surface, used in water quality assessment and environmental monitoring.

Sensor Technologies: Tools and systems designed to detect and measure the environment's physical, chemical, or biological parameters.

Spectroscopic Sensors: Instruments that analyze the interaction between matter and electromagnetic radiation to identify and quantify substances based on their unique spectral signatures.

Water Pollutants: Substances introduced into water bodies that degrade water quality, including chemical, physical, and biological contaminants.

Chapter 7
Smart Sensors for Water Quality Monitoring Using IoT

Kumud
D.S. College, Aligarh, India

ABSTRACT

Due to the increasing contamination and pollution of drinking water, water pollution has emerged as a major concern in recent years. Infectious illnesses spread by contaminated water have a domino effect on ecological life cycles. Early detection of water contamination allows for the implementation of appropriate solutions, therefore preventing potentially disastrous circumstances. It is important to monitor the water quality in real-time to ensure a steady supply of clean water. Improvements in sensor technology, connectivity, and the internet of things (IoT) have led to a rise in the importance of smart solutions for water pollution monitoring. This chapter presents a comprehensive overview of recent developments in the field of smart water pollution monitoring systems. An efficient and cost-effective smart water quality monitoring system that continuously checks quality indicators is proposed in this research. After running the model on three different water samples, the parameters are sent to the server in the cloud for further processing.

INTRODUCTION

Anthropogenic and trophic disruption of aquatic ecosystems (including wetlands, rivers, and lakes) have been on the rise in recent years. The role of aquatic ecosystems as both a reservoir and a route for human-caused pollution is growing. Our inability, unwillingness, and incapacity to sufficiently monitor ambient water quality on a large scale means that its precise scope and consequences are yet unknown. An increase in worldwide freshwater monitoring is necessary to halt this trend and learn how to clean up our waterways so they can support future generations. In order to manage freshwater ecosystems sustainably, it is essential to monitor water quality in aquatic ecosystems as a result of human activities and future climate change. Notably, there are new possibilities for improved modeling and monitoring brought about by the water sector's quick digitalization (Muinul et al., 2014). Natural and artificial abnormalities may be detected early on with the use of enhanced water quality monitoring, which is both

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innovative and cost-effective. Sewage intrusion, pollution, agricultural practices, and surface runoff are among the many human-caused and climate-related threats to freshwater ecosystems in the modern era. In the end, these stresses lead to a decline in water quality and a deleterious effect on aquatic ecosystems. In order to respond quickly to negative changes in freshwater ecosystems, it is crucial to constantly monitor aquatic ecosystems. Ponds, rivers, lakes, seas, and oceans are all susceptible to water pollution when harmful substances enter, dissolve in, or settle to the bottom of these bodies of water. Water quality and purity are both negatively impacted by pollution (Jianhua et al., 2015). The excessive use of chemicals and other impurities makes it very difficult to guarantee water that is both clean and safe to drink. Industrial waste discharge and municipal sewage are two of the most common sources of water contamination, however there are many more potential causes. Pollutants that seep into water bodies from many sources, such as soils, the atmosphere (via rain or groundwater systems), or both, are known as secondary causes of pollution. The majority of the materials found in soils and groundwater are the byproducts of current farming techniques and poorly managed industrial waste. Microorganisms, chemicals, parasites, drugs, insecticides, and plastics are among the most significant contaminants of water. Though they may be difficult to detect as pollutants, these substances will not necessarily change the water's hue. So, in order to find out how good the water is, scientists take a little sample from these water sources and look at marine life.

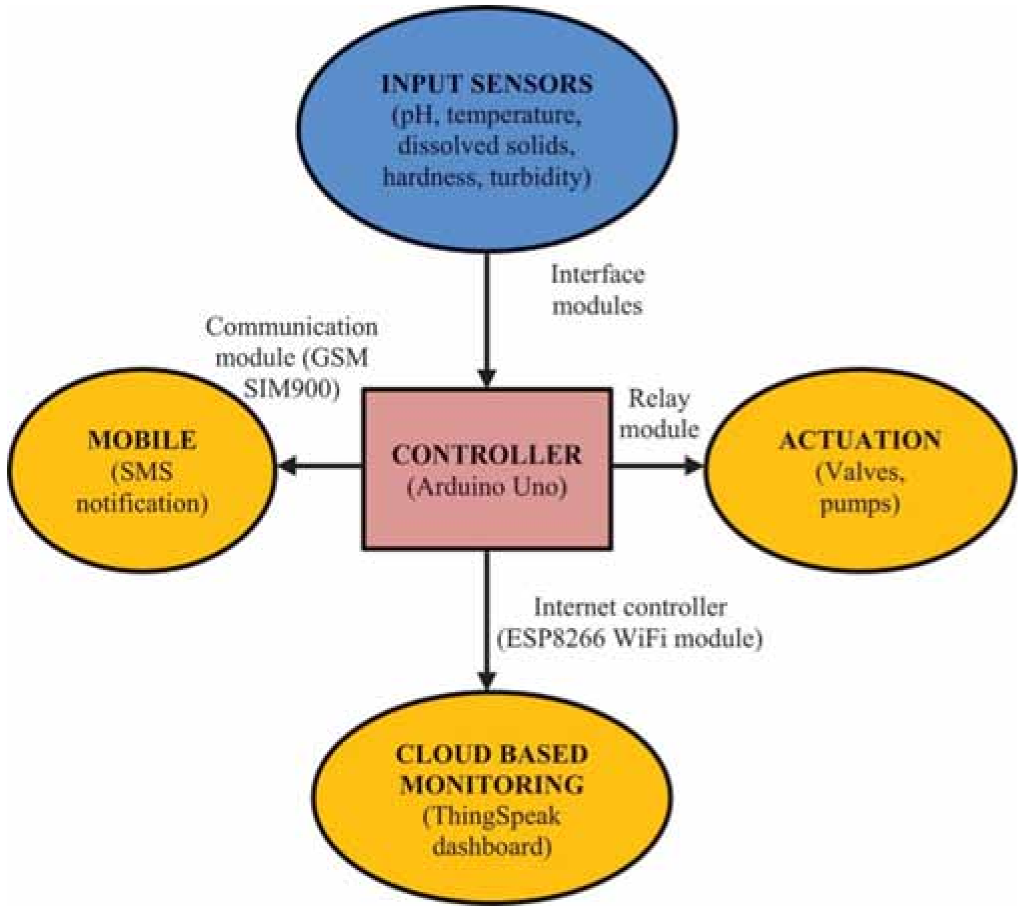
The health, ecology, and economics are all negatively impacted by water quality declines. The pollution of aquatic ecosystems is causing impact on economic growth and exacerbating poverty in various ways to different states. The GDP growth of the will fall by one-third if the biological oxygen demand, a metric for organic pollution in water, exceeds the threshold. The abundance of contaminants, the most of which are produced by humans, makes it difficult to guarantee that water is safe to drink. The over-depletion of natural resources is the primary driver of water quality issues. Water contamination has been further exacerbated by the fast-paced industrialization and increased focus on agricultural expansion, together with innovative technologies, chemicals, and the lack of enforcement of regulations. The uneven distribution of precipitation might worsen the situation at times. The quality of water is affected by individual habits as well (Central Ground Water Board, 2017).

Sewage overflow, industrial effluent, agricultural run-off, and urban run-off are all examples of non-point sources of pollution that degrade water quality. Droughts and floods, as well as consumers' lack of information and training, are other causes of water pollution. Involvement from users is essential for water quality maintenance, as is consideration of other factors such as sanitation, hygiene, storage, and disposal.

Disease, mortality, and societal and economic stagnation are all results of water that isn't up to par. In 2017, water-related illnesses claimed the lives of almost 5 million people globally (Water Resource Information System of India). Rainwater has the potential to wash away pesticides and fertilizers applied by farms, eventually ending up in rivers. Rivers and lakes also get industrial waste. Toxic amounts of these contaminants build up in the food chain, where they kill animals, fish, and birds. Additionally, chemical companies dump their effluent into waterways. A lot of factories get their water for running machines or cooling them down from rivers. Water temperature changes disrupt aquatic ecosystems by reducing dissolved oxygen levels (Central Ground Water Board, 2017). Water quality monitoring is crucial due to all of the aforementioned reasons.

In order to identify present conditions, establish trends, etc., water quality monitoring involves collecting information at specific sites and at regular intervals (Niel et al., 2016). The primary goals of conducting water quality monitoring online are to assess important water quality parameters to detect

Figure 1. Author's adaption
(Adopted from: Allen et al., 2022)



parameter variations; and to offer early warning of potential dangers. The monitoring system also analyses the data in real-time and suggests fixes based on what it finds.

There are two goals to this paper. One is to compile a comprehensive literature review on smart water quality monitoring including topics such as latest research, communication technologies, sensor kinds, and applications. The second objective is to provide a simplified smart water quality monitoring system that is both affordable and easy to use. This system will use a controller that has an integrated Wi-Fi module to track metrics including conductivity, turbidity, and pH. An alert feature is also a part of the system, which notifies the user when water quality metrics deviate from the norm.

REVIEW OF EXISTING LITERATURE

The following are the three primary subsystems that have been identified:

The data management subsystem consists of the application that accesses the cloud storage environment for data and presents the same to the end user. The data transmission subsystem is comprised of a wireless communication device that is equipped with built-in security mechanisms. This device is responsible for transmitting the data from the controller to the cloud which stores the data. The data collection subsystem is comprised of multi-parameter sensors and a wireless communication device that may be optionally used to transfer the information gathered from the sensors to the controller. The controller is responsible for collecting and processing the data.

When looking at the block diagram, the sensors are located at the very bottom. For the purpose of monitoring water quality indicators, there are several sensors available. These sensors are inserted into the water that is going to be tested, which refers to either water that is stored or water that is flowing. Through the use of an optional wireless communication device, sensors are able to transform the physical parameter into an equivalent quantifiable electrical amount. This electric quantity is then sent to controllers as an input. The controller's primary responsibility is to get the information from the sensor, do any necessary processing on it, and then transmit it to the application via making use of the communications method that is most suitable. The requirements of the application need to be taken into consideration while selecting the communication technology and the parameters that will be monitored. This application has functionality for managing data, doing data analysis, and providing an alarm system depending on the parameters that are being watched. A more in-depth discussion of the prior work that was completed in each of the subsystems is presented in this part.

Consumption of domestic water is meant for human consumption, including for the purposes of drinking and cooking. According to the Central Ground Water Board (2017), the Bureau of Indian Standards gives information on the allowed limits of pollutants such as aluminium, ammonia, iron, zinc, and other similar compounds. Traditional methods of measuring water quality involve the collection of water samples by hand from a number of different locations, the storage of those samples in a central location, and the subsequent testing of those samples in a laboratory (Thinagaran et al., 2015; Vinod & Sushama, 2016; Pandian & Mala, 2015; Azedine et al., 2000; Offiong et al., 2014). These methods are not regarded to be successful since there is a lack of information on the water's quality that is available in real time, there is a delay in the detection of pollutants, and there is no solution that is cost effective. Therefore, the need of continuous online water quality monitoring is brought to light in a number of studies (Xiuli et al., 2011; Sathish et al., 2016).

For applications involving lake and sea water, intelligent water quality measures have been taken into consideration. Such applications need the utilization of distributed wireless sensor networks in order to monitor the parameters across a more extensive region and transmit the data that is monitored to a centralized controller via the utilization of wireless communication. Chlorophyll (Francesco et al., 2015), DO content (Christie et al., 2014; Anthony et al., 2014), and temperature (Peng et al., 2009; Francesco et al., 2015; Christie et al., 2014) are some of the parameters that are often monitored by apps of this kind.

For the purpose of ensuring the healthy development of aquatic organisms, aquaculture facilities need to be equipped with water quality monitoring and forecasting systems (Goib et al., 2015; Gerson et al., 2012; Xiuna et al. 10). Using Arduino microcontrollers, the authors of the study (Gerson et al., 2012) have constructed biosensors in order to detect changes in animal behavior that are caused by pollution in aquatic environments. There is a possibility that the aberrant behavior of animals is an indicator that the water is affected by pollution. A smart water quality monitoring system that makes use of artificial neural networks has been suggested by the authors of the paper (Xiuna et al., 2010) in order to make predictions about water quality. For a period of twenty-two months, extensive experiments have been carried out at a local area network that is completely isolated, and the data has been sent to the internet by using CDMA technology. In the context of the management of distributed wireless sensor networks

(WSN), water quality monitoring in distribution systems presents a number of challenges. Eliades et al. (2014) made a presentation in which they discussed a water distribution network that was designed to monitor the quantity of chlorine. (Ruan & Tang, 2011) suggests that solar-enabled distributed WSN might be used for the purpose of monitoring parameters such as pH, turbidity, and oxygen density. For the purpose of monitoring water at various locations in real time, an architecture that is comprised of sensor nodes that are equipped with solar cells and a base station is used. There are a number of benefits associated with the approach that is presented in the research, including flexibility, minimal carbon emission, and low power use. Using additional sensors for monitoring air temperature and relative humidity, Mitar et al. (2016) suggest a combined system for assessing water and air quality. This system would be more accurate than the current approach.

MONITORING OF THE PARAMETERS

It has been determined, on the basis of extensive experimental evaluation carried out by the USEPA, that the chemical and biological contaminants that are utilized have an impact on a variety of water parameters that are monitored. These parameters include turbidity, ORP, EC, and pH. According to Theofanis et al. (2014), it is possible to infer the quality of the water provided that the parameters of the water are monitored and changes in those parameters are detected.Because it determines whether the water is basic or acidic, the pH of the water is one of the most significant aspects to consider while conducting an investigation into the quality of the water. It is possible for the eyes, skin, and mucous membranes to get irritated when using water with a pH of 11 or higher. According to Niel et al. (2016), the corrosive impact of acidic water (also known as water with a pH of 4 or below) may also induce irritation. It is essential for aquaculture facilities to take measurements of DO since this parameter is responsible for determining whether or not a particular species is able to live in the water source in question. A material's ORP is a measurement of the degree to which it is capable of oxidizing or reducing another chemical. When utilizing an ORP meter, the measurement of ORP is done in millivolts (mv). The ORP is positive for both tap water and bottled water. The concentration of such particles that are suspended in water is referred to as turbidity. Conductivity is a measure that may be used to determine the amount of contaminants that are present in water; the level of conductivity decreases as the water becomes cleaner. Conductivity is also closely related with TDS in many instances. However, this is not always the case.

Communication Between Sensors and Controller

Either directly via the use of the UART protocol or remotely through the use of the Zigbee protocol, sensors are linked to the controller. In wireless networks, ZigBee is a technology that allows for the transport of data. In addition to having a low energy usage, it is suited for use in multichannel control systems, alarm systems, and lighting control. For low-rate WPANs, ZigBee is built on the physical layer and media access control that are established in IEEE standard 802.15.4. The Zigbee protocol is used in smart water quality systems for the purpose of communication between sensor nodes and the controller. This is the case when the sensors are situated in distant locations that are not in close proximity to the controller. Direct connection between the controller and the sensors is the ideal method for providing in-pipe home monitoring (Tomoaki et al., 2016). A WSN system for monitoring water quality has been created by the authors. UART is used to establish connections between the transmission module and the sensors. This is accomplished via the use of the Internet connection and the 3G mobile network in order to communicate with the outside world of the sensor nodes. There is a water quality monitoring system that has been suggested by the authors of (Theofanis et al., 2014) for the purpose of in-pipe monitoring and the evaluation of water quality on flies. There are sensor nodes that are put in the pipelines that deliver water to the residences of consumers.

Transmission of Information Between the Controller and the Data Storage

Long-range communication technologies, such as Internet and 3G, are used in order to facilitate communication between the controller and the centralized data storage. The purpose of some of the earlier efforts is to send a text message to the user informing them about the water quality. An extra SIM card is required for the GPRS module that is linked with the controller in these kinds of systems (Wei et al., 2012). One of the disadvantages of such systems is that they incur extra costs for making use of SIM cards. Additionally, the user's premises do not have the capacity to store and retrieve significant amounts of data. IoT enabled solutions have recently gained relevance. The authors of the article "Alessio et al., 2016" provide a survey on the extensive variety of applications that may be achieved via the use of cloud computing and the Internet of Things.

The IoT is a relatively new communication paradigm in which objects that are used in everyday life are outfitted with microcontrollers and transceivers for digital communication. This will enable the objects to communicate with one another and with users, thereby transforming them into an essential component of the Internet (Andrea et al., 2014). An external Wi-Fi module is linked to the controller in the research conducted by Vijayakumar and Ramya (2015), Thinagaran et al. (2015), and Mitar et al. (2016). This establishes a connection between the controller and the closest Wi-Fi hotspot, which in turn allows the controller to establish a connection to the Internet cloud.

Utilized Sensors

A number of sensors are now available for purchase for the purpose of monitoring water quality. These sensors are used in the research conducted by Thinagaran et al. (2015), Vinod and Sushama (2016), and Niel et al. (2016). Among the works that have been published in the literature are examples of sensors that have been built for increased usability. (Tomoaki et al., 2016) makes use of a sensor node of the buoy type that has been manufactured for the purpose of parameter monitoring. In addition to a power module and a transmission module, the sensor that was manufactured also has a solar cell and a Li-ion battery. The research carried out by Mitar et al. (2016) makes use of a thick film pH resistive sensor that is produced in-house using TiO2. Additionally, the output of this sensor module may be directly linked to the microcontroller, eliminating the need for extra signal processing devices. The authors of the study (Theofanis et al., 2014) have created a turbidity sensor that is accurate, inexpensive in cost, and simple to use. This sensor is intended for continuous monitoring of turbidity in pipes.

Theofanis et al. (2014), Peng et al. (2009), Xiuna et al. (2010), Francesco et al. (2015), and Azedine et al. (2000) have all provided extensive data analysis and information processing. These examples may be found in the aforementioned publications. According to Haroon and Anthony (2016), a hierarchical routing method has been developed with the purpose of lowering the communication overhead and increasing the life time of WSN that are appropriate for monitoring river and lake water. A study of the Smart Water Grid system that incorporates ICT is presented in the publication that was published by the

Public Utilities Board of Singapore in 2016. (Woon et al., 2016) presents a discussion on an integrated management model that encompasses the whole water cycle, from the sources to the taps, with the goal of ensuring the consistency, safety, and efficiency of water.

POWER CONSUMPTION RELATED ISSUES

As a result of the fact that Internet of Things apps are most likely to run on batteries, power consumption is a significant limitation for these applications. One of the most significant sources of power consumption is the transmission of data. There are two phases of data transfer that take place for applications such as an intelligent water quality monitoring system. One kind of communication is that which occurs between the controller and the sensors, while the other type of communication occurs between the controller and the application. According to Al-Fuqaha et al. (2015) and Ray (2016), It has been determined by Shuker et al. (2016) that Wi-Fi is not an appropriate method for communication between sensor nodes and the controller due to the significant amount of power that is lost and wasted. As far as our literature review is concerned, every single study has used the zigbee protocol for the purpose of communication between the controller and the sensor nodes.

A home water quality monitoring system is the focus of the work that is being proposed. It is presumed that the sensors are linked at the in-pipe level. The user premises are the location where the controller and the sensors are put together as a single module. For this reason, the controller is directly linked to the sensors' devices. For applications such as monitoring the water in lakes, rivers, and the ocean, the controller and the sensors are separated by a significant distance throughout the process. The use of short-range communication protocols, such as Zigbee, is recommended in such circumstances. Wi-Fi is an attractive option for the purpose of facilitating communication between the controller and the application. When using these various short-range protocols, the sensor nodes are able to interact with the controller with relative ease. However, when attempting to link the system to the Internet, it is necessary to have an adapter of some kind that is capable of communicating with both the sensors and the Internet. The increased hardware overhead is caused by this. The aforementioned issue does not emerge while using Wi-Fi since there is already an infrastructure that has been constructed and is in operation at this point. The fact that the Wi-Fi standard was developed for personal computers and laptops, which have a totally different power need than battery-operated smart items, is one of the limitations of the technology. As a result, manufacturers have begun manufacturing Wi-Fi devices that possess low power consumption. The CC3200 is an example of an embedded low-power Wi-Fi device that has a major emphasis on power management and extending the battery life of its products. The microcontroller is run in one of the four power modes, which are Hibernate, Low Power Deep Sleep mode, Sleep mode, and Active mode (Texas instrument CC3200 Simple Link, 2017). This reduction in power consumption is accomplished by operating the microcontroller in one of these modes.

Thomas et al., 2016 examined the power consumption of a standalone microcontroller with Zigbee and BLE modules, as well as a controller that had an integrated Wi-Fi device. When compared to standalone microcontrollers, it has been shown that devices that have Wi-Fi integrated in utilize less power. This was discovered based on the results of the experiments. Because of the additional power consumption that occurs during the process of establishing and disestablishing a connection during transmission in standalone devices, this is the reason. When using the Wi-Fi integrated controller, the Wi-Fi module enters a sleep state, after which it maintains the connections that it has previously established. Since this is the case, it is not necessary to create a fresh connection each time the Wi-Fi module becomes active. The usage of electricity is significantly decreased as a result of this. A comparison of the CC3200 with the microcontroller and embedded boards that have been utilized in the research that has been published (Al-Fuqaha et al., 2015; Ray, 2016).

UTILIZATION OF WIRELESS SENSOR NETWORKS

In the most recent decades, WSNs have been created and are progressively being used for the purpose of monitoring water quality by researchers, municipalities, and commercial firms alike. According to Taperello et al. (2017), the characteristics of a general WSN system architecture include data gathering, transmission, processing, storage, and redistribution. These sensor probes have progressed to the point that they are now capable of measuring a wide variety of physicochemical parameters, including conductivity, turbidity, DO, and pH (Marcé et al., 2016). Data collecting is accomplished by the use of a network of in-situ sensor(s) as well as a certain sampling frequency. The data that has been collected is then sent to the central monitoring hub using various technologies. These technologies often include cellular networks like GSM, as well as more recent networks like ZigBee and even Wi-Fi. As the IoT continues to attract attention from researchers and expands in terms of commercialization, it is anticipated that these networks will continue to evolve. Processing, storing, and analyzing the data are all possible after it has been sent. Technologies such as these make it possible to perform remote continuous real-time monitoring and visualisation of water-body quality parameters at fixed locations (Tapparello et al., 2017). Additionally, it has been discovered that these technologies provide a more accurate description of water-bodies in comparison to manual methods, which enables the comprehension of biogeochemical processes (Kirchner et al., 2004; Ivanovsky et al., 2016).

WSNs provide a great deal of flexibility in terms of the frequency at which water quality parameters may be monitored. This is in contrast to systems that monitor water quality parameters at low frequencies, which are prone to ambiguity (Birgand et al., 2013). This is especially important for flashy streams, where timing sampling with peak flow can be difficult to achieve. Khalil and Ouarda (2009) conducted a review in which they discovered that the use of multiparameter sondes and the much finer possible temporal sampling resolutions were able to capture transient events that were likely to have been missed by grab sampling. However, despite the fact that high-frequency data collecting does not involve an excessive amount of expense, there are limitations to the transport and storage of data in systems that do not have automated telemetry (Chappell et al., 2017). A monitoring frequency that is too high may also return redundant information (Khalil and Ouarda, 2009), which can lead to an increase in the possibility for noise in the data. Additionally, it can increase the demand for power, which can lead to an increase in the capital cost of installing a renewable source (such as a solar panel) in the event that mains energy is unavailable. In light of these factors, it is necessary to locate a frequency that strikes a balance between the examination of each physicochemical parameter.

CONCLUSION

The pollution of water poses a significant risk to any nation since it harms people's health, the economy, and the biodiversity of the environment. Presented in this article are the causes and consequences of water pollution, as well as a detailed examination of several techniques of water quality monitoring and a discussion of an effective approach for monitoring water quality that is based on the IoT. Despite the fact that there have been a great number of successful intelligent water quality monitoring systems, the research field continues to be particularly difficult. This article provides an overview of the current work that has been carried out by researchers in order to create water quality monitoring systems intelligent, low powered, and highly efficient. The goal of these systems is to ensure that monitoring will be continuous and that alarms and notifications will be forwarded to the relevant authorities for further processing. In addition to being easy to use and economical, the model that was designed is also versatile. Three different samples of water are put through a series of tests, and the findings allow for the determination of whether or not the water is suitable for consumption. The IoT is used in the process of developing a system for the monitoring and management of water quality in real time for a water treatment facility. Through the use of a wireless sensor network, the system is able to deliver immediate results and enables real-time monitoring and control. In addition, a simulation model and a prototype that is operational are constructed in order to illustrate how the system functions according to a variety of field variables. The quality of the water is evaluated at each and every step of the treatment process, and any deviations from the WHO standard will result in the implementation of an independent control measure. The monitoring and regulation of water quality in real time contributes to an improvement in water security. It eliminates the need of conventional techniques of water filtration, which are unable to monitor and manage water quality parameters from the beginning stages of the process. In addition to this, it eliminates the need for human contact, which eliminates the time that is wasted when water samples are submitted to the laboratory for analytical testing as well as the expense of testing offline. This product makes a contribution to the prevention of the spread of diseases that are transmitted by water. As a recommendation for a future directive, it is suggested that the most recent sensors be used for the purpose of detecting a variety of other quality metrics, that wireless communication standards be utilized for improved communication, and that the Internet of Things be utilized to develop a more effective system for monitoring water quality, and that the water resources be made safe by prompt action.

LIST OF ABBREVIATIONS

BLE: Bluetooth Low Energy
DO: Dissolved Oxygen
EC: Electrical Conductivity
GDP: Groos Domestic Product
GPRS: General Packet Radio Service
ICT: Information and Communication Technology
IEEE: Institute of Electrical and Electronics Engineers
IoT: Internet of Things
ORP: Oxidation-Reduction Potential
UART: Universal Asynchronous Receiver / Transmitter
WPANs: Wireless Personal Area Networks

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Chapter 8
Sensors in the Marine Environments and Pollutant Identifications and Controversies

Minakshi Harod
Devi Ahilya Vishwavidyalaya, India

ABSTRACT

The quality of marine environments is influenced by a range of anthropogenic and natural hazards, which may adversely affect human health, living resources, and the general ecosystem. The most common anthropogenic wastes found in marine environments are dredged spoils, sewage, and industrial and municipal discharges. These wastes generally contain a wide range of pollutants, notably heavy metals, petroleum hydrocarbons, polycyclic aromatic hydrocarbons, and others. Real-time measurements of pollutants, toxins, and pathogens across a range of spatial scales are required to adequately monitor these hazards, manage the consequences, and to understand the processes governing their magnitude and distribution. Significant technological advancements have been made in recent years for the detection and analysis of such marine hazards. This chapter aims to review the availability and application of sensor technology for the detection of marine hazards and for observing marine ecosystem status.

INTRODUCTION

Marine debris detected as marine pollution involves solid materials, plastics and bags that are unintentionally or intentionally has been disposed in the ocean. Marine ecosystems act as natural sink of greenhouse gases and carbon dioxide. Anthropogenic activities are seen to severely pollute the oceans for last few centuries. Ocean is seen to contain enormous seawater with many ecosystem regulations, with global based heat cycles, climate systems and carbon cycles. Marine pollution is caused due to the discharge of the sewage within rivers and excessive dumping of pesticides as well as fertilizers is the main cause of marine pollution (Clark et al., 1989). Pollutants like oil, plastic, chemicals that are toxic, radioactive

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wastes are seen as the main pollutants in oceans. Long term protection as well as ocean management needs to be done in order to save the oceans from being polluted. Approximately 8 million tons plastic are seen to contribute 80% of the total ocean based pollution (Jambeck et al., 2015). In the light of the growing concerns remote sensors has been found to be usable and potential for monitoring environmental based issues in marine environment. In this regard, this chapter provides a wider knowledge about the sensors with the classification of the sensors that are used to prevent pollution in the ocean. In addition, the identification of the pollution using those sensors and their implication for the environment will be discussed. Plastic is the main cause of pollution in oceans while other pollutants are non-point-based sources, industrial chemicals, fertilizer runoffs and other sewage. This pollution is extremely harmful that kills ecosystems, affects human life and threatens wildlife also. This causes damage in the marine ecosystem and that creates a knock-on effect on wildlife populations. By getting entangled with fishing gear 100000 marine animals dies in each year (Simmonds and Peter 2012).

As in year 2023 estimated 170 trillion particles of plastics in the ocean is seen which is roughly 21250 plastics. This indicates a surprising fact that plastic is one of the main sources of pollutant in ocean ecosystem. International union for conservation of nature detected that 14 million tons plastic ends up every year in the ocean making 80% marine debris. As per the study of university of Cadiz 10 plastic products made up to 75% of the polluting items within ocean. Worst part from the lot states that plastic bags take 20 years for decomposition and stays there harming the marine animals causing pollution.

Ocean bound plastic as the name suggests generates 80% of the marine pollution and as per NIH meso-plastics, macro plastics and micro plastics makes litters in ocean and are the leading source of marine pollution.

INTRODUCTION TO OCEAN SENSORS

Oceanography has modern electronic tools that allow humans to investigate deep down analysis and monitor the highest depths in the ocean. Electronic techniques with low energy, delicate, and accurate sensors collect vital information, and have helped investigators to record and measure the environment of the deep sea. Transportable submersible robots and underwater drones with intelligent sensors are used for observing the temperature of the water, auto compass bearing, and depth, pitch, and roll, turns, have been created. For technological improvements, underwater drones can drive around freely nowadays, quickly, and more smoothly. Artificial intelligence and robots have been developed to investigate the oceans where people cannot reach. Human-like bodies in these robots with touch sensors can take out a combination of works in the deep of the sea. Sensors are the tools used to get information of the ocean. Modern instruments operating electronically in oceanography helped humans to explore the deeper and hidden facts underneath the ocean and sensors are among them.

In order to reduce this impact sensing the ocean with sensors has become a must. To study ocean pollution for example ocean chemists are likely to use sensors for detection of the synthetic compounds like plastics, petroleum, automobile exhaust, sewage runoff, fertilizers and chemicals.

Today due to rapid advances in biotechnology, nanotechnology and micro technology cost effective precision-based sensors has been introduced. It creates an observatory-based platform having unprecedented access to underwater vehicles that sends data after observation to the sender. In 2003 WHOI ocean life institute and deep ocean exploration institute along with national science foundation and office of naval research introduced one workshop *"The Next Generation of in situ Biological and Chemical*

Sensors in the Ocean." This created a roadmap to sensors where through quantum leaps observation of oceans is done. These sensors not only detected the temperature and salinity of the ocean but also helped in detecting the percentage of dangerous pollutants that are present in the ocean. However, between 2013 and 2016 European researchers developed innovative techniques to access pollutants. The BRAAVOO team prepared one specific sensor where chop sensors access the presence of pollutants through light. More light means more contamination in the water.

UNDERWATER SENSOR NETWORKS

Adhoc network operating wireless has the capability to monitor the oceans and marine environment. The proposal details an underwater wireless network where autonomous underwater vehicles (AUVs), unmanned undersea vehicles (UUVs) and buoys to receive data from sensors and periodically send back to a base station (Kerry Taylor-Smith 2018).

Ocean based sensors detects radiance and through imagery resolutions the plastics and other pollutants that are harming the oceans got detected. This creates nodes that communicate with neighbors with shorter range of acoustic communication. That acts as early warner that can prevent catastrophic events and protects the oceans. By the use of remote sensors detection of some properties of the ocean like is done:

- Reflectance
- Temperature
- Colour
- Roughness

The pollutant gets detected when any of the above property changes for example oil spills in the ocean dampens the surface of the water and so lower roughness-based signal means oil is there in huge quantity in the ocean.

TECHNOLOGIES TO DETECT SENSOR-BASED IDENTIFICATION OF POLLUTANTS

A broad type of sensor devices is operated in the sea, including benthic flow meters, dissolved oxygen sensors, mass spectrometers, hydrophones, resistivity probes, conductivity-temperature-depth, and turbulent-flow current meters. Remote sensors are used to capture the electromagnetic interaction with the water. Checking total absorption, non-algal pigments, and suspended sediments present in the water gets detected by the help of these sensors. These sensors, for identification of pollution, can be categorized into two types which are airborne and spaceborne (Ogola et al., 2010). Some other sensors are also utilized to detect water-based pollution for example dissolved oxygen sensors, benthic flow meters, hydrophones, mass spectrometers, resistivity probes, turbulent flow current meters, and conductivity-temperature depth. The Airborne sensors are utilized to detect water pollution, and for operating the Airborne sensors aircraft are used which fly at relatively lower altitudes. For spill surveillance airborne sensors are (Theo., 2008):

- Side-looking airborne radar
- Microwave radiometer
- Laser fluor sensor

Based on the satellite sensors water quality and other parameters are checked so that spills percentage can be checked.

The aircraft usually fly a few hundred meters to a few kilometers above the surface thus providing a higher level of accuracy and details regarding the data collected. For real-time monitoring of oil and chemical spills airborne data is particularly useful. The types of airborne sensors for pollution detection are listed below:

a) *Infrared/ultraviolet line scans (IR/UVLS)*

IR/UV Line scanner is regarded as a standard tool in oil spill remote sensing. IR/UV line sensors are capable of simultaneously mapping the total extent of oil spills as well as the areas where there are intermediate and large oil thicknesses. This sensor helps in resolving the issue of mapping the very thick and thin oil layers in the water surface. The IR/ULVS sensor is highly applicable in imaging remote sensors for thermal mapping applications and basic sensors for the automatic creation of the thematic map for the oil seen. The scanner is characterized by a unique optical design, excellent maintainability, and a broad operating temperature range.

b) *Laser floor sensors*

Laser floor sensors are capable of detecting oil and complicated petroleum products in marine, coastal, and terrestrial environments. The major capabilities of this sensor involve the ability to discriminate between oiled and various naturally occurring non-oiled substances such as seaweed. Laser door sensors reflect uniqueness by identifying the primary characteristics of oil, namely the unique oil fluorescence spectral signature whereas generic sensors depend upon the secondary characteristics of oil (Carl E Brown, 2011).

c) ***Space-based sensors***

Space borne sensors are used to cover extensive and remote areas for monitoring the water quality. Optical space borne sensors are utilized for marine monitoring and this operates in the sun synchronous orbit. The only difference is that the GOCI sensor, which is specifically designed for marine monitoring, is placed in the geostationary orbit. Spatial coverage of the space-bound sensors can vary from tens to hundreds of kilometers and the temporal frequency can vary from hourly to weekly monitoring (Hafeez, 2018).

Large algorithms have been developed for getting the water quality information such as the primary productivity, Chl-a variability,SS, total suspended solids (TSS), CDOM etc (Hafeez, 2018). The Orb View 2 was launched at 1 August 1997 with a spectral brand of 8 nm whose marine perimeter access was Chl-a. SeaWiFS made a simple but elegant measurement regarding the greenery of the earth from the period between 1998 -2001. The measurement provided the scientist an array regarding the capability of the planets to support life. The following data also enable the scientist to obtain a benchmark for studying the effect of the planet's response to a changing environment.

d) *Remote sensors*

Chlorophyll and algal blooms are the main planktons that form the base of the marine life. Accelerated growth of the algae mainly blocks the sunlight and too much dissolved oxygen that it takes is hazardous for marine life and this are checked by the remote sensors (O'Reilly, 2000). Based on the above figure it is seen that spectral response and level of chlorophyll concentration is checked. By the use of above sensors, the detection of pollutants are done and in later chapters elaborative discussion will be done.

CONTROVERSIES SURROUNDING POLLUTANT IDENTIFICATION AND MONITORING

Various controversies arise due to pollutant identification and monitoring through sensors. Despite the relevance of the sensors in oceans some challenges in the form of controversies are still seen. Purchase and maintenance of the sensors are the biggest controversy that is seen in sensor usage. Difficulty in maintenance of sensors in harsh conditions remains in the top list of controversy that will be discussed.

Reliability and accuracy: Main controversy that arises due to sensor useis how much reliable and accurate information it gives. As per the critics this technology may work on lower precisions, without proper diagnostics and faulty based alarm data can give wrong information to the radar and that can lead to wrong results on percentage of pollution calculation. Other error-based factors like fouling, calibration drift, and interference with the other substances in the water.

Accessibility and cost: Modern and innovative sensor-based technology has advanced more now and are seen to be less accessible among all countries. Lesser equality in access to all may lead to use of less effective sensors that could result in late detection or wrong detection of pollutants that has the potential to disparities in data collection-based efforts.

Detection Limits: Most top-rated controversy is seen in this aspect where sensors cannot detect accurate information especially in lower concentration. As per the critique limit of detection (LOD) is stated as the lowest concentration of sample analyte within 95% probability. In other words underestimation of the pollution levels mainly masks the true source of environmental harm. Wrong and timely detection constraints make this a poor and faulty instrument.

Validation and standardization: Lack of protocol-based standardization in terms of calibration, data interpretation and sensor deployment again arouse as a source of controversy. As per the argument done by critics without proper and consistent standards it becomes challenging to compare data that gets collected from sensors and this results in wrong measurement.

Data security and privacy: With the increased proliferation of sensor-based networks raised concerns on security and privacy has been seen as the main issue. Controversies like unauthorized access of sensors, wrong usage and tampered usage of sensors. It is seen that underwater sensor-based nodes gets installed in dangerous and harsh conditions that resulted in network attacks. External and internal attacks like high error rates, higher latency in propagation, computational based limitations in capability and limited bandwidth hampers the smooth operations of sensors.

Temporal and spatial resolution: Another controversy states concerns on temporal and spatial resolution for sensing data. With satellite sensors broader coverage of larger areas can be done but spatial resolution is seen to be restricted for small scale and localized based pollution events. Controversy that arises here states that frequency in the satellite passing by can capture only temporal variations within pollution levels.

Sensitivity to environmental conditions: The main challenges faced here is the environmental conditions that hampers the image generation of the sensors. Cloud and heavy fog can reduce the accuracy of the data as due to cloud proper picture can't be taken and that hampers the reliability and this has been raised as another controversy by the researchers. Atmospheric and water turbidity affects the reliability and quality of data. Data biasness and errors leads to errors in accurate monitoring of data.

Proper addressing of controversies involves collaboration with remote sensors-based scientists, policy makers, and local communities involve robust use of remote sensing technologies. Efforts for addressing ethical and privacy-based concerns have been seen subjective to further discussion.

SUMMARY

This chapter presented an overview of sensors that are used in ocean for detection of pollutants.

- It explained the common pollutants of the marine environment Ocean bound plastics, Ocean bound plastic, non-point-based sources, industrial chemicals, fertilizer runoffs and other sewage.
- Different type of sensors like autonomous underwater vehicles (AUVs), unmanned undersea vehicles (UUVs) Infrared/ultraviolet line scan (IR/UVLS), Laser floor sensors and) Space-based sensors has been found
- It has been learnt that several controversies like reliability and accuracy, detection limits, validation and standardization, temporal and spatial resolution and sensitivity to environmental conditions has made the sensor usage faulty and biased.

It has been concluded that by the use of sensors the detection of pollutants has become easier although there are many controversies still sensors have made the detection of oil spills, chemicals and sewage runoffs easier. This detection through remote and oceanographic sensors shows that measurements and detection earlier can help in reducing the harmful impacts of hazardous pollutants in oceans.

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Chapter 9

Removal of Heavy Metals From Waste Water Using Different Biosensors

Kamal Kishore
https://orcid.org/0000-0002-7870-4142
Department of Chemistry & Biochemistry, Eternal University, India

Yogesh Kumar Walia
Department of Chemistry, Career Point University, India

ABSTRACT

Recently, much effort has been made to reach to an effective strategy for wastewater monitoring. Several pieces of evidence support the special role of biosensors in plans for the administration of water resources. Concerning this fact, there are some technical and practical limitations and complications, which should be overcome to develop more efficient and commercial applicable biosensors. To achieve this goal for the detection of a broad range of wastewater pollutants, it is necessary to design novel sensing systems with larger detection range and capability for the simultaneous detection of several compounds. Additionally, the limit of detection in the lower concentration range should be possible, and also biosensor should have long-storage stability. This chapter explores the various ways by which heavy metals can be removed from wastewater. Different biosensors are under investigation that can be used to remove different pollutants form different ecosystems. This will help to solve the problem of water pollution and will also help to reduce human health impact.

INTRODUCTION

Although heavy metals are essential for life on Earth, they pose a threat when they build up in living things. Lead, nickel, cadmium, chromium, arsenic, and mercury are among the most common heavy metals found in environmental contamination. Various activities, both natural and man-made, emit cadmium into the atmosphere, and its exposure to animals and people varies. Industrial waste, surface runoff, and

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absorption all contribute to cadmium contamination of aquatic ecosystems. The metal cadmium may be toxic to humans if they consume it in the form of food, air, or water. cadmium lacks any properties that would be beneficial to plant development or metabolic activities.

The biosphere may include mercury, a very dangerous heavy metal. Additionally, it has grown into a significant air pollutant as a result of human activities and is becoming increasingly common in the air. The very toxic compound methylmercury is formed when mercury reacts with sediments in water (Ansari, 2017). The methylmercury contaminates human bodies as it passes through the food chain from marine organisms, such as shellfish and fish, that ingest pathogenic bacteria. as absorbed into the human body, it causes a variety of neurological disorders as it enters the circulation (Olaniran et al., 2008).

A non-biodegradable metal, lead occurs naturally in very minute amounts. Lead levels in the atmosphere are steadily rising due to human activities including mining, manufacturing, and burning fossil fuels. Lead poses health risks to people when exposure levels above the recommended safe threshold. Kids are more likely to have lead poisoning to begin with, and dust that contains environmental lead may make their condition worse (Zhou et al., 2017). Naturally occurring in various oxidation levels, manganese is the most prevalent of the hazardous heavy metals. Manganese oxides are released into the atmosphere when the petrol additive methylcyclopentadienyl manganese tricarbonyl (MMT) is burned. Consuming too much manganese is quite hazardous, even though it is necessary for many physiological processes (Kummu et al, 2016).

The metal chromium is both poisonous and carcinogenic. In comparison to chromium (VI), chromium (III) is not as dangerous. In the course of manufacturing, they are able to interconvert to one another. Because chromium (III) is less poisonous than chromium (VI), its conversion to chromium (VI) is less damaging to the environment. Numerous businesses utilise chromium, which is harmful to local climates.

Traditional analytical approaches for environmental contaminant monitoring are time-consuming, costly, and need specialised reagents. These methods include gas chromatography and high performance liquid chromatography, as well as capillary electrophoresis and mass spectrometry. To address the deteriorating state of the environment, there is an urgent need for more sensitive, less costly, quicker, simpler to use, and portable biosensing technology. These techniques would be ideal for monitoring contaminants that are harmful to ecosystems and individuals. Traditional techniques are worthless for in-situ measurements, such as in the event of an unintentional pesticide release or acute poisoning, since tiny, lightweight, and rapid equipment, such as environmental monitoring biosensors, is required. Nanotechnology is critical in the creation of successful biosensing devices; modern biosensors improve analytical performance, such as sensitivity and limit of detection, by adding nanoparticles and unique nanocomposites into their designs. Gold nanostructures, for example, offer a large surface area and excellent electron mediation capabilities, making them an ideal basis for enzyme immobilisation matrices. Furthermore, even in vivo, gold nanoparticles showed little citotoxicity and great biocompatibility. As a result, one present and future technical challenge in environmental science is how to increase the number of commercially available biosensors for in-situ measurements by enhancing the analytical performance of sensing systems through the inherent contributions of nanotechnology and biotechnology (Geng et al., 20-08).

Biosensors integrate chemical and physical sensing methods into a single analytical sensor. Their effectiveness stems from the fact that they have a physical or chemical immobilization mechanism that brings the biological and physicochemical components into close proximity with one another. At its core, a biological element is a receptor (bioreceptor), which allows it to interact with the medium of interest in order to identify a certain analyte. A physicochemical transducer takes the reaction that happens at the interface between analytes and bioreceptors and turns it into a quantifiable signal that can be processed and shown as values. The immobilization of the biological substance in close proximity to the transducer is necessary for accurate biosensor functioning. This immobilization may be achieved by chemical attachment or physical entrapment (Lyngberg et al., 1999). Since bio receptor molecules are to be employed for measurements several times, only minimal numbers are needed. Because of its versatility in detecting a broad variety of analytes, including contaminants, microbes, fungi, pharmaceuticals, and food additives, biosensors have seen fast and diverse development over the last few decades. The wide range of industries that may benefit from these characteristics includes robotics, security and defence, agriculture, forensic chemistry, pharmaceuticals, industry, environmental monitoring, medicine, food, and more. Biosensors are most useful when used to activities that are unique to that field. Their value in the food business was shown when it came to controlling quality and safety. They were able to distinguish between natural and fake ingredients, keep an eye on fermentation, and more. Control procedures are where they are most useful in industry. Their usage is highly recommended in the fields of drug development, clinical and medical sciences, and the quick detection of viruses and substances that cause a wide range of disorders, including cancer (Kokkinos, and Economou, 2017).

ELECTROCHEMICAL BIOSENSORS

Because they were the most often reported, electrochemical biosensors were the first to be developed and sold commercially. By generating or consuming ions or electrons, the chemical interaction between the biomolecule (bioreceptor) and the analyte (target) changes the electrical characteristics of the analyte solution (current, potential, etc.) in this biosensor type. The transducer can detect these variations in the analyte concentration in the sample solution since its electrochemical signal is proportional to it (Bachmann, and Schmid, 1999).

One benefit of electrochemical biosensors is their sensitivity even with very tiny sample volumes, and another is that they need very little sample preparation. Direct sample analysis is another option, opening the door to automation. Detections have issues with stability and repeatability. Biosensors based on (ISFETs), potentiometric, amperometric, and conductometric electrochemical sensors are the four main categories into which these devices fall. A customized electrochemical cell design is usually necessary when working with different measuring principles. A potentiometric biosensor works by placing an ion-selective membrane on top of an ion-selective electrode (ISE). This membrane acts as a selector, allowing the sensor to detect target ions even while other ions in the sample are interfering. These devices calculate the difference between the potentials of the working and reference electrodes with almost little current, which is a function of the analyte concentration. Amperometric biosensors dominate the electrochemical biosensor market. Compared to potentiometric biosensors, amperometric ones are slower and less sensitive, and they might be impacted by irrelevant electroactive species (Zhang et al., 2014).

The electrical conductivity of a sample solution measured between two electrodes is the basis of conduct metric biosensors, which are based on the biological process. Conduct metric biosensors are great for a lot of things as they aren't light-sensitive, they don't need a reference electrode, and they can be mass-produced utilizing inexpensive technology. The fourth category of electrochemical biosensors is those that can directly detect ions; these are biosensors built on (ISFETs). When the gate electrode comes into touch with the analyte solution, its potential changes due to changes in the sample's ion activity. Afterwards, the electric potential change is quantified (Saber, and Pişkin, 2003).

OPTICAL BIOSENSORS

When a bioreceptor interacts with a target analyte, optical biosensors measure the resulting changes in the input light's optical intensity, which are directly proportional to the analyte concentration in the sample. Being non-electrical biosensors, these optical devices have a number of benefits, including being able to be used in vivo, being simple, compact, and unaffected by electromagnetic interference. Biosensors may be either intrinsic or extrinsic, depending on their optical design. In intrinsic biosensors, the analyte is detected by means of the interaction between the incident light wave and a structure that permits it to pass via a wave guide or optical fibre. The optical fibre transmits the signal from an extrinsic biosensor, which uses light waves to react with the sample phase as they travel through it (Tagad et al., 2016).

Based on the observation that various analytes absorb light of different wavelengths, absorption-based biosensors are low-cost, straightforward instruments for determining analyte concentrations. The light may be sent from the source to the sample using a single optical fibre, and then from the sample to the detector using an additional cable. One kind of biosensor that uses light for detection is the surface plasmon resonance (SPR) sensor. This technique creates electromagnetic waves (plasmons) via excitation of electrons on a metal's surface at its interaction with a dielectric. Biomolecular interactions, such as the analyte's particular binding, may alter the material's refractive index close to the metal surface, which can have a profound effect on Plasmon propagation (Hayat and Marty, 2014).

By monitoring the wavelength shift in electromagnetic radiation, optical biosensors based on fluorescence may identify specific atoms or molecules. Alternatively, fluorescence energy transfer (FRET) or fluorescent markers may be used to conduct detection indirectly. Luminescent optical biosensors may be broadly classified into two categories: chemiluminescent and bioluminescent. Unlike fluorescence-based biosensors, these devices use an exothermic chemical process to get the target atoms or molecules to a triggered state. Upon returning to the ground state, the excited species create light with little heat. Bioluminescence is the result of this kind of chemical reaction taking place within living things (Zehani et al., 2015).

PIEZOELECTRIC BIOSENSORS

Devices that combine a bio recognition element with a piezoelectric material for transducing are known as piezoelectric biosensors. One of the most common types of materials with a piezoelectric effect is quartz crystal, which is widely used due to its abundance, high temperature tolerance, and chemical stability in water. This biosensor type relies on the piezoelectric material's capacity to undergo mechanical stress-induced electrical potential generation and electric field-induced elastic deformation as its fundamental measuring mechanism (Zehani et al., 2014).

THERMAL BIOSENSORS

Thermoelectric transducers detect changes in temperature that correlate with the concentration of analytes in thermal biosensors, which are also known as calorimetric or thermometric biosensors. Both thermistors and thermopiles are used as heat transducers in these apparatuses. Among the many benefits of thermal biosensors are their ability to detect reactions without labelling reactants, their lack of sensitivity to changes in sample electrochemistry or optical characteristics, and their lack of requirement for regular recalibration. Because enzyme-catalyzed reactions are exothermic, the majority of published research on this kind of sensor describes trials employing these sensors in conjunction with enzyme-based thermal biosensors (Yang et al., 2018).

BIOSENSORS FOR WASTEWATER MONITORING

Reusing wastewater and making informed decisions about treatment process design and operation are both impacted by the component concentrations in the wastewater. Due to the fact that wastewater contaminants may change over time and in different places, there has been a push to create new technology that can track these waste products in real-time and at low cost (Michael-Kordatou et al., 2015; Rehman et al., 2015).

Waste fluids, whether they are disposed of or reused, may have their various qualities measured using a battery of quality indicators. Many of these methods rely on laboratory procedures that are time-consuming and expensive due to the need to collect data often and treat it before analysis (Chong et al., 2013, Yang et al., 2015). Recently, there has been a great deal of effort put into creating biosensors that can identify environmental pollutants. One great thing about these sensors is that they can pick up toxins even in very little amounts in complex matrices, like wastewater. Biosensors are miniature devices that allow for the fabrication of portable sensors that can monitor wastewater on-site (Tsopela et al., 2016). This research organises different types of biosensors into four categories based on the processes they use for transduction: (i) electrochemical, (ii) optical, (iii) piezoelectric, and (iv) thermal biosensors. Molecularly imprinted polymer (MIP), immunochemical, non-enzymatic, whole-cell, and DNA elements are all part of these categories, which together include a wide range of biorecognition approaches. Recent years have seen a rapid expansion in the field of powerful biosensors based on nanomaterials. These sensors possess exceptional characteristics that allow them to detect chemical reagents and biological events. Existing techniques used to identify contaminants in wastewater were affected, and there was an increase in the number of initiative activities based on real-time biosensing of wastewater sources. There has also been a lot of study on nanotechnology-based wastewater treatment methods. References include Berekaa (2016), Cloete et al. (2010), and Henze et al. (2008).

Detecting Organic Substances With Biosensors

Anthropogenic and naturally occurring organic pollutants are present in effluents from a wide variety of sources, including households, farms, and businesses. Some of the organic molecules that may be discovered in industrial wastewaters include hydrocarbons, aromatic compounds, chlorine compounds, diphenylmethane, and surfactants. Polybrominated diphenyl ethers (PBDEs), polybrominated biphenyls (PBBs), and polychlorinated biphenyls (PCBs) are three examples of the persistent organic pollutants (POPs) found in wastewater, especially in industrial waste leachate (Weber et al. 2011). Agricultural wastewater sometimes contains harmful compounds, such as organic herbicides and pesticides, which are used to manage weeds, unwanted plants, and a variety of pests (Wauchope 1978). Many antimicrobial household cleaning solutions include organic compounds like triclosan, which, when discharged into wastewater and groundwater, might be harmful. Since these organic waste compounds may bind to endogenous hormone receptors as either agonists or antagonists, it is now necessary to identify endocrine disrupting chemicals (EDCs) in wastewater.

For the sake of both humans and the environment, it is crucial to accurately measure organic matter levels throughout wastewater treatment and water reclamation activities. There are certain issues with using organic components in wastewater treatment. As an example, they have the potential to foul membrane filtration systems and generate harmful by-products. It is usual practice to look at two factors when analysing the organic matter content of water. Biodegradable organic compound breakdown oxygen demand is quantified using the biochemical oxygen demand (BOD) index. There is also the matter of the chemical oxygen demand (COD), which shows the amount of oxygen that the water's chemical processes are using (Wacheux 1998). Traditional approaches to characterising BOD have relied on either short-term in-situ measurements or off-line monitoring for 5 or 7 days. When compared to the conventional method, biosensors detect these indices more quickly and accurately. The purpose of this section is to provide a synopsis of the most recent biosensing techniques for tracking organic matter in different wastewater resources, with a focus on transducing procedures.

OPTICAL BIOSENSORS FOR DETECTION OF ORGANIC MATERIALS

Some organic pollutants in wastewater, including triclosan, may be accurately identified using a combination of surface plasmon resonance (SPR) and molecular imprinting polymers (MIPs). Molecular imprinted-SPR nanosensors were created to accurately identify certain chemical substances in wastewater, such as triclosan, by simulating the activity of their biological receptors. Immunoanalytical techniques, which rely on fluorescently tagged antibodies having a strong affinity to the target component, are another prevalent mechanism used in optical biosensors for organic matter monitoring. Optical biosensors for organic contaminants often use this technique, called fluorimetry, for signal transduction. Groundwater samples have previously been used to track organic environmental contaminants such hormones, pesticides, endocrine disrupting chemicals, antibiotics, and sperm (Tschmelak et al. 2005). By monitoring variations in bioluminescence response, they demonstrated that this approach can detect COD in wastewater.

Biosensors That Detect Organic Compounds via Electrochemistry

Another option for detecting organic pollutants in wastewater is the use of electrochemical bio-receptors, which may include enzymes, antibodies, and even whole cells. When it comes to biosensors, ambulometric devices are considered superior. Nomngongo et al. (2012) used a biosensing device based on the horseradish peroxidase (HRP) bioreceptor to characterise persistent organic pollutants in wastewater samples using an amperometric transduction mechanism. Attaching HRPs electrostatically to a platinum electrode that had been treated with polyaniline (PANi) allowed for immobilization. To find the BOD in wastewater samples, a set of bespoke Clark-type oxygen sensors were used. Immobilised microorganisms on a bio-membrane linked to an amperometric sensor that monitors dissolved oxygen concentrations provide the fundamental basis of these systems. More specifically, Verma and Singh described a biosensor that used amperometric oxygen probes made of gold or silver attached to cellulose acetate membranes that had living bacteria immobilised on them. This instrument is perfect for assessing BOD in industrial wastewater because to its fast response time of around 7 minutes and detection limit of 1 mg/L (Verma and Singh 2012). In order to assess the biochemical oxygen demand (BOD) in wastewater in real-time, Yamashita et al. looked into a novel electrochemical open-type biosensor. Anodes of the open type, in contrast to their closed-type counterparts, are constantly exposed to oxygen when placed in an aerated tank containing wastewater (Yamashita et al. 2016). This biosensor provides effective detection in both aerobic and anaerobic environments, thanks to a high correlation (R2 > 0.9) between the generated current and the loading of BOD up to 250 mg/L in wastewater. Using a potentiometric sensor based on metal-ion polymers, Kou et al. (2013) developed a biosensor with a lowered limit of detection (LOD) for neutral bisphenol A as part of their investigation on the nanomolar quantities of organic toxicants in wastewater. Several biosensors for water quality monitoring have been developed recently using microbial fuel cells (MFCs). Chemical oxygen demand (COD), biological oxygen demand (BOD), and dissolved oxygen (DO) levels in water samples may be found with these instruments, and they are also often used to identify and analyse different organic pollutants (Zhou et al. 2017). Anaerobic bacteria are housed in the anode chamber of these electro-biosensors, which is separated from the cathode chamber by a proton exchange membrane.

HOT-SENSOR DETECTORS FOR ORGANIC INGREDIENTS

By tracking the rate of thermal change in wastewater and water, Yao et al. developed a biosensing device that effectively monitors chemical oxygen demand (COD). The COD values were determined using a flow injection analysis equipment with periodic acid solutions as oxidants (Yao et al. 2014). The detection range for COD in water samples from different sources was found to be broad and the LOD to be low using this sensing technique. The findings of the dichromate technique, which is used for conventional COD monitoring, are associated with the COD levels detected in wastewater samples. In terms of speed, stability over time, and robustness, the calorimetric COD determination technique outperforms the conventional method in terms of detection efficacy.

BIOSENSORS FOR DETECTION OF HEAVY METALS (HMS)

According to Sayari et al. (2005), heavy metal pollution in wastewaters is often associated with many industrial effluents, including agricultural runoff, chemical manufacture, mining, cosmetics, nuclear waste, metal processing, and painting. For metabolic reactions to occur in living organisms, certain amounts of HMs such as copper, iron, manganese, molybdenum, nickel, selenium, and zinc are required. The non-essential HMs lead, chromium, cadmium, mercury, arsenic, and antimony are very dangerous and carcinogenic even in trace amounts. By attaching to bacteria and then climbing the food chain, they have the potential to cause a wide range of chronic diseases in humans (Jaishankar et al. 2014). Analytical methods such as chromatography, ultraviolet-visible spectroscopy, and atomic absorption spectroscopy have been widely used for the control of these pollutants. Time and money required for sample preparation and pre-concentration restrict the uses of the previously listed procedures, even if they are sensitive and selective enough (Gumpu et al. 2015). Because of their great sensitivity, simplicity, and observable signals, biosensors have recently been proposed as a remarkable alternative to traditional sensing systems. We detail many biosensors and nanobiosensors that can detect HMs in this research.

Optical Biosensors for Heavy Metal Detection

Several microbial biosensors that emit bioluminescence signals were created to work in environments with low levels of HMs (Jouanneau et al. 2012). Recombinant Escherichia coli strains producing fluorescent proteins are the backbone of bacterial biosensors. According to Raja and Selvam (2011) and Ravikumar et al. (2012), when these bacteria come into contact with HMs, they increase their synthesis of fluorescent proteins, which allows them to detect potentially dangerous quantities of HMs in wastewater samples. Biosensors based on enzymes rely on the inhibitory effects of HMs. Because of its distinct optical properties, which improve detection efficacy, porous silicon (PS) structures have seen significant application as enzyme immobilisation substrates for the monitoring of chromium ions in water and wastewater (Biswas et al. 2017). Two optical fibre biosensors based on immobilised urease and acid phosphatase have been used in earlier attempts to detect low levels of HMs. Additionally, a colorimetric bioactive paper sensor that quantifies concentrations of $Ag+$, Ni^{2+}, and Cr^{4+} in parts per million (ppm) was created by using β-galactosidase (β-GAL). You can't beat the speed and accuracy of this sensor.

In light of recent developments in DNA-based devices and nanotechnology, a promising strategy for multiplexed heavy metal detection is the development of highly sensitive nanobiosensors using fluorescence resonance energy transfer (FRET). Xudong and colleagues used this technology to construct a new FRET sensor. The nanobiosensor's receptor is a thin film of silica that has been covalently attached to DNAzymes, two quenchers, and quantum dots (QDs). Because of their photostability, they have the potential to improve the selectivity and specificity of the system. The quantum dots exhibited a change in the fluorescence signals reflected by them when subjected to various metal ions. Many HMs may be measured in water samples at once using multidimensional aptasensors that contain Au- or Ag-NPs (Song et al., 2016).

METAL DETECTION USING ELECTROCHEMICAL BIOSENSORS

Zhao et al. (2018) developed innovative electro-biochemical sensors named sediment microbial fuel cells (SMFCs), single-chamber batch-mode cube microbial fuel cells (CMFCs), and double-chamber microbial fuel cells (DMFCs) to monitor HMs in wastewater influent in real-time. Biosensors may change voltage signals by including immobilised electrogenic microorganisms within them. These biosensors show promise as sensitive wastewater quality monitors, especially for HMs like Cr^{6+}, Cd^{2+}, Cu^{2+}, and Zn^{2+} that have low detectable quantities (Tao et al. 2017).

According to Nguyen et al. (2018) and Song et al. (2018), electrochemical biosensors that use nanomaterials may significantly improve device performance. For example, Chen et al. showed that an electrochemical apt sensor could be made more sensitive by using gold nanoparticles (GNPs) in their investigation on Cu^{2+} detection (Chen et al. 2011b). The biosensing method depends on the direct formation of guanine wire structures, which are based on the production of strong and stable T-Hg2^{+-} T mismatches in the presence of Hg^{2+}. Triggering the electrochemical oxidation of 3,3',5,5'-tetramethylbenzidine (TMB) using the generated guanine nanowire on the surface of the gold electrode results in a notable enhancement of the electrical signal. The feasibility of detecting Cd^{2+} and Hg^{2+} simultaneously using a modified Au electrode including multi-walled carbon nanotube (MWCNT)/peptide was investigated using samples of industrial effluent. The peak-current density, reaction rate, and sensitivity of the modified MWCNT electrode were enhanced by adding peptides. The limited detection limits (LODs) of these systems are below the limits specified by the EPA for Cd^{2+} and Hg^{2+} in drinking water (Rahman et al. 2012). Ganjali et al. detailed a nanobiosensor, an electrochemical sensor that uses an L-cysteine functionalized glassy carbon (GC) electrode. It was used to improve the detection of Cd^{2+}, Pb^{2+}, Cu^{2+}, and Hg^{2+} ions in industrial effluents. The World Health Organisation has established standards for the measurement of metal ions, and this platform allows you to do so with acceptable LOD values for several ions at once. November 2011 was the year.

Biosensor That Detects Heavy Metals Using Piezoelectric Technology

Ion sensors that monitor different ions have recently been produced using AlGaN/GaN HEMTs. Unlike many other kinds of ion sensors, these devices may function without a reference electrode and are sensitive to surface charge properties. Researchers Asadnia et al. demonstrated that ionophore-coated PVC-based membranes on such devices can detect Hg^{2+} and Ca^{2+} ions in water (Asadnia et al., 2017).

Devices for the Microfluidic Analysis of Heavy Metals

The use of portable microfluidic devices to detect HMs in various fluids has recently shown remarkable efficiency, suggesting that these devices may find use in dark seas. An unique example of this is a cost-effective biosensor for lead concentration monitoring that was produced by integrating a microfluidic technique with an optical transducing technology. In order to detect levels as low as 0.094 nM of Cr(III) and Cr(VI) in different water samples, Peng et al. (2017) created a (MWCNTS). Another approach was to use a bio-inspiration technique to create a microelectromechanical system (MEMS) that could detect lead on-site by simulating the function of a shark's olfactory sensory system (Wang et al. 2016). Another microfluidic Pb^{2+} biosensor that Cropek and colleagues developed was a microchannel made of polymethylmethacrylate (PMMA) that was immobilised with lead-specific catalytic DNA (Dalavoy et al. 2008). Microfluidic devices based on field-effect transistors (FETs) have been developed in a number of recent research. A protein-functionalized rGO thin-film structure was used to construct the sensing microchannel, which was shown to be able to detect metal ions in a variety of water-based solutions (Sudibya et al. 2011). At room temperature, this gadget quickly reacts to Hg^{2+} inside microfluidic channels and is completely portable.

BIOSENSORS FOR DETECTION OF MICROORGANISMS

Significant global mortality and morbidity are caused by a wide range of aquatic microbial illnesses. Many various kinds of microbes, including bacteria, viruses, protozoa, algae, fungus, and yeasts, find sewage to be a perfect environment for development. They have a wide range of organismal compositions and are mostly discharged into wastewater from food processing and domestic activities. Microorganisms may be either autotrophic or heterotrophic, and the amounts of these types of microbes can change depending on where they come from. In contrast, Grøndahl-Rosado et al. (2014) found that the sickness rate in a community, which might be an indicator of public health concerns, is closely related to the concentration of parasites and harmful viruses. Furthermore, different microbial pathogens have distinct minimum infective doses. Traditional approaches to microbial pathogen detection rely on microscopic techniques or artificial media, which come with a host of technical drawbacks such lengthy processing times, limited sensitivity, and poor detection accuracy. As an example, rather of monitoring microbes in general, coliform tests are typically used to evaluate coliform bacteria in environmental samples. There has been a lot of focus on discovering more efficient ways to detect tiny levels of viruses in dark waters because of the aforementioned shortcomings of the traditional approaches.

EYE-SENSORS USED TO DETECT MICROBRANTS

Two gram-negative bacteria, E. coli and Listeria, as well as gram-positive bacteria, were detected using surface-enhanced Raman spectroscopy (SERS) molecular probes, which showed very fast detection periods of bacterial specific antigens (Xiao 2010). In order to identify E. coli O157, a H7 strain, in wastewater samples, Yildirim et al. (2014) created a portable optical fibre biosensor. A specific aptamer that was fluorescently labelled was used to accomplish this. By combining them with complementary DNA probes that are surface-immobilized on an optical electrode fibre, one may ascertain the quantity of free aptamers. The higher fluorescent signal could be associated with the decreased E. coli level in the samples that were analysed. Due to its sensitivity, portability, low cost, and speed, the developed device is perfect for on-site wastewater testing.

Researchers have shown that silver and gold nanoparticles, as reported in studies by Singh et al.(2009) and Tripp et al.(2008), work well as substrates for SERS pathogen biosensors. Another potential mechanism by which nanomaterials enable the detection of microbial DNA is via the use of metal nanoparticles. The need for intricate and costly fluorescent labelling might be rendered obsolete by the colorimetric alterations induced by hybridization of gold nanoparticles with single-stranded DNA probes. According to Jyoti et al. (2016), bacterial sensing equipment often use Au NPs to assess the minute concentrations of organisms in samples of dark water. In the presence of the target bacteria, the aptamers undergo a conformational shift, leading to the aggregation of AuNPs and, as a consequence, a visible change in colour from red to pinkish-purple. This approach can directly quantify the total bacterial load without the need for specialized equipment or pretreatment; it is also quick, specific, and easy to implement. There is also an interesting method that labels an antibody against E. coli O157: H7 using carboxyl functionalized graphene quantum dots (cf-GQDs) via the antibody's main amines.

ELECTROCHEMICAL BIOSENSORS FOR DETECTION OF MICROORGANISMS

Numerous portable instruments have been developed in recent years to amperometrically detect and track the electrooxidation and electroreduction processes of different microbes. The fact that almost all E. coli strains possess β-D-Glucuronidase (GLUase) activity has been well-documented. In their study, Rochelet et al. used a paminophenyl β-D-glucuronide substrate to observe E. coli GLUase activity in wastewater samples using disposable, one-time use carbon screen-printed electrodes. This approach may have potential uses in water and wastewater analysis, despite its low sensitivity (Rochelet et al. 2015).

Yemini et al. demonstrated a cheap, fast, and sensitive amperometric biosensor that could detect minuscule concentrations of Mycobacterium smegmatis and Bacillus cereus. The amperometric biosensor's general construction allows for the rapid evaluation of various species' particular enzymes on electrodes in under eight hours (Yemini et al. 2007). Borisova et al. (2018) found that this approach can quickly identify very tiny amounts of real bacteria. Despite the lack of common usage for potentiometric techniques in bacterial contamination detection, Ercole et al. showed that they could measure Escherichia coli, DH5a in water using a tiny, quick, inexpensive, and very sensitive potentiometric alternating biosensor (Ercole et al. 2002). To detect Staphylococcus aureus (S. aureus) in water samples, Abbaspour et al. (2015) proposed an electrochemical dual aptasensor. The detection process began with an aptamer that was biotin-streptavidin-adhered to magnetic beads. The sandwich immunosensing approach, which involves secondary aptamer-conjugated AgNPs, was used to report the presence of S. aureus. Finally, the acidic solution's dissolved AgNPs produced a differential pulse stripping voltammetric signal. S. aureus quantitation in the samples was shown indirectly by this signal.

A bio nanocomposite of polypyrole (PPy)/AuNP/MWCNT/Chitosan was used to modify the graphite electrode and create a sensitive voltammetric immunosensor. The technology allowed the immobilisation of an anti-E. coli O157: H7 monoclonal antibody thanks to the large surface area given by MWCNT and AuNPs. E. coli O157: H7 monitoring for environmental and food quality management was much enhanced by this modified electrode technique. Güner et al. (2017) noted that a major obstacle to using this biosensor in real-world samples was the antibodies' inability to regenerate for future detections. Due to its dual nature, the impedance biosensor relies on complex mathematical formulas for its prediction. Despite the possibility of label-free recognition and the simplification of sensor setup, no research has been conducted on microbe identification using impedance biosensors so far. Muhammad-Tahir and Alocilja (2003) detailed a one-time use impedimetric technique for detecting E. coli. Using a self-assembled monolayer of gold electrode and an anti-E. coli antibody, an impedance immunosensor was shown for the detection of E. coli in samples of river water. This particular sensor can keep tabs on effluent. When E. coli specifically bound to the electrode, it increased the electro-transfer resistance, and Geng et al. (2008) demonstrated a direct association between bacterial concentration and this effect.

THE ROLE OF NANOTECHNOLOGIES IN BIOSENSING FROM WASTEWATER

Biosensors built using nanomaterials allow for further component miniaturization, according to Lv et al. (2018). When it comes to monitoring the composition of wastewater, the tiny size of the sensor makes it possible to integrate numerous processes into one device, allowing for the design of real-time monitoring of different materials.

A decrease in the cost and labour intensity of biosensing equipment is complemented by the prospective uses of nanotechnology. Nano biosensors rely on the hypersensitivity of nanostructures to contaminants and the selectivity of interactions between tiny biomolecules used as bio recognition components to work (Ghasemzadeh et al. 2014). According to Kaittanis et al. (2010), nanoparticles are very suitable for environmental specimen monitoring due to their unique properties such as significant extinction coefficients, strong photo stability, luminescence, and catalytic capability. In addition, as stated by Lim et al. (2015), portable microbial biosensors may achieve a greater retention time when nanomaterials are used in conjunction with the freeze-drying process. The detection of harmful substances in water has recently come to rely on nanomaterials, which are notable for their tiny size and distinct physicochemical properties (Dasgupta et al. 2017).

Environmental monitoring has been a primary focus of recent advances in nanotechnology's incorporation with physiologically sensing systems (Justino et al., 2017; Reverté et al., 2016; Stoytcheva et al., 2018). Not long ago, there were a plethora of groundbreaking biosensors that used nanomaterials to enhance the precision and efficacy of contaminant detection in wastewater samples. Several nanobiosensors have been developed for the detection of organic components, heavy metals, and microorganisms in dark water resources. These include the ones mentioned earlier Several intriguing avenues for improving biosensors for environmental wastewater monitoring may be explored by combining nanotechnology with specific bio recognition mechanisms and different transducing techniques.

TRANSITION TO COMMERCIALIZATION

When it comes to environmental monitoring, there aren't as many commercial options as there are for medical biosensors. Commercial usage in wastewater treatment facilities is still a way off for the majority of the existing biosensors, which need substantial improvements in sensitivity, selectivity, functionality, etc. Here, biosensors may be enhanced to detect lower concentrations of analytes, especially in turbid samples like wastewaters, by including efficient bio-recognition components, such as whole microbes or biomolecules. Utilising a biosensor that quantifies biological oxygen demand (BOD) is the gold standard for assessing water and wastewater quality. In 1983, according to our study (Iranpour et al., 1997), the first BOD biosensor was offered to the market by Nisshin Denki (Electric) Co. Ltd. Jouanneau et al. (2014) states that a commercial BOD biosensor using electrochemically-microbial fuel cell technology was created by Korbi Co., Ltd. Anam et al. (2017) describe a novel biosensor approach that uses mediator-less microbial fuel cells to measure BOM in wastewater. This approach has the potential to enter the commercial market in the near future. Numerous commercial solutions for toxicant detection have been developed to quench the bioluminescence activity of luminous bacteria, such as *Vibrio fischeri* or *Photobacterium phosphoreum*. Various optic biosensors are available for use in detecting organic chemicals and heavy metals in different environments. One of the several commercially available surface plasmon resonance (SPR) biosensors for application in environmental sample monitoring is the β-SPR biosensor from SENSIA in Spain, which can detect Carbaryl. Spreeta 2000, developed by Texas Instruments Inc. using nanotechnology, is a cheap and portable surface plasmon resonance (SPR)-sensor that can detect a variety of biomolecule pollutants in soil or water (Chinowsky et al. 2003). While nanotechnology has played a significant role in biomolecular detection, label-free cantilever sensors, such as Biocom's VeriScan 3000, have been developed to monitor more than 100 distinct chemicals in environmental samples. Companies have developed a plethora of operational systems for measuring microorganisms in physiological and environmental fluids; these systems may be expanded to include wastewater samples.

Notable among these patents are a few that showed exceptional promise for commercialization. Two new bio sensing systems were developed and patented by Corrèa and colleagues to detect and remove copper nanoparticles from industrial settings. These systems make use of the decomposing biomass of *Rhodotorula mucilagin*, *Hypocrea lixii*, and *Trichoderma koningiopsis* . Additionally, a patent was awarded for the purpose of detecting methane, a byproduct of biodegradation, in order to monitor organic compounds in wastewater and water fluids. This innovation used a microbe that produces methane without oxygen in a bio-electrochemical system that includes a reactor with anodes and cathodes (Silver et al. 2017). In their 2017 publication, Dooley and Burns detailed a method for monitoring wastewater concentration that involves selectively sensing the quantity of dissolved oxygen using two accurate oxygen sensors. Indeed, a very sensitive patent was obtained not long ago for the recognition of different viruses and macromolecules at very low levels. A substrate made of single-walled carbon nanotubes (SWNT) and two electrodes were used to non-covalently attach particular bioreceptors (April et al. 2018).

CONCLUSION

The health, nutrition, energy, and financial well-being of a population are profoundly impacted by water quality. Traditional methods of defining recycled water have many drawbacks, including inefficiency, high costs, and lengthy processing times, in addition to the fast expanding field of wastewater reclamation. This is associated with the inability to provide financial capacity above traditional monitoring systems and their technological constraints. Biosensors, a potential game-changer in the field of freshwater resource management, are a viable option for tracking down environmental contaminants using real-time, on-site tactics.

Predicting the physicochemical parameters, such as pH, conductivity, and turbidity, of wastewaters becomes challenging due to the diverse compositions of these samples collected from various locations and times. It is possible that the expected sample parameters and the detection of the target components might be impacted by the complicated matrix of dark waters. A further crucial consideration is the stability of the immobilized biological materials (e.g., cells, antibodies, tissue, enzymes, etc.) throughout transport, storage, and use. A stable biosensor, according to some research (Brecht 2005; Kissinger 2005), should be able to detect changes in biological variables over a period of six months when exposed to ambient conditions.

It is necessary to compare and contrast the current methods with conventional analytical systems that monitor water and wastewater. For each, it is necessary to develop standards for quantitative and qualitative validation (Cárdenas and Valcárcel, 2005). There has been a lot of recent focus on developing a reliable method for wastewater monitoring. Several pieces of evidence point to biosensors as playing a unique role in water resource management strategies. To create more effective and commercially viable biosensors, it is necessary to address certain technological and practical constraints and challenges related to this reality. New sensing technologies that can identify more chemicals at once and have a wider detection range are required to accomplish this objective of detecting a wide variety of wastewater contaminants. The biosensor must also have the ability to detect at low concentrations and remain stable for long periods of time. One approach being considered to address the significant challenges of using biomolecules as recognition elements is the creation of recombinant fragments that are specific to a target and the site-directed immobilizations of antibodies and enzymes. This would allow for the rapid, inexpensive, and in-situ screening of organic contaminants in wastewater. Alternately, biosensors may have their sensitivity and accuracy enhanced by nanomaterial integration; miniaturization and multi-sensor array devices can be used to increase detection efficiency; and so on. While the majority of the published research has focused on HM ion detection (e.g., Hg^{2+}, Pb^{2+}, Cd^{2+}, and Cu^{2+}), there is growing enthusiasm for tracking other inorganic elements as well. Developing commercial bacterial biosensors to monitor wastewater may be a challenging process. A low detection limit, strain and species selectivity independent of pre-enrichment procedures, and the capacity to identify living and dead microbes independently are all crucial. For the in-situ application, a portable device should be used to tackle these challenges. The limit of detection and standard calibration curves for the aforementioned substances also vary across various water resources. Additional research is needed to gain a better understanding of the concepts involved in measuring toxicants in wastewater, specifically for organic and heavy metal pollutants, microorganisms, and groundwater and river water. This is because numerous studies have used biosensors to measure toxicants in these environments. New possibilities for improved detection performance may arise as a result of recent developments in nanotechnology, which hold tremendous promise for enhancing certain features of biosensors (Aragay et al. 2012).

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Chapter 10
Sensors in the Oceans, Pollutant Identifications, and Controversies:
Radio-Isotopic Tracing of Pollutants in Marine Ecosystems and Controveries

Sanchari Biswas
https://orcid.org/0000-0002-1159-5826
Amity University, Kolkata, India

ABSTRACT

Oceans are the largest means of survival for millions of people and also the source of many life forms. Human activities have made the environmental conditions in marine habitats more dire for the last fifty years. The discharge of agricultural nutrients, heavy metals, and persistent organic pollutants (plastics, pesticides) threaten the coastal zones. Chemical compounds containing one or more radioisotope atoms are known as radiotracers, which are particularly useful for identifying and analysing pollutants as they can readily identify trace amounts of a particular radioisotope and short-lived isotope decays. It is thus important to identify such sources of contaminants by quantifying essential pollutants separately and gathering dependable information regarding their origin, movement, and ultimate destination. Nuclear and isotope techniques help in gathering such data. This book chapter gives an overview of the modern techniques available for probing the various contaminants across marine ecosystems and several drawbacks and controversies associated with the same.

INTRODUCTION

Primarily the source of survival for hundreds of millions of people, Oceans, are the greatest natural resource on Earth. It is also the source of most life forms. Unplanned coastal zone settlement and rapid industrialization were linked to ocean pollution, which was a major issue of the 20^{th} century. The 21^{st}

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century still sees it as a problem. In coastal zones, heavy metals, persistent organic pollutants including pesticides, hazardous algal toxins, and agricultural runoff of fertilisers pose the most environmental threats. A constant threat to birds, marine life, and beaches comes from oil spills from ships and tankers (Betti et al., 2011).

Marine pollution is a transboundary problem that is frequently brought on by economic activity that occurs inland and alters the marine environment's ecology. Examples include sewage discharges into lakes and rivers that encourage the occurrence of harmful algal blooms (HABs), the use of chemicals in agriculture, air emissions from factories and cars, and numerous other phenomena occurring hundreds or thousands of kilometres away from the coast. The ecosystem of estuaries, bays, coastal waters, and even entire seas is impacted by these operations sooner or later, which affects the maritime industry's economy. Furthermore, a lot of pesticides that are outlawed in the majority of developed nations are still in use today, and their transboundary dispersion pathway has an impact on marine ecosystems all over the world. Aside from these issues, permitted nuclear plant that release off radioactive materials into rivers and coastal areas have contaminated the marine environment and have the potential to do so in the future. This has resulted in the ocean dumping of radioactive waste. To guarantee the sustainable use of marine ecosystems, it is imperative to quantify contaminants separately and gather dependable information regarding their origin, concentrations, movements, and ultimate destination. Isotope analysis offers a special source of data for tracking the movements of both nuclear and nonnuclear pollutants in the environment and determining their biological consequences (Betti et al., 2011).

For more than 150 years, radioisotopes have been employed in earth and environmental studies. They offer special instruments for the in-depth study of environmental processes at all scales, from the level of individual cells to that of oceanic basins. Through lab and field research, these nuclear approaches have been used to better understand coastal and marine ecosystems and how aquatic species react to various environmental stresses such as temperature, pH, nutrients, metals, organic anthropogenic pollutants, and biological toxins. Global marine problems that affect marine environments and impose different threats to the environment and economy include ocean warming, deoxygenation, plastic pollution, acidification of the ocean, prolonged and intense harmful algal blooms (HABs), and coastal contamination.

Isotopes and nuclear methods can be effectively used to analyse the various sources of pollution and the related diffusion mechanisms.

The ability to consistently evaluate the state of marine and coastal ecosystems and their potential responses to future disturbances might yield crucial insights for society in managing their marine environments sustainably. This book chapter contains information on emerging concerns that would benefit from present and novel radiotracer technologies, a summary of the historical use of radiotracers in these systems and an explanation of how current techniques of radioecological tracing can be modified for specific contemporary environmental issues. Additionally, the potential and problems associated with using radioecological tracers are discussed, along with ways to make the most of their use and significantly improve environmental managers' capacity to manage coastal and marine ecosystems using evidence.

The health and sustainability of coastal and marine ecosystems are threatened by a number of environmental issues that are caused by or made worse by a multitude of anthropogenic stressors that are made worse by a changing ocean and climate (Dwight et al., 2005). The marine habitats are being impacted by global marine challenges, which pose a variety of environmental and economic threats (Speers et al., 2016; Yagi, 2016; Creswell et al., 2020). These issues include ocean warming, deoxygenation, plastic pollution, ocean acidification, increased duration and severity of toxic harmful algal blooms (HABs), and coastal contamination (Beaumont et al., 2019). To manage their maritime environments sustainably, society can benefit greatly from having access to reliable knowledge about the state of coastal and marine ecosystems and how they can react to upcoming disturbances. The application of a variety of radioactive isotope tracers or radiotracers, in field settings (Fowler, 2011; Harmelin-Vivien et al., 2012) and controlled lab experiments (Stewart et al., 2008; Metian et al., 2019) has aided in learning about the impacts of the same in coastal marine environments.

Radioisotope analysis is a swift, cost-effective method of element analysis that allows for element experiments at trace quantities, far lower than those found in most natural water. Thus, this approach has proven helpful in determining the following characteristics of pollutants: bioavailability (the percentage of the total exposure that can be absorbed by biota); bioaccumulation (contaminant uptake from food and water into an organism); bioconcentration (the amount of contaminant present in the system of living organism contrasting with ambient water); and, primarily for organometallic compounds, biomagnification (the process through contaminant concentration levels in the tissues of a predator exceeds compared to its prey).

New insights into the rates and routes of absorption (such as bioaccumulation) and biomagnification of both radioactive and non-radioactive pollutants have been made possible by nuclear techniques. Similar to this, these methods have been applied to the quick identification and measurement of biochemical toxins in seafood, the evaluation of metabolic processes in the presence of rising ocean temperatures, and the assessment of the effects of persistent ocean acidification on a variety of calcifying organisms. Likewise, the reconstruction of Earth's geochemical evolution and the historical reconstruction of important environmental processes and rates have been made possible by isotopes.

This book chapter discusses determining the benefits of utilizing radioisotopes to address both established and emergent environmental processes in marine ecosystems. This book chapter has been divided into four parts for a constructive understanding of the following parts:

- an overview of the past applications and advantages of radiotracers used in marine and coastal environments.
- a section outlining the evolution viz. current radiotracer techniques
- a section listing novel, frequently interdisciplinary instruments and methods for addressing current maritime and coastal problems that could be helped by using radiotracers to evaluate the state of ecosystems
- a segment outlining the prospects and problems in this industry moving ahead

BRIEF HISTORY OF RADIO-ISOTOPIC TRACING OF MARINE POLLUTANTS

One of the most important factors in assessing the prevalence and seriousness of contaminants in the marine environment is identifying the sources of the contamination. The effects of human activities have worsened the environmental conditions in marine ecosystems during the last fifty years. In essence, a variety of waste and discharge from local, sub-regional, and regional enterprises and activities mix with global ocean currents to produce a worldwide dispersion of toxins. Nations need to implement environmental regulations that balance environmental protection on a local and global level with socio-economic development to stop these phenomena. However, the only way to effectively regulate the environment is to establish a clear connection between known processes or sources and the diffusion of contaminants. Analyses using stable carbon isotopes can be used to locate the sources of organic contaminants. A composite series of events culminates in a contaminant's stable isotopic composition in the environment. It is anticipated that chemicals made from various sources using essentially different techniques will have unique isotopic compositions that can be utilised to pinpoint the sources.

Knowledge of natural processes has improved as a result of the investigation and application of radioisotopes in environmental science. Using Pb isotope systematics (Patterson et al., 1955; Creswell et al., 2020) a timeline of Earth's differentiation and planetary evolution was developed. Over the last 60 years, as analytical techniques have been established and greatly improved, the utility of radioisotopes has continuously changed. Applications of radioisotopes have ranged from using products of legacy nuclear weapons testing to derive sedimentary age models to generating a pedagogy of evolution of the Earth using Pb isotope systematics. The Suess effect—which relies on radiocarbon (^{14}C) dendrochronology—became the main argument in favor of human-caused global warming and contributed to the measurement of CO_2 exchange rates between the ocean and atmosphere (Revelle and Suess, 1957; Swart et al., 2010). In the marine sciences, radionuclides—which can be man-made or natural—have been utilized to track numerous processes. Radionuclides are powerful timepieces because of their ability to be used as a clock to trace the rate of various processes due to their rate of radioactive decay, or loss. The development of nuclear energy for civil purposes and atmospheric nuclear weapons testing from 1945 to 1980 (peaking in 1963) had released several manmade radionuclides into the marine environment, including ^{3}H, ^{238}Pu, ^{137}Cs, ^{239}Pu, ^{90}Sr, ^{129} I, ^{240}Pu (Creswell et al., 2020).

The traditional three U-Th series radioactive decay chains were used more frequently to study marine processes almost simultaneously, as a result of advancements in analytical chemistry and technology (Benitez-Nelson et al., 2018). One of the first initiatives to use radionuclides to examine basin-scale processes was the GEOSECS (Geochemical Ocean Sections) program (Broecker and Peng, 1982). Since the early 1970s, recent silt has been dated and sedimentation rates have been calculated using natural and artificial fallout radionuclides (Appleby, 2008; Creswell et al., 2020). Sediment partition coefficients (Kds) and bioconcentration factors (BCFs) of long-lived radionuclides in marine sediments and organisms were compiled as a result of the many studies that started to characterize the sorption of radionuclides to marine sediment and the bioaccumulation of radionuclides in aquatic biota in the 1960s and 1970s (IAEA, 2004). In modelling efforts to assess the cycling and possible effects of radionuclides in marine ecosystems, these Kds and BCFs have been employed (ICRP, 2008; Creswell et al., 2020). Additionally, several research studies investigated the use of man-made and natural radionuclides to assess processes like sediment geochronology (Luoma and Rainbow, 2005; Baumann and Fisher, 2011), sediment plume dynamics, carbon flux, GEOTRACES/GEOSECS/JGOFS programs, ground water discharges and water mass ventilation (Creswell et al., 2020).

Additionally, stable water isotopes like δ^{18O} can be coupled with radiotracers like ^{222}Rn and ^{226}Ra to differentiate between fresh and saline groundwater discharge, as well as source terms of submarine groundwater discharge. This knowledge may prove important to groundwater resource managers responsible for generating potable water budgets and marine resource managers interested in providing contaminants and nutrients carried by SGD to coastal ecosystems (Rocha et al., 2016).

CURRENT TECHNIQUES OF RADIO-ISOTOPIC TRACING IN MARINE POLLUTION

The development of compound-specific stable isotope analysis (CSIA) is the most significant in analytical chemistry in recent years. This method, which measures specifically carbon isotopic content of individual chemicals within a complex mixture, is based on gas chromatography/isotope ratio mass spectrometry (GC/IRMS). Natural pollutants include chlorinated solvents, refined hydrocarbon elements, crude oils, PCBs (polychlorinated biphenyls), PAHs (polycyclic aromatic hydrocarbons and crude oils can all be individually identified by carbon-semi conductance analysis (CSIA).

The nitrogen and hydrogen isotopic composition of certain substances can be determined using GC/IRMS. A class of pollutants known as hydrocarbons and oil products have a complex and varied makeup. They affect living things in many ways, causing anything from physical and physicochemical harm to cancerous consequences. Based on statistics from 1988-1997, it is projected that 1,245,200 tonnes of oil enter the maritime environment annually from ships and other sea-based operations.

A study published in Science Advances and detailed in an IAEA stated that only approximately seventeen per cent of the plastic manufactured between 1950 and 2015 has been recycled and is still in use. Roughly twelve per cent have been burned, and the remaining sixty per cent have been dumped in landfills where they could potentially contaminate rivers, groundwater, and the ocean. The IAEA estimates that as 2025 proceeds, the chance is that one metric tonne of plastic in the oceans for every three metric tonnes of fish, might exist, and by 2050, there might be more plastic than fish. This prediction is based on current trends. The establishment of NUTEC Plastics aimed to support nations in incorporating isotope and nuclear methods to combat plastic pollution. It takes two approaches: (i) to present data based on science to evaluate and characterise marine microplastic contamination; and (ii) to show how ionising radiation can be used to convert plastic trash into useable resources. The IAEA claims that NUTEC Plastics will improve labs' capacity to investigate the effects of plastic pollution in marine and coastal ecosystems by using nuclear techniques to precisely track and measure the movement and effects of co-contaminants and microplastics (Joanne Liou, 2021).

AN OUTLINE OF OTHER AVAILABLE TECHNIQUES FOR DETERMINING CONTAMINANTS IN ENVIRONMENTAL SAMPLES

Table 1. Some commonly used techniques in the last decade for determining Radionuclide stressors

S.No	Detection Technique	Range of Applications	Author
1	Accelerator Mass Spectrometry- AMS, Inductively Coupled Plasma-Mass Spectrometry-ICP-MS, Resonance Ionization Mass Spectrometry-RIMS, Secondary Ion Mass Spectrometry-SIMS, Thermal Ionization Mass Spectrometry-TIMS	Radionuclide (^{129}I)	Povinec (2017)
2	Accelerator Mass Spectrometry- AMS	$^{240}Pu/^{239}Pu/^{241}Pu$	Garcia-Leon, M (2018)
3	ICP-MS coupling with linear quadrupole, TOF (Time of Flight), FTICR (Fourier transform ion cyclotron resonance)	$^{135}Cs/^{137}Cs$ ratios	Russell et al., (2015)
4	Combined with traditional radioanalytical techniques and mass spectrometric measurement techniques	^{99}Tc	Shi et al., (2012)

STRESSORS AND MULTIPLE CONTAMINANTS THAT INFLUENCE THE BIOAVAILABILITY OF METALS IN OCEANS

Bioavailability of Metals

There are two implications of "bioavailability" in the ecotoxicology of metals which can be categorized primarily as environmental and secondarily as toxicological. The metal that is accessible for absorption by living forms and incorporated into its metabolic processes is referred to as bioavailability in the environment. The percentage of a metal's concentration which thus gets absorbed and/or adsorbed (bodily) is known as toxicological bioavailability. When the absorbed fraction interacts with physiological sites and receptors essential to the body's metabolism, harmful effects follow (Rainbow and Luoma 2011).

Metal exposure in aquatic animals can happen through consumption or by direct absorption via the water. Feeding is the main way that predators, such as some fish, amphibian, and invertebrate species, and animals that scavenge, are exposed to and accumulate metals. The concentration of metals deposited in the tissues of exposed animals is often not connected with harmful effects, even though many research have sought to determine the toxicokinetics of metals. Metals can either permanently or temporarily chelate with different ligands inside the body, which prevents them from being accessible to disrupt metabolism (Wang 2013).

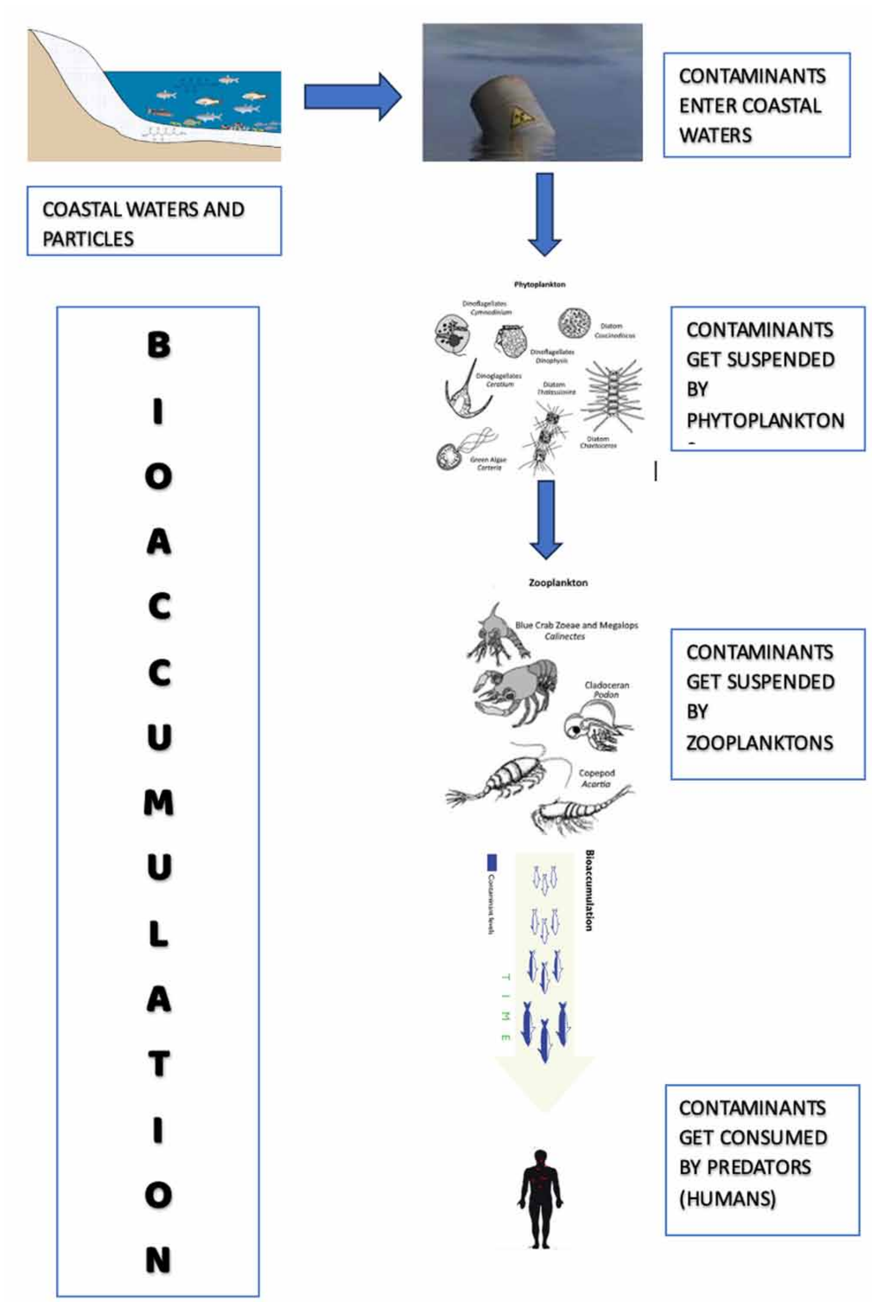
It has long been known that the physical and chemical speciation of metal pollutants can affect how bioavailable they are to aquatic species, such as animals and plants like phytoplankton. In relation to metals dissolved in freshwater and saltwater, this has been thoroughly researched (Paiva Magalhães et al., 2015). The assessment of metal contaminants' bioavailability in sediments has proven to be difficult, especially when it comes to the impact of metal speciation in sediments on benthic animal bioavailability. Even though the bioaccumulation of metals from sediments has been the subject of countless research (Wang et al., 1999). The speciation of metals, especially those associated to iron and manganese oxides, may vary seasonally due to the eutrophication of sediments, especially those found in coastal sediments. This might impact the bioavailability of these metals for organisms that live on the bottom.

As a result, estimating their harmful effects in the environment or bioaccumulated levels stands challenging. The use of biomonitoring instruments, such as biomarkers and bioindicators, has proven to be a more uncomplicated and reliable methodology in detecting environmental conditions, owing to the intricacy of generating toxicokinetic patterns.

The speciation of metals, particularly those associated with iron and manganese oxides, may vary annually due to the seasonal changes in redox conditions in sediments brought on by eutrophication, especially in coastal sediments. This variation can therefore impact the bioavailability of these metals for organisms that live on the bottom.

The Fukushima-Daiichi nuclear power plant accident raised the bioavailability of ^{137}Cs from contaminated soils off the coast of Japan. As a result, benthic fish in Japanese coastal waters have higher amounts of this pollutant than pelagic fish (Buesseler et al., 2017; Creswell et al., 2020). Although the speciation of sediment-bound Cs in those areas has not been thoroughly investigated, data indicates that Cs can accumulate in benthic food chains by way of assimilation in deposit-feeding worms, which then transfer Cs to fish or macroinvertebrates from contaminated sediments (Wang et al., 2016). The bioaccumulation of metals and radionuclides may also be impacted by physical changes in the world's oceans, such as the temperature and pH of the saltwater. It is yet unknown

Figure 1. The pathway and fate of contaminants entering the coastal ecosystem network



how much these physical characteristics might affect the bioavailability of contaminants. Although field conditions are difficult to duplicate in controlled laboratory sorption experiments, radiotracers provide a quick way to comprehend the parameters controlling contaminant partitioning between the phases of sediment, solution, and suspended particulate matter, which can help with field data interpretation (Payne, et al., 2004).

Hydrocarbons

A group of pollutants known as hydrocarbons and oil products have a complex and varied makeup. They affect living things in different ways, ranging from physicochemical and physical harm to carcinogenic consequences. Based on statistics from 1988-1997, it is projected that 1,245,200 tons of oil enter the maritime environment annually from ships and other sea-based operations (GESAMP, 2007). Most molecular fingerprint recognition was used in source apportionment studies of hydrocarbons in the environment until recently. Nonetheless, because of preferential compound losses or degradation, hydrocarbons being impacted by a series of processes in the marine environment viz. photooxidation, dissolution, biodegradation and evaporation, may change the initial hydrocarbon molecular profiles, raising the possibility of ambiguity when using molecular profiles in source identification. Numerous isotopic signals are produced during petroleum genesis, and these signals generally deviate greatly from the isotopic compositions of clean marine environments. It is possible to categorize crude oils, petroleum products, and tars using the distinctive carbon-13/carbon-12 ratios produced by the intricate isotopic fractionation patterns brought about by physical and biological processes.

Other stable isotopes have several forensic applications, but bulk carbon isotopes have received the majority of attention regarding source and correlation work. Isotopic abundances of sulfur, nitrogen, and deuterium also provide source and geological formation histories, including ratios unique to individual oil fields. It is possible to "fingerprint" oils spilled into the environment to identify the source or sources by using the distinctive isotopic ratios of these elements. The compound-specific isotope analysis of various elements within a typical and specific oil constitutes a distinctive indication of its origin and maturity, even though bulk measurements offer valuable information.

Forensic identification of gasoline and crude oil spills has been attempted using GC-IRMS in conjunction with currently available biomarker technologies. By comparing the isotopic makeup of specific hydrocarbons, it is possible, for instance, to establish a correlation between hydrocarbons spilled in aquatic habitats and their presumed source or sources. It is easy to spot differences in the isotopic makeup of specific compounds within a sample of gasoline or crude oil, as these differences correspond to the various sources of the chemicals.

In this context, weathering can lead to a notable loss of volatile hydrocarbons; nevertheless, non-volatile and semi-volatile molecules' $\delta^{13}C$ values remain unchanged and their isotopic profiles can be utilized to pinpoint and track the origin of an oil spill.

Crude oil hydrocarbons exhibit a wide compositional variety of hydrogen isotope ratios and are conserved during biodegradation (aerobic). Measurement of hydrogen isotope ratios (specifically in petroleum hydrocarbons) additionally, is a potent tool to determine the source of the pollutant. In the future, tracking the origins of pollution and keeping an eye on biodegradation should take into account data from both hydrogen and carbon isotopes.

Aside from stable isotopes, measurements of radiocarbon (carbon-14) may also reveal information on oil contamination. While organic matter derived from petroleum is free of carbon-14, all marine organic matter is labelled with carbon-14, which is created naturally in the atmosphere by nuclear weapons explosions as well as cosmic radiation. Therefore, a relevant quantitative indicator of the petroleum carbon contribution to the total marine organic matter occurs as a result of the absence of carbon-14 signal (in contaminants) that originates from fossil fuel.

Polycyclic Aromatic Hydrocarbons (PAHs)

The main ways that organic pollutants known as polycyclic aromatic hydrocarbons (PAHs) enter the marine environment are through oil spills and atmospheric deposition. They can originate from incomplete combustion of organic matter (such as coal, oil, or wood) or be a substantial component of crude oil (petrogenic origin). They may also have a diagnostic origin (biological and physiochemical transformation) from organic material that happens in sediments after deposition. Since some PAHs have the potential to cause cancer and mutagenesis, understanding their sources is crucial because of their eco-toxicological nature, which poses long-term health risks to nearshore marine systems and has an impact on social and commercial uses of marine resources as well as ecological processes and public health. When combined with molecular fingerprint analysis, the molecular stable carbon isotopic composition of PAHs by GC/IRMS is a potent method for researching the origins and environmental destiny of hydrocarbons in the contemporary environment.

For example, the isotope signals of the PAH products can be used to trace air pollutants from combustion source materials, such as soot from burning coal, natural gas, biomass, and vehicle exhausts, back to the source materials (Macko, 1994; Ballentine, 1996; Betti et al., 2011).

Persistent Organic Pollutants (POPs)

The majority of halogenated organic compounds fall under the category of persistent organic pollutants, which are known to bioaccumulate and have harmful and mutagenic consequences when they move up the food chain. To create baseline data for the identification of these anthropogenic contaminants in the future, a few studies have reported the carbon-13 compound specific isotope analysis (CSIA) of PCNs (polychlorinated naphthalene mixtures) and PCBs (some commercial polychlorinated biphenyls), such as Phenoclors, Aroclors and Kanechlors. Some bi-pyrrolic halogenated organic compounds have also been shown in recent investigations to be present throughout the world and building up in marine food webs (Powell, 1999: Reddy et al., 2004). Determining whether these substances are natural products or the result of industrial synthesis has proven to be challenging thus far.

A tracer used to identify between natural and manmade chemicals is called radiocarbon, or carbon-14. Since all recent natural products have modern or contemporary quantities of carbon-14, radiocarbon analysis can be utilized in this context to determine the origin of halogenated organic molecules. Conversely, there is no detectable carbon-14 in synthetic compounds made from petrochemical processes.

STABLE ISOTOPES FOR BIOREMEDIATION RESEARCH

One of the most significant approaches to lessen the harm caused by hydrocarbon spills and other marine oil spills is in situ bioremediation. On the other hand, precise comprehension and measurement of biotransformation processes are essential. When engineered remediation is used, quantifying intrinsic biodegradation may help lower the cost of site remediation. The natural abundance of stable isotopes of carbon, hydrogen, and oxygen—the elements necessary for the biodegradation processes—is used to track the occurrence of in situ biodegradation as well as the pathways, rates, and extent of biodegradation of fuel or chlorinated hydrocarbons. The natural abundance of stable isotopes of carbon, hydrogen, and oxygen—the elements necessary for the biodegradation processes—is used to track the occurrence of *in situ* biodegradation as well as the pathways, rates, and extent of biodegradation of fuel or chlorinated hydrocarbons.

Analysis of the isotopic compositions of (a) the degradation products, (b) the residual fractions of the contaminant, and (c) the dissolved inorganic carbon of the water can be used to monitor *in situ* biotransformation using stable isotopes because isotopic fractionation leads to a preferable degradation of chemical bonds with lighter compared to heavier isotopes (Sturchio et al., 2009). The characteristic carbon-13 isotope ratios of carbon dioxide are caused by the oxidation of organic materials, the solubility of inorganic carbon, or the breakdown of contaminating hydrocarbons. Their carbon-13 levels are valuable instruments for evaluating in situ biodegradation in intricate settings. Moreover, microbial processes are the main factors influencing the oxygen isotopic compositions of molecular oxygen, nitrate, and sulphate in complex systems; isotopic fractionation during microbial respiration results in a notable alteration in the δ^{18O} of the leftover molecules. Carbon dioxide comes from living things The isotopic compositions of CO^2 and O^2 work together to estimate microbial respiration rates and to differentiate between aerobic and anaerobic CO^2 generation.

MONITORING BIO-MAGNIFICATION OF POLLUTANTS USING STABLE ISOTOPES

Because they are hydrophobic, a large number of persistent organic pollutants (POPs) found in aquatic environments tend to accumulate in aquatic species. These compounds' pervasiveness and persistence have been connected to several negative environmental impacts, such as water, sediment, and aquatic food chain pollution. Exposure to these substances can cause a variety of health impacts, from immune system or nervous system issues to an increased risk of some cancers. Stable isotope ratio measurement of bio-elements, such as carbon and nitrogen, has made it easier to examine the biomagnification5 profiles of POPs, including PCBs, PAHs, Organotins, and trace elements across aquatic food webs within the past 20 years. In a food chain, the stable nitrogen isotope ratio ($\delta^{15}N$) typically rises by 3–4% for each trophic level. Therefore, the value of $\delta^{15}N$ can be used to determine each organism's trophic position within a food web. A food web's principal carbon sources can be identified using the stable carbon isotope ratio, $\delta^{13}C$, which is slightly enriched by around 1% at every trophic level.

The Application of Radioisotopes in Harmful Algae Blooms (HABS) to Identify Toxins

The production of toxins by some algae species, which can build up in seafood items (mostly fish and shellfish) and endanger human health, is one of the most concerning effects of HABs. Although it is unknown when hazardous algal blooms (HABs) begin and produce biotoxins, certain environmental factors (such as temperature, light, and nutrients) are probably necessary for the blooms to occur. Trace metals affect phytoplankton not only by toxicity and nutritional limitation, but also by increasing the production of toxins by HABs due to their bioavailability (Sunda, 2006; Creswell et al., 2020). The presence of pseudonitzschia and the neurotoxic domoic acid after iron fertilization studies or with the addition of copper are the most thoroughly researched (Trick et al., 2010; Creswell et al., 2020). Bloom dynamics may also be influenced by interactions between algae and bacteria, with siderophore-producing bacteria possibly providing iron to HAB species (Yarimizu et al., 2018).

Figure 2. Global patterns showing coastal phytoplankton and harmful (algal) blooms HABs across the world between 2003 and 2020
(Dai et al, 2023)

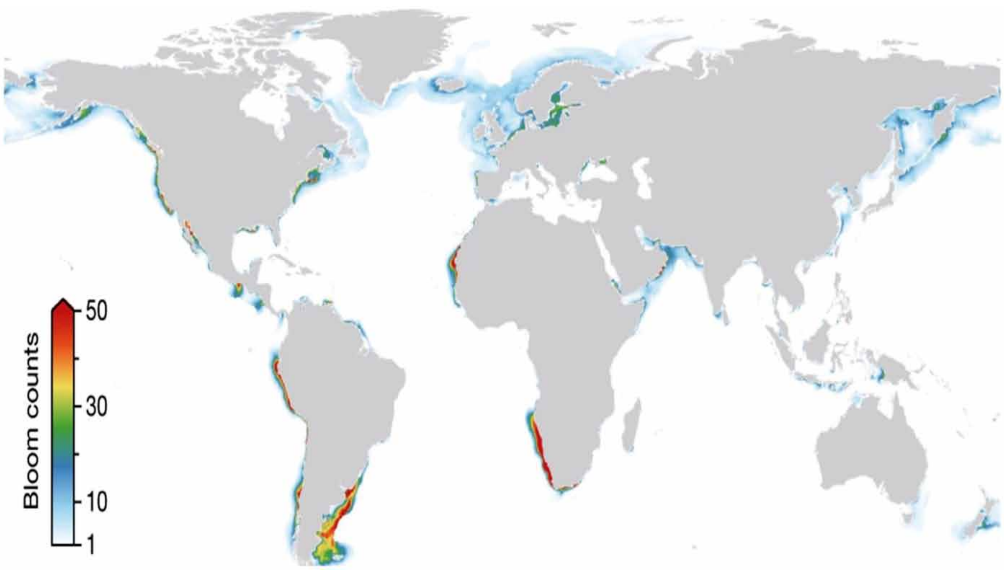
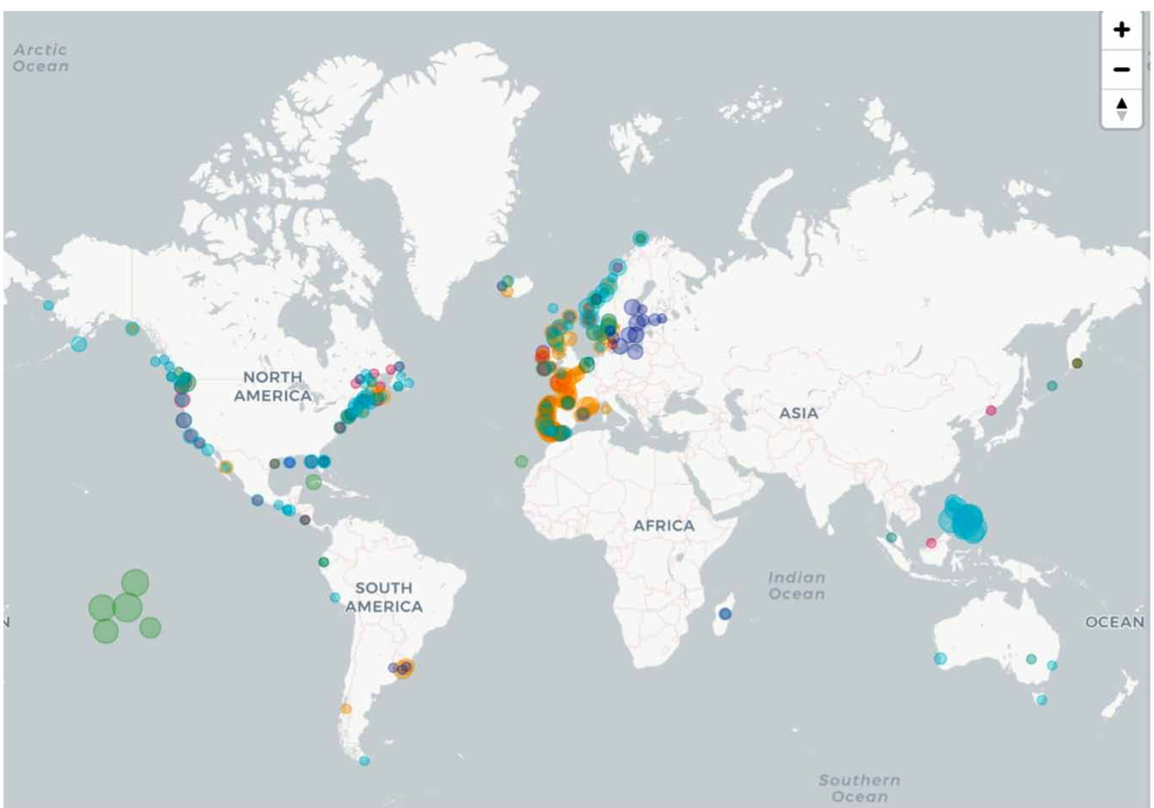


Figure 3. Global patterns showing Harmful Algal Information System (HAIS),
(https://data.hais.ioc-unesco.org)



Trace elements including Li, Se, and Ni have been connected to HAB species in other research (Kudela et al., 2010). Using sensitive radiotracers, such as ^{59}Fe, allows tests with ecologically relevant amounts of compounds, potentially involved in biotoxin synthesis, initiating HAB and its physiology, given the possible connections between different trace metals and HAB toxin production. The exact identification of trace elements and possible localization of such elements within cells or in the surrounding phycosphere would be made possible by radiotracer techniques.

Toxin detection and quantification are difficult due to the heterogeneity both within and between toxin classes. Toxins produced by various algae species vary in type; Fig. III-4 provides examples. Many methods have been developed for toxin detection; they are generally divided into three categories: quantitative instrumental analysis, in vitro bioassays, and whole animal (in vivo) bioassays. The receptor binding assay is a helpful analytical method that uses radioisotopes (RBA). The extremely specific interaction between a toxin and a biological receptor is known as the toxin's function or medicinal activity, and this is the basis of the RBA approach. For instance, saxitoxins (STXs) are poisonous because they attach to and block sodium channels in specific human tissue types, impairing muscle function and ultimately resulting in death or paralysis. When doing a receptor binding experiment for STXs, the sodium channel makes the most sense choice of the receptor. Toxins that impact the sodium channel, such as PSP, NSP, and CFP toxins, have given rise to RBAs (Vandola et al., 1994; Betti et al., 2011). A liquid scintillator counter then measures how well the toxin molecules containing radionuclides, like tritium (^{3}H), attach to the receptor sites.

CONCLUSION

Isotope studies have a special diagnostic ability that can be used to understand the dangers being faced at the marine environment. Only nuclear and isotope techniques can be used to investigate the majority of major pollution issues, affecting the marine environment. These techniques provide the diagnostic and flexible data required to probe the contamination's origins, its originating history, environmental pathways, and its effect on the ecosystems. To make cost-effective mitigation decisions, such techniques need to be incorporated.

Although radioecological tracers have been used for almost 60 years, there is a serious risk that these methods will become obsolete at one point in time because there are a meagre number of scientists working in this area. This is caused in part by the stringent safety and regulatory criteria that must be met for the transportation, storage, use, and disposal of radioactive materials. It is also partly attributable to the recent decline in training in radiochemical and radiobiological techniques. The assessment of nuclear accidents (like the one at Fukushima), the siting and possible effects of future nuclear installations, and the decommissioning of outdated nuclear power plants all require the expertise of an era of scientists with radioecological specialization. Furthermore, to develop fresh approaches for addressing newly emerging problems with coastal and marine ecosystems, the environmental science field must continue to advise and instruct upcoming scientists in the field of radioecological tracers. A deeper comprehension of the state of coastal and marine ecosystems can be attained by fusing traditional environmental biological and chemical approaches with radioecological tracing techniques. When combined with newly emerging "omic" techniques (detecting genes, proteins, to mRNA), the advancement of radioecological tracer technologies should prioritize tackling specific environmental challenges, such as alterations in animal physiology in response to anthropogenic stressors and changing climate conditions.

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Chapter 11
Identification of Different Pollutants in Lotic and Lentic Ecosystems by Biosensors

Afaq Majid Wani
College of Forestry, India

Pritam Kumar Barman
https://orcid.org/0000-0002-5630-4965
College of Forestry, India

Satyendra Nath
College of Forestry, India

ABSTRACT

Environmental pollution is becoming a major global concern, especially about new pollutants, poisonous heavy metals, and other dangerous agents. Pollutants have a profound impact on ecosystems and present serious threats to the health of both the natural world and human communities. Water is one of the most important resources on the planet, since it is required for all species' survival and well-being. Surface water in an aquatic system is referred to as an inland water environment and is divided into lentic and lotic systems. In contrast to lotic water ecosystems, which share continuous habitats through the connection of many basins in unidirectional flow within the dendritic structure of river networks, lentic water ecosystems display discontinuous habitats as aquatic matrices inside the terrestrial system. The lentic water ecology is more similar to terrestrial waters than the lentic water ecosystem, which differs greatly. Aquatic ecosystems are diverse and, despite making up just a little of the planet's surface, are essential for several reasons.

INTRODUCTION

A specific environment, or biotope, and the species that inhabit it, referred to as the biocenosis, make up an ecosystem, also known as an ecological system (GWP/INBO, 2015). Numerous services provided by

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the planet's ecosystems are essential to our everyday existence. Ecosystems on habitable planets can be broadly divided into two groups: terrestrial ecosystems that are based on land and aquatic ecosystems that are based on water. An ecosystem of or about land, as opposed to an ecosystem of water, is called a terrestrial ecosystem (Reddy et al., 2018). A subgroup of ecosystems where water plays a significant role is known as an aquatic environment (GWP/INBO, 2015). Ecosystems that rely mostly or partially on freshwater flooding are known as aquatic ecosystems (Reddy et al., 2018). All of the components of a water-based environment, both living and non-living, and their interactions together comprise an aquatic ecosystem (Reddy et al., 2018). Production, regulation, and organization are just a few of the many tasks that a healthy aquatic environment may undertake (GWP/INBO, 2015). Humans and water ecosystems have long been associated. 71% of the Earth's surface is generally covered by aquatic habitats. Unlike saltwater habitats, which make up three-fourths of the planet's surface, freshwater ecosystems only make up a small portion of the planet's surface. Nearly 70% of people on Earth reside in regions that are adjacent to bodies of water, such as lakes, rivers, and coasts, where civilizations have historically flourished (Reddy et al., 2018). Freshwaters are strongly linked to land use and climate. The sustainability of ecosystems and society depends on fresh water. The natural sciences (such as limnology, hydrology, and ecology), which highlight water quality, hydrological fluxes, and habitat quality as possible ecosystem services, have traditionally been used to study freshwaters. Freshwater ecosystem services include recreation, transportation via water, and the provision of clean water. Freshwater from streams, rivers, and lakes is necessary for human survival and provides essential functions. A varied collection of habitats depending on water, aquatic ecosystems contain significant biodiversity and offer numerous advantages to humans.

Since it is essential to the existence and well-being of all living beings, water is one of the most important resources on Earth and vital to all forms of life (Ahmed et al., 2017). Wetlands and other aquatic ecosystems offer homes for several kinds of plants as well as a place for animals to eat, rest, and reproduce (GWP/INBO, 2015). Aquatic ecosystems are abundant in biodiversity and support a wide range of species and habitats, benefiting the nation's economy and society in many ways. Many different species can be found in freshwater habitats on the surface of the Earth. A sizable portion of the biological variety of Earth is comprised of these aquatic species and the environments in which they coexist (Reddy et al., 2018). Freshwater that flows off land into rivers, lakes, and wetlands is what makes all land an essential component of an inland water ecosystem, as seen from the perspectives of ecology, hydrology, the environment, and socioeconomics. Water ecosystems on land are found in inland waters. Non-saline water, or water with very little or no salt content, is found in freshwater habitats. Within continental landmasses, the ecology of inland water is a complex of living things in free water. Within the Earth's surface, inland aquatic ecosystems make up less than 1%, but they are frequently among the most productive regions (Reddy et al., 2018). The study of all freshwater and saltwater aquatic systems, including wetlands, lakes, bogs, marshes, streams, ponds, rivers, reservoirs, oceans, and so on, with an emphasis on their physical, chemical, and biological properties, is known as limnology (Ziauddin, 2021). Lotic and lentic ecosystems are two different types of aquatic environments, each with its own population, special traits, and ecological dynamics. In addition to delivering a variety of ecosystem services, these ecosystems are essential for maintaining biodiversity and controlling regional temperatures. It is easier to recognize their importance and the need for their conservation when one is aware of their variations and roles.

The term "lotic" refers to flowing water that flows in a single direction, derived from the Greek word *"lavo"*, meaning "to wash" (Eramma et al., 2023). Water flowing through rivers, streams, tributaries, waterfalls, springs, canals, and creeks is a defining feature of lotic ecosystems. Their continuous movement modifies the habitat, affecting the way organisms are distributed and the ecosystem's physical makeup. The richness of their ecosystems was influenced by the size, pace, and volume of water that streams and rivers contain. Different species have different habitats at headwaters, which are usually small and swift-moving, compared to lower reaches, which are usually broader and slower-moving. There is a lot of variation among lotic habitats. Low salt content characterizes littoral environments. Water flows through lotic ecosystems from a source, like a spring or glacier, to a terminus, which could be an ocean, a bigger stream or river, or another kind of reservoir. In lotic ecosystems, gravity causes the surface water to flow downhill along the slopes. The majority of decisions in lotic ecosystems are made by the velocity and current of the flowing water because they create pathways and influence living things. In flowing rivers, the surface current is more noticeable than the bottom substrate. Because of this, the bottom substrate conditions resemble those of lentic environments. A path to the ocean is formed by the connections between numerous lotic habitats (Reddy et al., 2018). In the form of biological matter flowing strongly in one way, the lotic ecosystem is essentially an open system. However, the energy input of solar radiation and the close connection between streams and the nearby terrestrial ecosystems allow running waters to remain energetically viable.

The Latin word *"lentus"*, which means sluggish, is where the word "lentic" originates (Reddy et al., 2018). Standing, or comparatively still, water is a defining feature of lentic ecosystems, which include ponds, lakes, and wetlands. Lakes and other lentic environments are created by glaciers, volcanoes, tectonic plate movement, and occasionally by human activity. The area, depth, and nutrients of these bodies of water vary greatly, creating a variety of ecosystems that are home to a vast variety of creatures. Lakes are larger and can be classified as oligotrophic (low nutrients) or eutrophic (rich nutrients), depending on their nutrient content. Ponds, on the other hand, are the smallest among lentic ecosystems and are frequently shallow and temporary. However, bogs, swamps, marshes, and are all considered to be wetlands because of their saturation and the presence

Figure 1. Types of lotic ecosystem, e.g., river
(Author)

of specific plant and animal species that have evolved to survive in wet environments. Compared to the lotic ecosystem, the lentic ecosystem has a significantly lower oxygen level due to its intense breakdown at the bottom and a small percentage of its surface area being in direct contact with the environment. A greater salt content is seen in certain lentic ecosystems, while freshwater environments have a lower salinity level. Little, transient ponds and massive lakes are examples of lentic habitats. A community of both abiotic and biotic interactions exists in lentic environments. Various creatures are supported by distinct layers in lentic habitats, which vary based on temperature and light levels. Lentic ecosystems are areas of standing water that are home to a wide range of creatures, such as fish, birds, frogs, and plants with rooted and floating leaves. A lentic ecology is the perfect home for frogs and ducks.

Both lotic and lentic environments support a wide variety of plants and animals (Padmanabha, 2017). While lotic habitats may be home to algae, mosses, insects, fish, amphibians, and mammals like otters and beavers that have adapted to the flowing water and the nearby land, lentic environments are frequently home to species like water lilies, cattails, frogs, turtles, fish, and various bird species. These ecosystems have intricated and interrelated dynamics. For example, in lentic ecosystems, the growth of plants and algae is influenced by nutrient levels, temperature fluctuations, and water depth. These factors also affect the availability of habitat and oxygen levels for other organisms. Temperature variations, sediment transport, and flow rate all influence the physical environment and the life cycles of the resident species in lotic ecosystems. Lotic and lentic ecosystems are severely impacted by human activity. These ecosystems are delicately balanced, but pollution from industrial waste, agricultural runoff, habitat degradation, and the introduction of alien species upset the equilibrium. Additionally affecting the integrity of these ecosystems are overfishing, damming, and modifications to natural river flows. For lotic and lentic ecosystems to remain healthy and preserved, conservation measures are essential. The negative consequences of human activity are lessened through programs including pollution control, wetland restoration, watershed preservation, and sustainable fishing methods. To protect these important

Figure 2. Types of lentic ecosystem, e.g., pond
(Author)

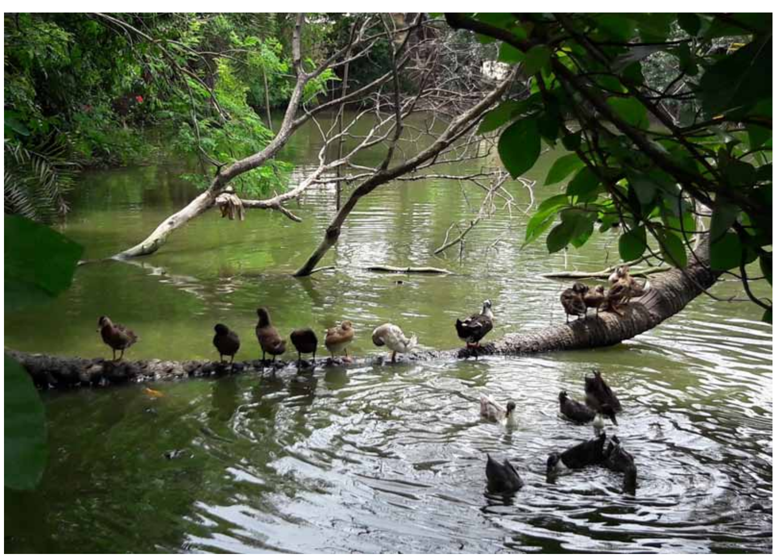


Table 1. Characteristics of lotic and lentic ecosystems

S. No.	Characteristics	Lotic Ecosystem	Lentic Ecosystem
1	Water source	Fed by springs, precipitation, rain, snowmelt, and lower-order streams and diffuse inputs	Surface water predominated, fed by higher-order streams; lotic waters from rivers, streams, and creeks flow into lakes and ponds in addition to ground water.
2	Width of water body	Comparatively limited	Comparatively wide
3	Depth of water body	Shallower	Deeper
4	Morphometry of water body	Longer, narrower, shallower, linear basin with a more intricate border	Deeper, round basin with a simpler border
5	Landscape position	Placement at natural flow	Lower in the watershed
6	Water flow	Consistent and precise guidance	Lacks a continuous, clear direction of flow
7	Duration of water retention and/or water residency	During a drought, there may be very little water, and the area would dry out, killing several creatures. Occasionally, there is a lot of water, such as after a strong storm.	Last longer and allow organisms to survive in spite of the reduced supply
8	Regional distribution and function	Determined by the geomorphology	Impacted by the local need for ecosystem services associated with dams
9	Permanence	Last several thousand years	Last several hundred to several thousand years
10	Adaptability of creatures	Need to become used to their outdated surroundings	Also need to adjust to their surroundings
11	Current velocity	High	Low
12	Dissolved oxygen content	High	Low
13	Salt content	Low	High
14	Speciation rates	Low	High
15	Geographical range size	High	Low
16	Species diversity	High	Low
17	Stability	High	Low

Source: Reddy et al., 2018, Eramma et al., 2023

aquatic habitats for future generations, public knowledge and participation in conservation initiatives are essential. Pollution in lotic and lentic environments must be closely monitored to keep aquatic ecosystems healthy and in balance.

The lotic and lentic environments provide distinct habitats for a wide variety of flora and fauna, and it is important to recognize the importance of pollutant monitoring in these regions (Sharma and Giri, 2018). Because water velocity directly affects the dispersion of contaminants, monitoring pollution in lotic ecosystems is essential. Introduced pollutants into these systems have the potential to move quickly downstream, impacting wider areas and a variety of ecosystems. Aquatic life and water quality are at risk from contaminants, including pesticides, fertilizers, and heavy metals, that are introduced via improper waste disposal, agricultural runoff, and industrial discharges. Frequent monitoring aids in the identification of pollution sources, the evaluation of the level of contamination, and the development of control and restoration plans for the environment. Because of their comparatively closed systems, which can cause pollutants to accumulate over time, it is imperative to monitor contaminants in these environments. Runoff from adjacent areas, urbanization, and industrial operations can contaminate these bodies of water with chemicals, fertilizers, and silt, which can cause algal blooms, eutrophication, and deterioration of water quality. To preserve the equilibrium of these ecosystems, it is helpful to study the ecological changes, pinpoint the sources of pollution, and put remedial measures in place.

To evaluate the general state of aquatic ecosystems, pollution in both lotic and lentic environments must be monitored. Knowing how contaminants affect biodiversity, the food chain, and the overall ecological balance is made easier with its assistance. The maintenance of water quality standards is ensured through routine monitoring. Assuring the water's suitability for drinking, farming, and recreation, it assists in identifying variations in pH levels, dissolved oxygen, nutrient levels, and the presence of hazardous materials. Many types of aquatic life are supported by lentic and lotic settings. The identification and mitigation of hazards, the prevention of habitat deterioration, and the preservation of biodiversity are all made possible by the monitoring of pollutants. Many activities are supported by these bodies of water, which also serve as sources of drinking water. The protection of human health from contaminants that may be harmful due to recreational or water-related activities requires continuous monitoring of pollutants. Using sustainable resource management techniques is made easier by having an understanding of how contaminants affect lotic and lentic settings. To stop pollution and encourage conservation, it helps stakeholders and policymakers make well-informed choices. To comprehend, mitigate, and prevent the harmful consequences of pollution on aquatic ecosystems, biodiversity, human health, and sustainable resource management, it is imperative to monitor pollutants in both lotic and lentic habitats. Informed decision-making is essential to protecting these essential water systems for coming generations, and it forms the basis for that effort. One of the most important factors in achieving environmentally sustainable development and reducing poverty in the context of global change is better governance that respects the environment. For a complete grasp of freshwater ecosystems, one must be able to identify, define, and comprehend their features. Thus, appreciation and knowledge can result in better management and preservation of all freshwater ecosystems, ensuring the sustainable use and provision of freshwater ecosystem services (Reddy et al., 2018).

In the field of biotechnology, the use of biosensors for industrial applications and environmental monitoring is important. Better environmental control is now required by law and public concern. More appropriate analytical techniques are also needed due to the growing number of analytes that need to be monitored. Samples must be submitted to a laboratory for testing to conduct a traditional "off-site" analysis. Conventional procedures are the most accurate with low limit of detection (LOD), but they require highly skilled individuals and are costly and time-consuming. The present trend of conducting field monitoring has increased the development of biosensors as novel analytical instruments capable of delivering affordable, quick, sensitive, and dependable measurements many of which are intended for on-site examination. Many biosensors use is being developed, such as environmental and bioprocess control, food quality management, agriculture, the military, and, most notably, medical applications. The majority of biosensor systems that are sold commercially are used in the pharmaceutical and clinical industries. As a result, this field has received the majority of research and development attention. Biosensors can deliver quick and precise information on contaminated sites for environmental control and monitoring. They provide additional benefits over existing analytical techniques, including the potential for portability, the ability to operate on-site, and the capacity to measure contaminants in intricate matrices with little sample preparation.

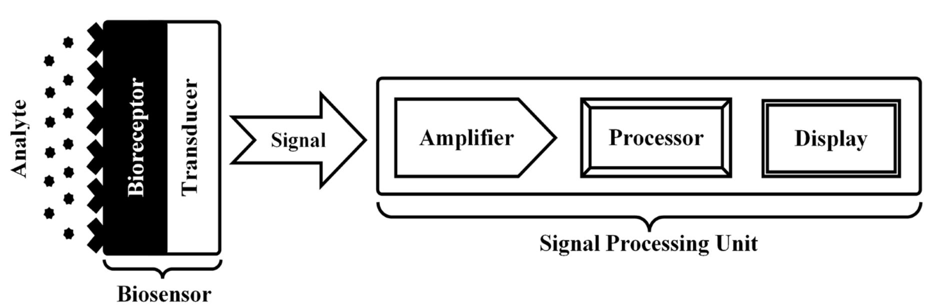
BIOSENSORS: PRINCIPLES, TYPES AND ROLE IN POLLUTANT DETECTION

The word "sensors" comes from the Latin word *"sentire"*, which implies perception. When it comes to the detection and removal of environmental contaminants found in tainted soil, water, and air, biotechnology is crucial (Ahmad and Kumar, 2020). Biotechnology is a significant factor in the treatment and monitoring of environmental toxins found in contaminated soil, water, and air. A biosensor is a biotechnology-based analytical method for pollutants that consists of components for a signal transducer that, while sensing contaminants, produces observable or quantifiable signals (Huang et al., 2023). A biosensor combines transducer and biological sensing elements, such as proteins, enzymes, nucleic acids, and microbes, to produce a signal proportionate to the measured analyte quantity. In a biosensor, the input transducer's job is to change the biological signal to produce a measured reaction. This response can be potential, current, or absorption through an electrochemical or optical process (Ahmad and Kumar, 2020; Nigam et al., 2015; Pakshirajan et al., 2015; Khanam et al., 2020, Kumar et al., 2020). Differential signals are created depending on whether the microbe is acting on the analyte or if it produces a biological recognition element. Enzymes, oligonucleotides, and antibodies are more frequently used as biosensing elements in biosensors than microorganisms. When compared to other biological elements, using microorganisms as a response element has advantages in terms of being more cost-effective and adaptable (Kumar et al., 2020). The types and guiding concepts of biosensors are as follows:

1. Biological recognition element: a biochemical shift is brought about by this component's specific interactions with the target analyte. Enzymes, antibodies, DNA/RNA, cells, or entire organisms could be involved.
2. Transducer: creates a measurable output (such as an electrical, optical, or mass-related signal) from the biochemical signal produced by the contact.
3. Signal processing unit: generates a quantitative result that expresses the concentration or existence of the target analyte by amplifying, processing, and translating the transducer output.

Compared to traditional systems and techniques, biosensors for environmental monitoring have several benefits, such as portability, miniaturization, and the capacity to measure a contaminant with a minimum number of samples. Several benefits, including real-time monitoring, downsizing, and improved selectivity and sensitivity, are associated with electrochemical biosensors. Furthermore, complex

Figure 3. Schematic diagram of a biosensor
(Gieva et al., 2014)



signalling components are not required because electrochemical reactions deliver electronic signals. This enables the creation of mobile systems for on-site environmental monitoring and clinical testing (Arduini et al., 2017). Advances in sensitivity, stability, selectivity, and their use in environmental monitoring have been emphasized in recent studies (Kaur et al., 2015; Justino et al., 2017; Felix and Angnes, 2018; Berberich et al., 2019; Gavrilaș et al., 2022). Biosensors are often categorized into multiple fundamental types based on signal transduction and biorecognition principles. Typically, they are categorized based on the transducer or the bio sensitive element. The biosensors' classification based on the transducer is illustrated in Figure 4.

There is an increase in potentially dangerous pollutants affecting the environment. Developing monitoring systems is essential for ongoing environmental monitoring. To do this, new technology and suitable operational procedures must be developed. The biosensors are suitable choices in the present scenario. By enabling the quick and accurate identification of several pollutants, toxins, and biological agents, biosensors are essential to environmental monitoring. In general, there are two types of environmental pollutants: inorganic and organic substances. Organic pollutants include pesticides, hormones, dioxins, polychlorinated biphenyls, phenols, bisphenol A (BPA), surfactants, linear alkylbenzene sulfonates, alkanes, polycyclic aromatic hydrocarbons, and antibiotics. Metals, inorganic phosphates, and nitrate are examples of inorganic contaminants (Marrazza, 2014; Goradel et al., 2018). Using appropriate biosensors, pollutants from the environment can be identified and monitored. Table 2 displays the types of biosensors used for organic and inorganic pollutant detection.

Figure 4. Classes and sub-classes of biosensors based on the type of transducer
(Gieva et al., 2014)

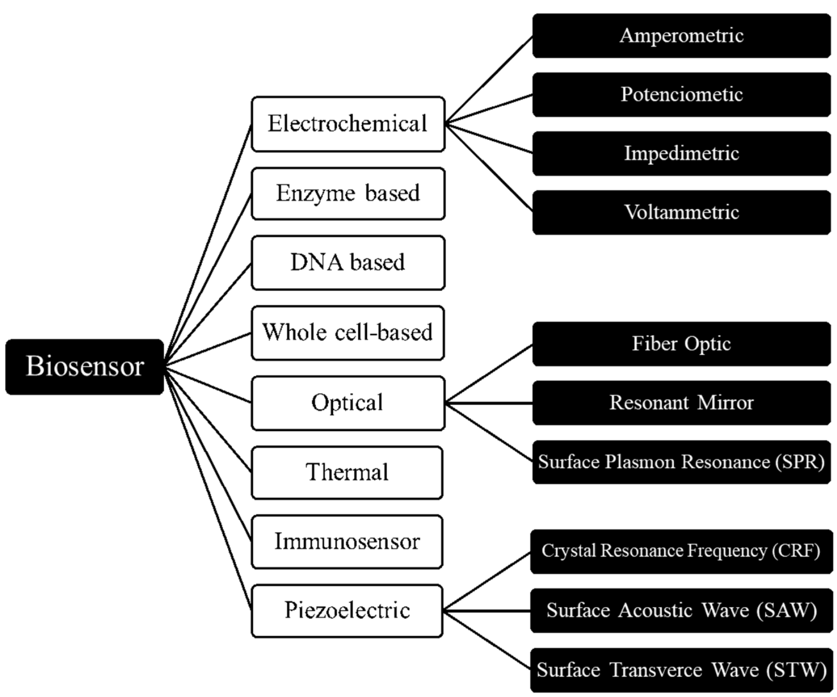


Table 2. Types of biosensors used for organic and inorganic pollutant detection

Target class	Biological sensing element	Physical transducer	Reference
Arsenite, Selenite	Microorganism (*E. coli*)	Optical	Ooi et al., 2015, Goradel et al., 2018
Atrazine,	Antibody	Piezoelectric	Jia et al., 2013
Carbaryl	Piezoelectric	Antibody	Wang et al., 2014
Catechol	Microorganism (Lactobacillus)	Electrochemical	Vogrinc et al., 2015
Copper	Enzyme (HRP)	Electrochemical	Moyo et al., 2014
Copper	Microorganism (yeast)	Optical	Vopálenská et al., 2015
Methyl Parathion	Microorganism (Flavobacterium)	Optical	Vogrinc et al., 2015
Serotonin	Microorganism (yeast)	Optical	Nakamura et al., 2015
Zinc, Cadmium	Microorganism (*E. coli*)	Optical	Vogrinc et al., 2015

Environmental quality assessment can greatly benefit from their usefulness due to their characteristics, including portability, specificity, and real-time monitoring. Biosensors are useful instruments for environmental monitoring and analysis because they have many advantages for pollution detection. In terms of pollutant detection, biosensors have the following major benefits:

1. High Sensitivity and Selectivity: Pollutants can be detected by biosensors with high sensitivity, even at low concentrations. Target pollutants can be selectively detected, reducing negative results, through the use of particular biological recognition elements like enzymes, antibodies, or whole cells.
2. Rapid Response Time: Rapid detection and reaction times are frequently offered by biosensors. In contrast to conventional analytical techniques, biosensors' biological components enable swift interactions with the target contaminants, enabling speedier and real-time monitoring.
3. Miniaturization and Portability: Pollution may be monitored in situ and on-site with biosensors because of their compact and portable design. Because of their small size, they may be easily deployed in various environmental conditions, making them appropriate for field applications.
4. Cost-Effectiveness: Biosensors can sometimes be more affordable than conventional analytical techniques. They are frequently easier to make with less expensive components and reagents. Savings are further increased by the fact that certain biosensors can be reused.
5. Ease of Use: The use of biosensors requires little technical knowledge and is intended to be user-friendly. This enables them to be used by non-experts, such as field workers and community members, enabling more extensive and broad-based environmental monitoring.
6. Multiplexing Capability: To monitor complicated environmental samples with a variety of pollutant profiles, biosensors can be designed to detect numerous pollutants at once. Monitoring efforts are more effective thanks to this multiplexing feature.
7. Biocompatibility: Because biosensors can be designed to detect numerous contaminants at once, complex environmental samples with a variety of pollutant profiles can be monitored. The efficiency of monitoring efforts is improved by this multiplexing feature.

8. Long-Term Stability: Many biosensors have strong long-term stability, making it possible to monitor continuously for lengthy periods. Understanding temporal fluctuations in pollution levels and trends depends on this characteristic.
9. Potential for Real-Time Monitoring: Real-time monitoring is possible with biosensors, which can provide ongoing information on the concentrations of pollutants. Being able to comprehend dynamic environmental processes and react quickly to emergent pollution events are critical skills.
10. Integration with Emerging Technologies: Environmental monitoring systems can be made more capable and effective by integrating biosensors with other cutting-edge technologies, such as data analytics and wireless communication.

SOURCES OF POLLUTANTS IN LOTIC AND LENTIC ECOSYSTEMS

The term "pollutant" refers to any material or agent released into the environment that harms ecosystems, living things, or the environment in general. In addition to man-made sources, including industrial operations, transportation, agriculture, and waste disposal, pollutants can also come from natural sources like volcanic eruptions or wildfires. These chemicals may negatively impact the air, water, soil, or other environmental components. They can exist in a variety of forms, such as solid particles, liquids, gases, or energy. Pollutants can have a negative effect on plants, animals, people, and the general equilibrium of ecosystems. Identification, monitoring, and mitigation of pollution sources and effects are necessary for effective pollution management and control to reduce environmental harm and advance sustainable practices. Contaminants such as pesticides, heavy metals, industrial chemicals, and pathogens are examples of water and soil pollutants. Water pollution can endanger human health, damage aquatic habitats, and lower the quality of drinking water. In addition to harming ecosystems and lowering agricultural productivity, soil pollution can contaminate food. When heated water from power plants or industrial activities is dumped into natural water bodies, it is referred to as thermal pollution. High temperatures have the potential to harm biodiversity and aquatic habitats. It is critical to remember that continual investigation and observation are essential to comprehending newly emerging contaminants and creating sensible environmental management plans.

The heavy metals represent some of the most the most dangerous pollution issues. Both the environment and human health are at risk, even at low doses. Lead, zinc, mercury, cadmium, and copper are the heavy metal contaminants that are most frequently found in the environment. The examination of heavy metals in the environment is the primary purpose of many biosensors that use bacteria as a sensing element. Certain types of bacteria serve as sensors and are resistant to a variety of heavy metals, including zinc, copper, tin, silver, mercury, and cobalt (Gieva et al., 2014). When treating different plants or fertilizing the soil, nitrates are frequently utilized as a protective agent. They are harmful to human health, have an adverse effect on hemoglobin, and may have irreversible effects. Pesticides are compounds or mixtures of substances used to keep pests away. Due to their long half-lives in the environment, pesticides are a concern for the environment. These have been shown through studies to persist in solids and sediments for extended periods. Pesticides are the most prevalent contaminants in the environment, present in soil, water, air, plants, and food. Using herbicides, particular undesirable weeds are eliminated without harming the intended crop. They may be carcinogenic and have highly variable toxicity. Although the effects are highly diverse, several herbicides have a deleterious effect on bird populations. Dioxins are environmental and persistent organic contaminants that are byproducts of several industrial processes.

As contaminating residues found in soil and water, dioxins are potentially hazardous substances that have a significant effect on the environment. Long-distance industrial dioxin emissions can be carried by wind, rivers, and sea currents. Dioxins can be continually recycled in the environment and have a long half-life, ranging from years to centuries.

Plants and microbes both create phenolic compounds, which can also be manufactured commercially. Phenolic structures are present in a large variety of environmental organic contaminants. Phenols and the derivatives they produce from the manufacturing of pharmaceuticals, polymers, paper, pulp, plastics, dyes, and oil refineries, among other things, have harmful effects in people, animals, and plants. Phenolic compounds alter the taste drinking water even at lower concentrations. Numerous contaminants have the potential to negatively harm the health and biodiversity of lotic and lentic ecosystems. Depending on the distinctive characteristics of these habitats and the adjacent land uses, pollutants in lotic and lentic ecosystems can differ.

LOTIC ECOSYSTEMS

1. Sedimentation:
   - Source: Soil erosion from construction sites, agriculture, and deforested areas.
   - Effect: Sedimentation can degrade water quality, impair habitats, and interfere with the reproductive processes of aquatic organisms.
2. Nutrient Pollution:
   - Source: Agricultural runoff, urban stormwater, and wastewater discharges.
   - Effect: Excessive nutrients may cause algal blooms, oxygen depletion, and changes in the composition of aquatic communities.
3. Industrial Discharges:
   - Source: Effluents from manufacturing processes.
   - Effect: Discharge of pollutants from industries can introduce toxic substances, heavy metals, and other contaminants into flowing water, affecting aquatic life.
4. Channelization and Altered Flow:
   - Source: Modifications to river channels for navigation, flood control, or agriculture.
   - Effect: Changes in natural flow patterns can disrupt habitats, alter sediment transport, and impact the health of lotic ecosystems.
5. Urban Runoff:
   - Source: Stormwater runoff from urban areas.
   - Effect: Urban runoff can affect aquatic ecosystems and water quality by introducing contaminants, including chemicals, heavy metals, and oil, into rivers.
6. Invasive Species:
   - Source: Introduction of non-native species.
   - Effect: In lotic ecosystems, invasive species can displace native species, modify food webs, and upset the ecological equilibrium.

LENTIC ECOSYSTEMS

1. Nutrient Pollution:
    - Source: Agricultural runoff, urban stormwater, and wastewater discharges.
    - Effect: Overnutrition (nitrogen and phosphorus) can cause eutrophication, which can harm aquatic life by creating algal blooms and oxygen depletion.
2. Sedimentation:
    - Source: soil erosion in deforested areas, agricultural areas, and construction sites.
    - Effect: Aquatic environments can be harmed by sedimentation, which can veil the water and reduce light penetration. Pesticides and fertilizers are among the associated contaminants that it can carry.
3. Toxic Chemicals:
    - Source: Industrial discharges, agricultural runoff, and urban runoff.
    - Effect: Pesticides, heavy metals, and other hazardous substances have the potential to damage aquatic life, interfere with food chains, and build up in sediments.
4. Pathogens:
    - Source: Untreated sewage, stormwater runoff, and agricultural runoff.
    - Effect: Water contamination by pathogens like bacteria and viruses can endanger aquatic life as well as human health.
5. Thermal Pollution:
    - Source: Discharges of heated water from industrial processes and power plants.
    - Effect: Warm water can have detrimental effects on aquatic ecosystems by decreasing the solubility of oxygen and altering the metabolic rates of organisms.
6. Floating Debris:
    - Source: Improper waste disposal and urban runoff.
    - Effect: Floating debris, including plastics and other materials, can degrade water quality, entangle wildlife, and disrupt aquatic ecosystems.

To monitor pesticides and herbicides, biosensors are essential. Furthermore, these substances might accumulate in grains and vegetables, impacting human health and development. By changing the fertility of the soil and eliminating numerous beneficial insects and bacteria, these chemicals can also modify the ecosystem during their operations. This can have a negative influence on biodiversity (Ahmad and Kumar, 2020). It is crucial to remember that the presence and effects of pollutants can differ significantly depending on the unique qualities of each water body, the land used in their catchment areas, and local environmental laws. In lotic and lentic ecosystems, regular monitoring and management techniques are crucial to reducing the negative effects of pollution.

APPLICATION OF BIOSENSORS FOR POLLUTANT DETECTION IN LOTIC AND LENTIC ECOSYSTEMS

Biosensors play a crucial role in monitoring and managing lotic and lentic ecosystems. Biosensors contribute to biodiversity and ecological studies by providing data on key environmental parameters. This information aids in understanding the relationships between environmental conditions and the diversity of aquatic ecosystems. The continuous development of biosensor technology enhances their capabilities for environmental monitoring, making them valuable tools for maintaining and preserving the health of lentic ecosystems. Their applications contribute to the assessment of water quality, detection of pollutants, and understanding ecological dynamics. The following are some important uses for biosensors in lotic and lentic environments.

Pesticides

Pesticides are extensively used in agriculture to improve yields and productivity, which has resulted in their widespread presence in the environment (Verma and Bhardwaj 2015). Pesticides are often present in natural streams since they are extensively used in agriculture. Pesticide concentration restrictions in certain environmental waterways have been imposed by the European Community due to concerns about their toxicity and long-term environmental persistence. A limit of 0.1 μg/l for individual pesticides and 0.5 μg/l for total pesticides has been imposed by Directive 98/83/EC concerning the safety of water for human consumption (Rodríguez-Mozaz et al., 2004). Chemical structure is used to categorize pesticides into five groups: inorganic pesticides, carbamate, synthetic pyrethroids, organochlorine (Atrazine), and organophosphate (Parathion) (Verma and Bhardwaj 2015). Organochlorine pesticides negatively impact fish reproduction (Vigneshvar et al., 2016). Among the most pervasive pesticides due to its slow breakdown, atrazine has been found in water bodies all over the world and is an endocrine-disrupting chemical (EDC) that affects fish, amphibians, reptiles, and mammals' ability to develop effectively (Scognamiglio et al., 2019).

Several approaches have been used in recent studies to quantify pesticides in water using biosensors. Liu et al., (2017) achieved an LOD of 7.53 μg/L for 2,4-D, a popular herbicide, by using fluorescence biosensors to detect it. Gosset et al., (2019) tested three distinct kinds of algae and three different pesticides; the best outcome they obtained was an LOD of 10 μg/L. Duan et al., (2020) tested the liquid crystal resonator biosensor using two analytes; the LOD was achieved at 1 pg/mL for dimethoate and 0.1 pg/mL for fenobucarb. Utilizing the latest interferometer technology, Ramirez-Priego et al., (2021) achieves an LOD of 0.29 ng/mL. In accordance with Fang et al., (2020), who employed immunosensors for the last five years to detect pesticides, they reported that immunosensors work well for detecting a variety of matrices because of their high sensitivity, ease of use, simplicity, and wide linear range.

The majority of current research on the detection of pesticides in lotic and lentic ecosystems has employed either fluorescence or interferometers. Interferometers have low LODs, and high sensitivity. A resonator that could detect even lower amounts has been developed recently (Herrera-Domínguez et al., 2023).

Table 3. Types of biosensors used for pesticides detection

Analyte	Biological sensing element	Physical transducer	Source	Reference
Atrazine	MIP	Fluorescence	Lake water	Liu et al., 2011
Atrazine	Antibody	Grating couplers	River water	Gao et al., 2017
Fenobucarb Dimethoate	Enzyme	Resonator	River water	Duan et al., 2020

Heavy Metals and Toxins

Because heavy metals can bioaccumulate in living things, particularly marine organisms, and because their levels in the environment are rising, it is crucial to find any residues of these metals, which include Cu, Cd, Hg, and Zn. Strong acids are typically used to evaluate metal content after digestion. Ion chromatography, inductively coupled plasma, and polarography are frequently employed analytical methods. Ion-selective electrodes can also be used to measure heavy metals. Being able to react just to the accessible fraction of metal ions is one benefit of whole-cell sensors. Recombinant bacterial sensors have been developed and employed to determine the presence of a certain metal. Chemical analysis techniques and nonspecific toxicity biosensors are less sensitive than specific biosensors, which are based on inducible promoters linked to reporter genes (Rodríguez-Mozaz et al., 2004).

Industrial operations such as mining raise the number of heavy metals. Because they are not biodegradable, heavy metals gradually build up in the environment. ROS are produced by almost all heavy metals, which transmit their harmful effects (Gutiérrez et al., 2015). Heavy metals like cadmium, cobalt, copper, and nickel can be found using glucose oxidase (GO) inhibition as a biosensor. The activity of a reporter gene driven by an inducible promoter serves as the basis for optical biosensors that detect metals. The reporter signal level rises with the pollutant concentration in this technique, known as "turn-on assay". The most often used reporter genes in biosensor systems are GFP, luciferase (*luc*), and β-galactosidase (*lacZ*) (Gutiérrez et al., 2015; Goradel et al., 2018). Gieva et al., 2014 reported that optical and electrochemical biosensors are the most commonly utilized for heavy metals detection.

The collection of substances known as toxins is highly diverse and can impact several biochemical processes, including ion transport, transmitter release, membrane function, and DNA and protein synthesis. In many cases, it is necessary to comprehend the finer points of a toxin's molecular method of action and site of action. A sulfur-oxidizing bacterium (SOB)-based biosensor was used in the online detection of heavy metals and other harmful compounds in water, as reported by Eom et al., (2019). In harmless water, sulfuric acid (H_2SO_4) is produced when elemental sulfur (S_8) is oxidized by SOB, lowering the pH of the water while raising its electrical conductivity (EC). In 2019, Chouler et al., developed an MFC-based biosensor that uses a microbial fuel cell to detect toxic compounds in water on-site. The MFCs are easy to use and create a bio-electrochemical sensor that is sensitive, portable, and reasonably priced by using microalgae.

Pharmaceuticals

One of the current concerns about water contamination is improper excretion of hospital wastes. Commonly founded pharmaceuticals in the water are likes of antihypertensive drugs, beta-blockers, analgesics/anti-inflammatories, antibiotics and psychiatric drugs. Therefore, detection of these compounds is essential to prevent life threating effects on human and other living organisms. Enzyme-based biosensors using peroxidases, laccases, and tyrosinases are main biosensors for the detection of pharmaceuticals (Rebollar-Pérez et al., 2015). When pharmaceutical substances are excreted or their residues are improperly disposed of, they end up in the environment. Similar to pesticides, these substances are persistent and build up in the environment; some even affect the development of some species of algae and microalgae and have estrogenic effects on particular creatures (Herrera-Domínguez et al., 2023).

Pharmaceuticals in water can be found using SPR and LSPR, two widely used techniques (Herrera-Domínguez et al., 2023). To detect the antibiotic ciprofloxacin, Luo et al., (2016) developed an SPR

Table 4. Optical biosensors and electrochemical biosensors used for toxic heavy metals detection

Sensing material	Contaminant	Limit of detection	Working range	Detection time
Optical sensors				
RGO	Hg^{2+}	1 nM	1–28 nM	tens of seconds
SWCNT (no probe)	Hg^{2+}	10 nM	10 nM to 1 mM	few seconds
Au NP/RGO	Hg^{2+}	25 nM	25 nM to 14.2 µM	few seconds
Au NP/RGO	Pb^{2+}	10 nM	10 nM to 10 µM	few seconds
SiNW	Pb^{2+}	1 nM	1–104 nM	few seconds
Au NP	Pb^{2+}	3 nM	3 nM to 1 µM	6 minutes
Au NP	Hg^{2+}	9.9 nM	9.9–600 nM	10 minutes
Au NP	Hg^{2+}	5 nM	50 nM to 10 µM	10 minutes
Au NP	Hg^{2+}	1 nM	1 nM to 1 mM	15 minutes
GO QD	Pb^{2+}	0.09 nM	0.1–1000 nM	20 minutes
SWCNT	*E. coli* DH5a	3×10^3 CFU mL^{-1}	3×10^3–1×10^6 CFU mL^{-1}	20 minutes
RGO	*E. coli* O157:H7	803 CFU mL^{-1}	803–10^7 CFU mL^{-1}	25 minutes
Au NP	Pb^{2+}	100 nM	0.1–50 µM	25 minutes
Graphene	*E. coli* K12	10 CFU mL^{-1}	10–10^5 CFU mL^{-1}	30 minutes
CNT	Cd^{2+}	88 nM	88 nM to 8.8 µM	30 minutes
Electrochemical sensors				
$MgSiO_3$	Pb^{2+} (0.1 M NaAc–HAc)	0.247 nM	0.1–1.0 µM	tenths of seconds
Fe_3O_4/RTIL	As^{3+} (acetate buffer)	0.01 nM	13.3–133 nM	few minutes
Nanosized Co.	H_2PO_4 – (KH_2PO_4 solution)	-	10^{-5} to 10^{-2} M	1 minute or less
Au	As^{3+} (1 M HCl)	0.26 nM	0.26–195 nM	100 seconds
Au–Pt NP	Hg^{2+} (1 M HCl)	0.04 nM	0.04–10 nM	100 seconds
Au NP/CNT	Hg^{2+} (0.1 M $HClO_4$)	0.3 nM	0.5 nM to 1.25 µM	2 minutes
Carbon NP	Hg^{2+} (1 M HCl)	4.95 nM	4.95–49.5 nM	2 minutes
CNT	Pb^{2+} (1 M HCl)	0.96 nM	9.6–480 nM	180 seconds
MWCNT/GO	Pb^{2+} (0.1 M NaAc–HAc)	0.96 nM	0.96–144 nM	3 minutes
Bi–CNT	Pb^{2+} (0.1 M acetate buffer)	6.24 nM	9.6–480 nM	300 seconds
Graphene/nafion	Pb^{2+} (0.1 M acetate buffer)	0.096 nM	2.4–240 nM	300 seconds
Nanosized hydroxyapatite	Pb^{2+} (0.2 M HAc-NaAc)	1 nM	5.0 nM to 0.8 µM	10 minutes
Graphene nanodots	Cu^{2+} (ammonium acetate solution)	9 nM	9 nM to 4 µM	15 minutes

Source: Hernandez-Vargas *et al.,* 2018.

biosensor using a molecularly printed polymer. It was estimated that this biosensor has an LOD of 0.08 µg/L. One of the most remarkable developments is the biosensor created by Shrivastav et al., (2015), which combines fiber optics with SPR and LSPR. The biosensor in this particular case has been made up of an optical fiber with a portion of its core exposed. With tetracycline as the target chemical, they obtained an LOD of 0.97 µg/L.

The most recent attempt to use fluorescence to detect antibiotics, Huang et al., (2021) were able to quantify ciprofloxacin by obtaining an LOD of 6 µM. Another substance that has been identified by fluorescence is diclofenac. Schirmer et al., (2019) developed this biosensor using yeast cells that illuminate when the drug is present. They obtained an LOD of 10 µM. Weber et al., (2017) developed an alternative method for antibiotic detection that involved the quantification of penicillin using an interferometer with a minimum concentration test of 0.25 µg/mL.

E. coli

The primary pathogen-transmission vector is surface water. In contaminated, treated, and untreated waterways, bacteria, viruses, and other microbes are frequently detected and represent a global public health concern. Since controlling diseases from these sources can benefit from proper monitoring of the water supply for the presence of pathogens, new technologies such as biosensors have been developed to provide fast identification of contamination by microorganisms at the source and in real-time, whereas conventional analytical methods take days or weeks to produce a result. The traditional approach to quantitative microbiological investigation involves counting visible microbial colonies for a wide range of prokaryotic and eukaryotic bacteria. A single culture cell in a sample can grow into an obvious colony, which is one of the benefits of colony-counting tests' straightforward methods and great sensitivity. However, the method hasn't advanced much since colony-counting tests were created in the past (Woldu, 2022).

Peixoto et al., (2019) developed bioactive paper sensors for real-time water quality monitoring. This study describes a technique for the very sensitive and specific multiplexed detection of *E. coli* utilizing a lab-on-paper test strip (bioactive paper) that is based on the activity of intracellular enzymes (β-glucuronidase (GUS) or β-galactosidase (B-GAL). Roda et al., (2019) used lectin and a porous silicon substrate to detect *E. coli* and Staphylococcus aureus, and they were able to acquire an LOD of 103 cells/mL. An optical biosensor was created by Jung and Lee (2016) for automated, continuous monitoring of the establishment and expansion of microbial colonies in water. The device may use high-resolution sub-pixel sweeping microscopy to dynamically identify individual microcolonies.

Biochemical Oxygen Demand

The oxygen needed to neutralize organic wastes over five days at 20°C is known as biochemical oxygen demand (BOD), or BOD_5. This metric is frequently used to determine the amount of biodegradable organic material present in water (Abdelghani and Jaffrezic-Renault, 2001). The traditional BOD test has a few advantages, including the ability to measure the majority of wastewater samples universally

Table 5. Types of biosensors used for pharmaceuticals detection

Analyte	Biological sensing element	Physical transducer	Source	Reference
Ciprofloxacin	MIP	Fluorescence	River water	Huang et al., 2021
Sulfadimine	Antibody	Fluorescence	Lake water	Liu et al., 2014
17β-estradiol	ER hERα	SPR	Pond water	Liu et al., 2021
Tetracycline	Aptamer and Antibody	SPR/LSPR	River water	Kim et al., 2017

and the lack of expensive equipment requirements. However, because of its time-consuming nature, it is not appropriate for online process monitoring. As a result, creating a different approach that may get around the traditional BOD test's drawback is imperative. Biosensor-based techniques could accomplish quick BOD determination.

Early on in the development of the new technology, biosensors were created to measure BOD. An amperometric sensor for measuring dissolved oxygen was developed in 1962 by Clark and Lyons. A self-powered BOD biosensor for signal-frequency-based water quality monitoring was developed by Pasternak et al., (2017) using an electroactive microbe. This biosensor is self-powered and has a five-month autonomy period because it is made from electroactive microorganisms. More research on the reliability of MFC-based biosensors is necessary and frequently goes unreported, as reported by Cui et al., in 2019. The catalysts used in MFC are self-renewing microorganisms. However, bacteria may adapt efficiently to modifications in their environment during long-term operation. Consequently, bacteria with a high extracellular electron transfer rate may be screened to enhance MFC-based biosensors, as this will negatively impact the biosensors' sensitivity, selectivity, and repeatability.

Endocrine Disrupting Compounds

Endocrine-disrupting chemicals (EDCs) have drawn more attention to themselves as pollutants found in municipal wastewater. According to recent studies, these substances are frequently not effectively removed in WWTPs and may have detrimental effects on the ecosystem (Woldu, 2022). Rapini & Marrazza, (2017) used aptamer-based electrochemical biosensors to evaluate water quality. Certain EDCs are tested for toxicity using a two-stage, multi-channel mini-bioreactor that is based on genetically modified bioluminescent bacteria (Shi et al., 2014). For determining EDCs, other biosensing techniques such as cell proliferation, luciferase induction, ligand binding, antigen-antibody interactions, or vitellogenin induction are available (Woldu, 2022).

Organic Compounds

Industrial supplies, fuels, detergents, personal care items, and derivatives made of plastic are all included in this category. Phenolic and halogenated chemicals are among them. Their detrimental impacts on aquatic species and even humans draw particular attention to them (Herrera-Domínguez et al, 2023). A biosensor based on an enzymatic membrane was proposed by Shahar et al., (2019) to detect organohalide, a halogenated compound, using an optical fiber reflectometer. An LOD of 0.908 mg/L was attained using this technique. BPA is one of the compounds that SPR biosensors have identified. Xue et al., (2019) employed functionalized gold nanoparticles using an inhibitory format; as a result, they acquired an LOD of 5.2 pg/mL. BPA is used in the making of plastics and can operate as an endocrine disruptor. Förster Resonance Energy Transfer (FRET) is an additional method of using fluorescence as an analytical tool. This method is based on how energy is transferred in biological systems. A biosensor for the detection of BPA was created by combining FRET with graphene; the outcome of this effort was an LOD of 0.1 ng/mL (Gupta and Wood, 2017). Cheng et al., (2022) developed a biosensor that measures variations in an immunoassay's fluorescence using a smartphone. The data is processed in an app that allows real-time tracking of the measurement. Using antibodies tagged with the Cy5.5 dye, the immunoassay was used to detect BPA in water samples from a lake and tap water, with an LOD of 0.1 nM for free Cy5.5.

Table 6. Types of biosensors used for organic compounds detection

Analyte	Biological sensing element	Physical transducer	Source	Reference
BPA	DNA	Fluorescence	River water	Gupta and wood, 2017
BPA	Antibody	Fluorescence	Lake water	Cheng et al., 2022
Dichloroethane	Enzyme	Fiber optic	River water	Shahar et al., 2019

CHALLENGES AND FUTURE DIRECTIONS

Biosensors are incredibly promising tools that can be used to quickly, easily, affordably, and reliably screen a large number of real samples. These devices' inherent qualities make them applicable to a wide range of industries, but the biological, agricultural, and environmental sectors seem to benefit the most from their frequent use in repetitive analysis. For the identification of contaminants in lotic and lentic environments, biosensors present a promising alternative. However, there are a few difficulties related to these environments in their implementation:

Lotic Ecosystems

1. Flow variation: Constant water flow in rivers and streams can alter the stability and positioning of sensors. It can be difficult to maintain sensor locations in quickly moving waters to provide reliable data.
2. Biofouling: An important problem is biofouling, or the build-up of organic materials on sensor surfaces. It may impede the functionality of the sensor, decreasing accuracy and requiring regular cleaning or maintenance.
3. Sensitivity to environmental conditions: There can be variations in turbidity, pH, and temperature in lotic ecosystems. The accuracy and dependability of sensors may be impacted by their sensitivity to these changes.
4. Limited access: Installing, maintaining, and retrieving sensors for calibration or repair can be challenging in lotic ecosystems because of their remote and frequently inaccessible nature.

Lentic Ecosystems

1. Stratification: Layers of differing environmental conditions are frequently found in lakes and ponds. As water depths vary, so do the temperature, oxygen content, and pollution dispersion. These variations must be taken into consideration by sensors.
2. Sediment interference: Sediment build-up at still water bodies' bottoms may prevent direct contact with the water or change the chemical composition being measured, which can both have an impact on sensor accuracy.
3. Biological interference: In lentic ecosystems, interactions between sensors and aquatic life can cause biofouling or even modify the way the sensors' function.
4. Spatial variability: Selecting sensor locations that effectively represent overall water quality can be difficult due to the variation in the spatial distribution of contaminants in lakes and ponds.

Biologists, environmental scientists, engineers, and technology developers must work with multidisciplinary teams to overcome these challenges. The development of advanced sensor technologies, persistent calibration techniques, and innovative deployment approaches is a continual effort to mitigate these concerns and augment the efficacy of biosensors in the surveillance and detection of contaminants in lotic and lentic environments. Biosensors for environmental monitoring have several advantages over conventional environmental analysis techniques, including low cost, low technical expertise and sample pre-treatment requirements, feasibility for on-site use, energy savings, and non-use of hazardous compounds (Thavarajah et al., 2020). The field of biosensor technology is rapidly developing, and there are several possible developments and future paths that might be taken to improve analyte identification and monitoring. The following are some crucial areas for future development:

1. Nanotechnology Integration: The sensitivity, selectivity, and response times of biosensors can be improved by integrating nanomaterials, such as nanoparticles, nanotubes, and nanowires. Nanomaterials can help create biosensor platforms that are more sensitive and effective by offering a large surface area for immobilizing biological recognition elements.
2. 3D Printing Technology: Complex and customized constructions can be manufactured with 3D printing. 3D printing can be used in biosensor development to build intricate designs that increase biological component immobilization and boost sensitivity and performance.
3. Flexible and Wearable Biosensors: Biosensors that adapt to the outlines of surrounding surfaces or the human body may be developed as a result of developments in flexible and wearable electronics. Particularly for health-related applications and environmental exposure evaluations, these biosensors may provide continuous, non-invasive monitoring capabilities.
4. Integration with Mobile Devices: Biosensors can offer intuitive interfaces for data collection, processing, and transfer when they easily connect with mobile devices, including smartphones and tablets. This integration allows for real-time monitoring in a variety of scenarios and improves accessibility.
5. Artificial Intelligence (AI) and Machine Learning: Biosensors can handle data more efficiently if AI and machine-learning algorithms are integrated. These technologies can improve the accuracy and dependability of biosensor-based measurements by helping with pattern identification, data interpretation, and the creation of predictive models.
6. Energy Harvesting: Developing biosensors that use energy harvesting methods, such as piezoelectric or triboelectric materials, can enable self-powered sensor systems. In remote or resource-constrained situations, this would lessen reliance on external power sources and improve the sustainability of biosensor deployments.
7. Single-Cell Analysis: Technological developments in biosensors may make single-cell analysis possible, enabling the identification and observation of biological substances at the cellular level. Understanding complex biological processes and using this expertise for medical diagnostics would be especially beneficial.
8. Multi-Analyte Detection Platforms: Using integrated sensor arrays, future biosensors might concentrate on the simultaneous identification of several analytes. The capacity to identify many analytes at once is essential for the thorough monitoring of complex samples, including biological fluids or environmental waters.

9. Biosensors for Biomarker Discovery: When it comes to finding biomarkers for a variety of illnesses and environmental circumstances, biosensors can be extremely important. The discovery of novel biomarkers and the creation of biosensors for early illness detection and monitoring could result from further study in this field.
10. Synthetic Biology Integration: By utilizing synthetic biology techniques, biosensors can be developed with more functions, increased target specificity, and increased stability. Additionally, biological components with specific qualities for use in biosensor applications can be created with the aid of synthetic biology technologies.
11. *In vivo* Biosensors: Advances in *in vivo* biosensors could make it possible to continuously monitor the physiological characteristics of living things. These biosensors could be applied to illness management, personalized therapy, and the comprehension of dynamic biological processes.

Future biosensor technology is expected to be driven by interdisciplinary research, scientific-engineer collaboration, and advances in materials science and bioengineering. These factors will likely result in more advanced, dependable, and adaptable sensing platforms for better identification and monitoring across a variety of fields.

SUMMARY

Emerging remediation technologies and governance techniques are being developed with a sustainable future in mind, acknowledging the growing demand for more socially, economically, and environmentally responsible societies. Pollution severely impacts ecosystems, which has a debilitating effect on economic growth. Pollutants also threaten human life and the lives of other living things. Biotechnology places a lot of importance on the usage of biosensors in industrial settings and for environmental monitoring. Building monitoring systems are essential for ongoing environmental monitoring. To do this, new technology and suitable field procedures must be developed. Since biosensors perform better than any other diagnostic instrument on the market regarding sensitivity and selectivity, they will quickly become indispensable analytical tools. Numerous biosensors were previously developed in research labs, and a sizable body of literature has been written about them. Although biosensors have been created for many uses, environmental analysis applications have demonstrated the greatest potential for biosensor development in the future. As a result, these techniques for identifying environmental contaminants must be improved. Although biosensors have many benefits, it is vital to remember that they also have drawbacks, including issues with repeatability, standardization, and possible interference from intricate sample matrices. These issues are still being researched, and new developments in technology are helping to overcome these obstacles and raise the general efficacy of biosensors in pollution detection. Lotic and lentic ecosystems, in summary, are complex and varied aquatic environments, each with its own distinct characteristics and ecological dynamics. Realizing the complexity of these ecosystems and their many benefits to humans and wildlife alike emphasizes how crucial conservation efforts are to ensuring their sustainability.

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KEY TERMS AND DEFINITIONS

Biosensor: A device that combines biological material and transducers, usually in intimate association, to signal the presence of a particular substance or group of substances.

Ecosystem: A functional ecological unit in which the biological, physical, and chemical components of the environment interact.

Environment: The term “environment” refers to the surrounding area and includes all of the factors that influence an organism’s life. The environment encompasses the interactions between water, air, and land, as well as their impact on humans, other living organisms, and property.

Lentic: Still water system, *i.e.*, ponds and lakes.

Lotic: Running waters, such as rivers and streams.

Pollutant: The components, chemicals, and particles that cause pollution are called pollutants; it is widely known that exposure to these substances can have negative impacts on human health as well as plant health.

LIST OF ABBREVIATIONS

% : Percent
μg : Microgram
μM : Micrometre
2,4-D : 2,4-dichlorophenoxyacetic acid
3D : Three-dimensional
AI : Artificial intelligence
BOD : Biochemical oxygen demand
BPA : Bisphenol A
Cd : Cadmium
CNT : Carbon Nanotube
Cu : Copper
DNA : Deoxyribonucleic acid
E. coli : Escherichia coli
EC : Electrical conductivity
EDC : Endocrine-disrupting chemical
GFP : Green fluorescent protein
GO : Glucose oxidase
Hg : Mercury
L : Liter
LOD : Limit of detection
LSPR : Localized surface plasmon resonance
M : Meter
MFC : Microbial fuel cell
mL : Milliliter
mM : Millimeter
ng : Nanogram
nM : Nanometer
pg : Picogram
pH : Potential of Hydrogen
RGO : Reduced graphene oxide
RNA : Ribonucleic acid
ROS : Reactive oxygen species
SOB : Sulfur oxidizing bacteria
SPR : Surface plasmon resonance
SWCNT : Single-wall carbon Nanotube
WWTPs : Wastewater treatment plants
Zn : Zinc
α : Alpha
β : Beta

Chapter 12
Limnology and the Science of Biosensors

Hemendra Wala
Devi Ahilya Vishwavidyalaya, India

ABSTRACT

Increasing concern about levels of pollution in the aquatic environment has led to the adoption of a number of preventive measures to assist in maintaining the quality of water bodies. The development of new user-friendly, portable, and low-cost bioanalytical methods is the focus of research, and biosensors are in the forefront of these research works. Biosensors have various prospective and existing applications in the detection of contaminants in the aquatic environment by transducing a signal. Biosensors are able to detect a wide range of analytes in complex matrices and have proven a great potential in environment monitoring, clinical diagnostics and food analysis Hence, the aim of this work is to provide a description of the state of the art about the development and application of biosensors to detect contaminants in freshwater ecosystems.

INTRODUCTION

Limnology is the study of inland water bodies, including ponds, lakes, rivers, and streams, with interactions between environmental factors. Limnology plays a primary part in the use of water and distribution, and nature habitat security. Limnologists work in reservoir management and lake, river, and stream protection, wildlife and fish enhancement, water pollution control, and artificial wetland construction. Limnology is the study of inland waters, streams, rivers, wetlands, groundwater, and reservoirs as systems of ecology related to their waste inlets and the environment. A biosensor is a tool that calculates chemical and biological reactions by developing signals symmetrical to the engagement of an analyte in the response. Despite protecting only 0.01% of the world's entire surface, they deliver essential services to the ecosystem, such as water, energy, and food provisions to billions of individuals. The oceans include 97.3% of all sources of water in the world. Accordingly, the ratio of freshwater sources is just 2.7% of all the sources of freshwater, and just 2.9% of it is open to people in the state of freshwater rivers, groundwater, and lakes **(Nakamura, 2018)**. The analyte connects to

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the substance of biology, including a determined analyte, which causes countable electric responses. Electrochemical biosensors are easy tools that operate as bio electrodes and are used to calculate electric present conductance and ionic changes. Biosensor is an integrated receptor-transducer device that can convert biological responses into electrical signals.

Tropic State Index

The health and water quality of the oceans depend on their nutrient concentrations and water clarity. It includes three parts, mainly eutrophic, mesotrophic, and oligotrophic, which are determined by the level of nitrogen, prosperous, and chlorophyll concentration.

The Seasonal Cycle: Stratification and Mixing

In ponds and lakes moderately deep, the water undergoes mixing and thermal satisfaction's seasonable cycle. Warm water is lighter than cool water, which indicates that in summer., the surface water warms and becomes lighter, hovering above the heavier cool water that drops to the bottom(**Moore *et al.,* 2009**). Cold winds and air cool the water at the surface, which becomes heavier and drops in the column of the water, blending with the ground, water that stays cool all summer. In the winter season, when ice appears on the surface of the lake, the water below stays diverse but with slight temperature variations. Cold water poses instantly below the ice, while water straight, roughly 4 degrees Celsius, stays at the bottom of the lake. The water from dissolving ice is colder than the lake water. Hence,, this heavier, colder water drops to the bottom of the lake, and the surface water warms, directing to summer stratification of the column of the water.

Figure 1. Connecticut DEEP trophic categories

Category	T.P. (ppb)	T. Nitrogen (ppb)	Secchi Depth (m)	Chlorophyll a (ppb)
Oligotrophic	0 -- 10	2 -- 200	6 +	0 -- 2
Oligo-mesotrophic	10 -- 15	200 -- 300	4 -- 6	2 -- 5
Mesotrophic	15 -- 25	200 -- 500	3 -- 4	5 -- 10
Meso-eutrophic	25 -- 30	500 -- 600	2 -- 3	10 -- 15
Eutrophic	30 -- 50	600 -- 1000	1 -- 2	15 -- 30
Highly eutrophic	50 +	1000 +	0 -- 1	30 +

OVERVIEW OF FRESHWATER ECOSYSTEMS AND THEIR CHARACTERISTICS

Freshwater ecosystems are a subset of the world's aquatic ecosystems, and they can be contracted with oceanic ecosystems, which include a more extensive salt content—limnologists who are studying freshwater ecosystems. Freshwater ecosystems are interactive techniques in biotic species in their development and adaptation. It connected biological productivity, energy flows, and nutrient cycling between plants, inland marine microbial, as well as animal communities combined with their atmosphere **(Boehm *et al.,* 2017)**. The organic matter and nutrient range of drainage water from the area of the catchment is changed in the stream and wetland littoral. In addition to terrestrial features, water carries down gradient to and within the reservoir or lake itself. An ecosystem of freshwater includes a lot of minerals and nutrients, and it is small-salinized when likened to different ecosystems. The freshwater habitat experiences a temperature of 30 to 71° F during summers and 35 to 45° F in winter. The three kinds of freshwater ecosystems are lotic, wetlands, and lentic. Lotic ecosystems are fast-moving water like rivers and streams, and wetlands ecosystems are areas where the ground is inundated or saturated for a part of the time. Lentic ecosystems are gradually moving water like lakes, ponds, and pools.

Freshwater Ecosystems Characteristics

The ecosystem of freshwater is a habitat for different animal and plant species. The main reason is that it is particularly wealthy in words of minerals and nutrition. The ecosystem of freshwater is slightly salty, unlike the ocean ecosystem. The ecosystem's temperature changes depending on the same elements like season, depth, and location from the surface of the water. In the summer, the freshwater ecosystem's temperature typically varies from 30- 70 degrees Fahrenheit. However, in the winter the temperature varies from 35-45 degrees Fahrenheit. The shape and size of the freshwater ecosystems vary depending on the water bodies' depth, area covered, and location **(Laffoley *et al.,* 2020)**. The ecosystem of freshwater contains residues at the ground. In gentle-flowing still-water bodies and freshwater bodies the residues stay in place. The ecosystem of freshwater delivers a suitable atmosphere for different species of fauna and flora.

Importance of Water Quality Monitoring in Limnology

Water quality monitoring involves the repeated study of water quality at specific locations, which helps to identify trends and take action to intercept and remediate any adverse effects caused by human activity on the marine environment. Parameters such as dissolved oxygen, ORP, pH, turbidity, temperature, chloride, ammonia, nitrate, and algae are continuously monitored to ensure water quality **(Lin et al. 2022)**. Monitoring the quality of ocean water (OWQ) provides a better understanding of the ocean's water quality as well as the near shore atmosphere. OWQ measurements can include biological, chemical, and physical characteristics of marine waters. Low values of OWQ measurements indicate an unhealthy ecosystem. Ocean water quality refers to the existence or absence of any pollutants in sea waters. More essential pollutants are heavy metals, plastics, nutrients, oil, thermal pollution, and sedimentation. Monitoring of water quality depends on taking appropriate measurements of seawater. In oceans, there are 5.25 trillion plastic waste calculated, 4 billion microfibers in every km^2, and 269,000 tons float live under the surface. In the ecosystems, there are 70% of waste sinks present, 15% land, and 15% float on the beaches. 8.3 million tons of plastics are scrapped in the ocean yearly **(Topp *et al.,* 2020).**

OCEAN ACIDIFICATION IN THE SALISH SEA

It has just become a rapidly growing danger to many exposed locations in the Salish Sea. It is the incremental growth in acidity in the earth's seas because of their carbon dioxide (CO2) uptakes from the environment. Scientists calculate that the seas have found roughly 1/3 of carbon dioxide, which is human-produced over the last 250 years, and it has shown a 30% growth in acidity. Ocean acidification is an international problem caused by the international growth in atmospheric CO2, influenced instantly not only by carbon dioxide's local emissions and different greenhouse gases but also by sources of freshwater **(Falkenberg *et al.,* 2020).** For example, organic carbon and nutrients from ground runoff can show improved algae growth and the algae mortality cycle. The growth in photosynthesizing algae boosts CO2 consumption and oxygen production in the waters at the surface of the coast during the day, but at night algae deliver CO2 during respiration.

Moreover, as algae sink and die, bacteria spoil the other organic issue that comes to the sea bottom, which can occasionally generate hypoxic situations. The Salish Sea is inherently more acidic than further waters, primarily due to increased rates of nutrient upwelling, so actually, small differences in pH can create a danger to ocean animals in the area. Acidic waters make it hard for oysters and various shellfish to construct their calcium carbonate bodies while in the stage of larval. The effect of ocean acidification on shellfish has fundamental economic developments **(Sallée *et al.,* 2021).** Gathering shellfish has been a rule in many coastal Indigenous societies since the immemorial period. However, as sea acidity boosts and permits shellfish reduction, the flow of learning from seniors to childhood becomes disrupted. "The Governor's Marine Resources Advisory Council" was created in "Washinton State" to handle the danger of sea acidification in 2013. "The Washington State Legislature" has since funded about $10 million in the research of sea acidification, modelling, and monitoring, with the help of the board. It has helped the shellfish enterprise start adjusting their methods to enhance shellfish survival. It has started promotions to wastewater remedy plants, which will facilitate local nutrient intakes that contribute to acidification.

What is Being Done About It?

A prohibition on plastic bags in "Washinton State" was marked into regulation in 2020, and the regulation came into effect in 2021. A prohibition on the one-time use of plastics will also be implemented in Canada before 2021 (**Cantonati*et al.* 2020**). These measures will help decrease the quantity of microplastics in the sea. Promotions to the "Annacis Island Wastewater Treatment Plant in Delta, B.C." will even take place starting in 2020. This promotion will enhance the power of the works to treat better wastewater and will fix and substitute older regions of the works.

DEFINITION AND PRINCIPLES OF BIOSENSORS

Biosensors are tools that are used for environmental monitoring and can be used to evaluate biological or chemical mixtures of water. These are machines that are used to evaluate the information of living organisms' early responses to environmental stressors and to provide signals on ocean ecosystem harm and pathology due to both natural and artificial pollution **(Navaand Leoni, 2021).**

The biosensor is a type of detection system using typical biomolecule recognition factors, significantly interacting with ocean toxins and discovering the positively sensitive detection of exact signal transformation. Due to the profitability, autorotation, and miniaturization of related tools, biosensors have an appropriate application option for online monitoring and in-field detection **(Koehnken *et al.,* 2020)**. The sensor is formed in an empty carbon electrode changed with carbon microspheres and palladium particles and can reach a precision between 96% ± 1% and 105% ± 3%. A specific biosensor includes a transducer, a display, an analyte, and a bioreceptor.

TYPES OF BIOSENSORS AND THEIR APPLICATIONS

Ocean pollutant perseverance and biosensors present many benefits with specificity, quick response times, and high sensitivity. Some kinds of biosensors are typically used for noticing pollutants in seas with their applications which are

Immunosensors

Antigens and antibodies are immobilized on the surface of the sensor to grab specific contaminants, including a complex of antigen-antibody. Helpful in detecting pollutant levels like pesticides, toxins, and metals, in seawater. **(Majors *et al.,* 2020)**.

Enzyme Based Biosensors

Enzymes like peroxidases, hydrolases, and oxidases are immobilized on the surface of the transducer. Applications contain the detection of organic pollutants like phenols, pesticides, and petroleum hydrocarbons in seawater. **(Da Silva *et al.,* 2022).**

DNA-Based Biosensors

DNA oligonucleotides or strands are immobilized on the surface of the sensor, and differences in their design or exchanges with target contaminants are detected. Good for noticing typical DNA arrangements of genetically or pathogens changed organisms in ocean samples. **(Suslova and Grebenshchikova, 2020)**.

Whole Cell Biosensors

Living cells, such as algae, yeast, and bacteria, are employed as feeling elements. Applications range from observing the seawater's toxicity due to heavy metals, organic pollutants, and pesticides to noticing pathogens in oceanic environments.

Nanomaterial-Based Biosensors

Nanomaterials, such as graphene, nanoparticles, and carbon nanotubes, are operated to improve selectivity and sensitivity.

Aptamer-Based Biosensors

Aptamers, molecules of single-stranded DNA or RNA, are established to bind expressly to target contaminants.

Optical Biosensors

optical properties such as surface plasmon resonance (SPR) and absorbance are operated to notice differences generated by pollutant binding. Good for real-time observation of pollutants like chemical contaminants, microplastics, and oil spills in seawater.

These biosensors discover applications in different areas of ocean pollution observation, including evaluating the effect of human movements, detecting pollutants in aquaculture, and protecting ocean ecosystems and general health **(Villalobos *et al.,* 2020)**. Additionally, progressions in remote sensing, nanotechnology, and miniaturization are directed to the growth of transportable and independent biosensor designs appropriate for in-situ monitoring of sea pollutants.

Pollution of heavy metals is often removed as an anthropogenic result, and activities of industry and their corruption threaten the environment and human health. Elements like Cu, Mn, Zn, and Fe, then highly toxic As, Hg, Cr, Cd, Pb, etc, are extremely immune to biodegradation. Heavy metals are enchanted into the atmosphere, particularly water sources, and efficiently fascinated by living organisms **(Baronas et al. 2021)**. For their apparent toxicity, these heavy metals are essential for observing the atmosphere. Observing water contamination is vital for environmental protection and the deterrence of conditions. For the collection in the atmosphere and nature, such as animals and plants, heavy metals create a threat over a long time. Many techniques have been created to notice their engagements and existence in the matrix of the environment. Specifically, biosensors can notice the heavy metal levels and resolve how much corruption they caus. Biosensors can efficiently notice the existence of heavy metals to control and operate water quality and safety **(Sezginturk, 2020)**. The whole-cell biosensors represent a future strategy for the detection of heavy metals and are required for sensitivity and selectivity. Furthermore, biosensors can be combined into pollutants direction and operated to forecast chemical pollution in the atmosphere.

ORGANIC POLLUTANTS MONITORING

Anthropologic activities confirm that organic contaminants pollute the natural atmosphere. A broad range of pollutants develops from various household, agricultural, and industrial activities. Agricultural waste pesticides and organic herbicides include toxic mixes mostly discovered in wastewater, and the mixtures are broadly used to extract pests' unwanted vegetation and weeds. "Persistent organic pollutants (POPs)", including "polybrominated biphenyls (PBBs)", "phthalate esters (PAEs)", "polybrominated diphenyl ethers (PBDEs)", "polychlorinated biphenyls (PCBs)", and other dangerous contaminants exist in industrial wastewater **(Alin *et al.,* 2023).** Observing the particular organic topic in wastewater is an essential element of the environment and human health, especially water reclamation methods and wastewater treatment. Biosensor applications for noticing organic pollutants in wastewater receive the quickest and most precise effects compared to different traditional methods.

Wastewater quality monitoring and environmental viability

Biosensors offer stimulating solutions for observing sea pollutants, but many challenges continue, along with appearing locations for future growth. There are some challenges and future directions in the biosensors for seas:

Durability and Stability: Biosensors deployed in sea atmospheres must resist harsh situations such as temperature variations, biofouling, and salinity. Producing full protective coatings and sensor materials to provide long-term equilibrium and implementation is crucial.

Sensitivity and Selectivity: Enhancing the selectivity and sensitivity of biosensors to notice low attention of contaminants amidst the complicated matrix of seawater remains a challenge. Future investigations should focus on improving the particularity of biological distinction elements and producing creative signal amplification methods **(Tetyana *et al.,* 2021).**

Biofouling Mitigation: Biofouling, the collection of algae, microorganisms, and different ocean organisms on the surface of the sensor, can interfere with sensor implementation over time. Research measures may concentrate on creating antifouling materials and techniques to resolve this issue.

Real-Time Monitoring: Improvements in data processing strategies and sensor technologies are required to allow real-time observation of sea pollutants. Wireless transmission and small sensing abilities can enable continuous data communication and analysis.

Emerging contaminants: Continuously observing and noticing emerging contaminants in seawater, such as pharmaceuticals, personal care products, and microplastics, creates new challenges that need creative sensor techniques and detection procedures **(Bhattarai and Hameed, 2020)**.

Managing these challenges and increasing the abilities of biosensors for seas will need interdisciplinary collaborations concerning researchers from fields like biology, materials science, oceanography, chemistry, and engineering. Moreover, expanded funding help and assets in ocean technologies for monitoring are essential for driving the creation and summarizing of research results into practical explanations for conservation efforts and environmental management.

SUMMARY

This chapter offered an overview of Limnology and the Science of Biosensors of the ocean.

- It presents an overview of the freshwater ecosystem and its characteristics. It also represents the importance of water quality monitoring in limnology and Ocean Acidification in the Salish Sea.
- Different types of biosensors like immunosensors, whole Cell Biosensors, Optical Biosensors, DNA-Based Biosensors, and Enzyme based biosensors have been found.
- The application of biosensors in limnology, wastewater quality monitoring, and environmental viability are also discussed.

It has been concluded that the use of biosensors to detect ocean pollutants is easier. This detection via biosensors sensors indicates that proportions and detection earlier can support reducing the damaging effects of dangerous pollutants in seas.

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Chapter 13
Biosensors for Environmental Monitoring

Rajni Gautam
K.R. Mangalam University, India

ABSTRACT

Environmental monitoring is essential to safeguard our planet's ecosystems, public health, and natural resources. Biosensors have emerged as powerful tools for assessing environmental parameters due to their sensitivity, specificity, and versatility. From the detection of pollutants to the monitoring of water and air quality, biosensors offer a wide array of applications that contribute to comprehensive environmental assessment. In this chapter, the principles, applications, and significance of biosensors in the context of environmental monitoring are explored in detail. Future prospects and challenges are discussed as well.

INTRODUCTION

Biosensors are analytical devices that play a pivotal role in environmental monitoring, offering the capability to detect and quantify specific analytes in the environment. These biosensors function through a combination of biological recognition elements and transducers, which work synergistically to provide accurate and reliable data in environmental monitoring applications (Huang et al., 2023) as shown in Figure 1.

Biosensors employ biological recognition elements such as enzymes, antibodies, DNA, or whole cells. Based on the target analyte of interest in environmental monitoring, these components have been carefully chosen. For example, enzymes are frequently used in biosensors to catalyze particular interactions with molecules of interest or environmental contaminants, including pollutants in the air or water. Conversely, antibodies are useful for identifying diseases or allergens in a variety of environmental samples due to their high specificity in identifying certain antigens. In order to help with the assessment of biodiversity and the existence of genetically modified species, DNA-based identification elements are able to identify genetic material from microorganisms in soil or water. The physiological reactions of whole cells, usually bacterial strains or microorganisms, to environmental changes are monitored,

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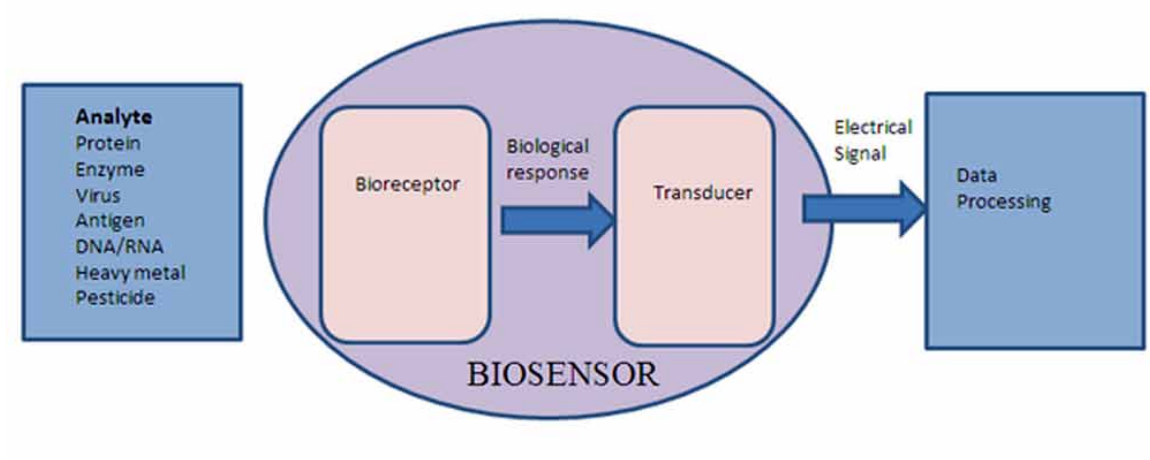
Figure 1. Components of a biosensor



which makes them adaptable for detecting a variety of analytes in environmental samples (Geng et al., 2017; Justino et al., 2017).

Another essential part of biosensors are transducers, which turn the biological response produced by the recognition element into a signal that can be measured. Transducers are frequently made with optical or electrical systems interfaces when used in environmental monitoring applications For example, electrochemical transducers can produce an electrical signal in response to the interaction between the recognition element and the analyte. To identify the presence of the target analyte, optical transducers may rely on variations in light absorption, fluorescence, or luminescence (Pohanka, 2018). These transduction processes are necessary for distant sensing, real-time data provision, and continuous monitoring of pollutants and environmental conditions.

The sensitivity and specificity of biosensors are of utmost importance when detecting trace amounts of environmental contaminants accurately. High sensitivity allows for the detection of analytes at low concentrations, which is crucial when monitoring pollutants or microorganisms in the environment. Specificity ensures that the biosensor responds only to the target analyte, minimizing false-positive results (Hashem et al., 2018). Achieving these qualities involves optimizing both the biological recognition elements and the transduction mechanisms. Selection of the appropriate recognition element with high affinity for the target analyte and engineering transducers for optimal signal amplification are key considerations to enhance sensitivity and specificity (Justino et al., 2017; Pohanka et al., 2018).

In the food industry, bisensors are integral for monitoring both temperature and humidity levels in storage facilities (Kryuk et al., 2023), ensuring optimal conditions for food preservation and safety. In the pharmaceutical industry, they play a crucial role in quality control by simultaneously measuring parameters like pH and conductivity during drug manufacturing processes, ensuring product consistency and efficacy (Polshettiwar et al., 2021). In biomedicine and healthcare (Mohankumar et al., 2021), bisensors are utilized for real-time monitoring of physiological parameters such as glucose levels and blood pressure, enabling precise diagnosis and personalized treatment regimens. In industrial settings, bisensors contribute to process optimization by monitoring variables like pressure and flow rate simultaneously, enhancing efficiency and product quality in manufacturing operations (Kišija et al., 2020). These applications demonstrate the versatility and importance of bisensors in enabling multifaceted monitoring and control across various sectors.

Biological recognition components and transducers are used by biosensors for environmental monitoring to identify and measure particular analytes in environmental samples. Enzymes, antibodies, DNA, and entire cells are examples of recognition elements that offer selectivity by interacting with specific substances or microorganisms, guaranteeing the biosensor's capacity to target particular environmental contaminants. Transducers are frequently made to connect with optical or electronic systems for real-time data collection and remote sensing. They do this by converting the biological reaction into a measurable signal. Accurate detection depends on sensitivity and specificity, which are optimized by carefully choosing and designing the transduction mechanisms and recognition elements. Biosensors are still essential to environmental monitoring because they help us recognize environmental problems and find solutions.

TYPES OF BIOSENSORS FOR ENVIRONMENTAL MONITORING

Enzymatic Biosensors

Enzymatic biosensors, a prominent category of biosensors, are widely employed in environmental monitoring due to their capacity to detect a diverse range of environmental parameters. These biosensors are instrumental in assessing parameters such as biochemical oxygen demand, heavy metals, and organic pollutants, making them indispensable tools for environmental researchers and regulators.

One of the key features that render enzymatic biosensors particularly valuable for environmental monitoring is their ability to capitalize on enzymatic reactions. Enzymes, as biological recognition elements, exhibit high specificity for particular substrates. When applied to environmental analysis, enzymes catalyze reactions with the target analytes, converting them into detectable signals. This catalytic activity is crucial for the accurate and selective measurement of various environmental parameters. For instance, in monitoring BOD, enzymes like glucose oxidase are used to catalyze the oxidation of organic compounds, generating a measurable electrochemical signal (Radhakrishnan et al., 2022). In this context, the enzyme's activity is directly proportional to the concentration of organic material in the water, providing a quantitative assessment of water pollution.

Additionally, enzymatic biosensors are widely utilized in the detection of heavy metals in environmental samples. Heavy metals, such as lead, cadmium, and mercury, can have severe ecological and health impacts when present in elevated concentrations. Enzymatic biosensors, leveraging the specificity of enzymes for certain metal ions, are capable of detecting these contaminants at low levels. For instance, the enzyme alkaline phosphatase can be used in biosensors to detect heavy metal ions by inhibiting its enzymatic activity in the presence of these ions (Mishra et al., 2018).

Moreover, enzymatic biosensors are essential tools for monitoring organic pollutants in environmental samples. These pollutants can originate from industrial discharges, agricultural runoff, or various human activities, and they can pose significant risks to aquatic ecosystems and human health. Enzymes such as acetylcholinesterase or tyrosinase have been employed to detect specific organic pollutants through enzymatic reactions, producing quantifiable signals proportional to the pollutant concentration (Rai et al., 2016; Li et al., 2023).

Immunological Biosensors

Immunological biosensors represent a critical category of biosensors that are extensively applied in environmental monitoring. These sensors play a pivotal role in recognizing and quantifying specific environmental antigens, including pathogens, toxins, and allergens. Their application is particularly significant in the monitoring of water and air quality, where the identification and quantification of these specific agents are essential for ensuring the safety of ecosystems and public health.

The core principle of immunological biosensors involves the use of antibodies as the biological recognition element. Antibodies exhibit an exceptional degree of specificity in binding to antigens. When applied to environmental monitoring, immunological biosensors can specifically recognize and quantify a range of environmental antigens, offering a high level of selectivity in the process.

In the context of water quality monitoring, immunological biosensors are instrumental in the detection of waterborne pathogens. Pathogenic microorganisms, such as bacteria and viruses, can pose significant threats to human health when present in water sources. Immunological biosensors, equipped with antibodies designed to target specific pathogens, enable the rapid and precise identification of these microorganisms. This is crucial for timely responses to potential disease outbreaks and ensuring safe drinking water (Zhao et al., 2023).

Immunological biosensors also have vital applications in air quality monitoring, particularly in detecting allergens and toxins. Allergens can be found in the air and can lead to respiratory issues, making their detection important for public health. Toxins, such as those produced by mold or harmful airborne chemicals, can pose health risks when inhaled. Immunological biosensors equipped with antibodies specific to these allergens or toxins can accurately detect and quantify their presence, providing data for assessing air quality and mitigating potential health hazards (Aghababai et al., 2022).

These biosensors allow for the accurate identification and measurement of pathogens, poisons, allergens, and other pertinent chemicals by utilizing the high specificity of antibodies for specific environmental antigens. Protecting public health, maintaining ecosystem health, and mitigating possible environmental hazards all depend on this competence.

DNA-Based Biosensors

DNA-based biosensors have gained significant recognition in environmental monitoring due to their unique capability to identify genetic material from environmental microorganisms. These biosensors have proven invaluable in a variety of applications, including the detection of pathogens, genetically modified organisms (GMOs), and the assessment of biodiversity.

One of the primary applications of DNA-based biosensors in environmental monitoring is the detection of pathogens. Pathogenic microorganisms, whether in water sources, soil, or air, can pose serious health risks to humans, animals, and ecosystems. DNA-based biosensors can target specific DNA sequences unique to these pathogens. When environmental samples are tested using these biosensors, they can accurately identify the presence of pathogenic DNA. This capability enables early and precise detection of potential disease outbreaks and helps guide public health measures (Ali et al., 2021).

Another crucial application of DNA-based biosensors is the detection of genetically modified organisms (GMOs). The introduction of GMOs into the environment, whether intentionally or unintentionally, can have ecological and health implications. DNA-based biosensors, by targeting specific DNA sequences characteristic of GMOs, provide a reliable means of identifying their presence in the environment. This is vital for regulatory compliance, biodiversity preservation, and risk assessment (Bennett et al., 2019).

Additionally, DNA-based biosensors are used in biodiversity assessment. Environmental DNA (eDNA) is genetic material shed by various organisms into their surroundings. By analyzing eDNA using DNA-based biosensors, researchers can gain insights into the presence and diversity of species in a given ecosystem. This non-invasive approach has revolutionized biodiversity assessment, allowing for the monitoring of aquatic and terrestrial ecosystems without disturbing the organisms themselves (Deiner et al., 2017).

Whole-Cell Biosensors

Whole-cell biosensors represent a cutting-edge and versatile category of biosensors used in environmental monitoring. They utilize live microorganisms, such as bacteria or yeast, as the biological recognition elements, and these organisms are engineered to monitor changes in their physiology in response to exposure to environmental contaminants. These sensors have the unique advantage of being adaptable to detect a wide range of analytes in various environmental samples.

The fundamental principle of whole-cell biosensors is based on the fact that microorganisms respond to the presence of specific analytes by triggering changes in their physiology (Yagi, 2007). These changes can include alterations in gene expression, enzyme activity, or metabolic pathways. By introducing genetic modifications, researchers can tailor the response of these microorganisms to target analytes of interest. This engineering process allows for the creation of biosensors with remarkable specificity and sensitivity, making them suitable for the detection of a wide array of contaminants in the environment (Van der Meer & Belkin, 2010).

One of the key strengths of whole-cell biosensors is their versatility. These sensors can be designed to detect a broad spectrum of environmental analytes, including heavy metals, organic pollutants, toxins, and various chemicals. For example, when engineered to respond to heavy metals, whole-cell biosensors can exhibit changes in fluorescence, bioluminescence, or electrical conductance when exposed to these contaminants (Roggo et al., 2017).

Whole-cell biosensors are particularly valuable in environmental monitoring scenarios where there is a need to assess the presence of multiple analytes simultaneously. For instance, in the context of monitoring water quality, these sensors can be designed to detect various pollutants, providing comprehensive data for assessing the overall environmental health. Their ability to produce real-time, in-situ data makes them indispensable for field applications, where timely responses to environmental changes are crucial.

Optical and Electrochemical Biosensors

Optical and electrochemical biosensors are two major classes of biosensors that find extensive application in the realm of environmental monitoring. These biosensors are capable of detecting a wide range of environmental parameters, including pH, heavy metals, and dissolved gases. Their attributes, such as rapid response times and compatibility with data transmission systems, make them ideal for in-situ and remote monitoring applications.

Optical biosensors rely on the measurement of light-related properties to detect changes in the environment. They offer exceptional sensitivity and are particularly useful for monitoring various environmental parameters (Sharma & Sharma, 2023), (Chen & Wang, 2020).Optical biosensors are frequently used for pH measurements in environmental samples. They function by detecting changes in the absorption, fluorescence, or luminescence properties of indicator dyes in response to alterations in pH. These sensors are valuable for assessing water quality and soil conditions. They can also be engineered to detect heavy metals through the use of specific fluorescent dyes or quantum dots. When heavy metals bind to these recognition elements, they induce changes in the optical properties, allowing for their sensitive and selective detection. Certain optical biosensors can also be designed to detect dissolved gases, including oxygen and carbon dioxide. These sensors utilize luminescent indicators to monitor changes in gas concentrations, making them suitable for applications in environmental science and aquatic research.

Electrochemical biosensors, on the other hand, are based on the measurement of electrical signals generated by biochemical reactions at the sensor's surface. These sensors are known for their high sensitivity, rapid response, and applicability to various environmental parameters (Ariyant et al., 2020),(Cesewski et al., 2020), (Kaya et al., 2021) . Electrochemical biosensors are widely used to monitor pH levels and ion concentrations in environmental samples. These sensors rely on pH-sensitive or ion-selective electrodes that produce electrical signals in response to changes in the sample's ionic composition. They are critical for understanding water quality and soil conditions. They can detect heavy metals through specific redox reactions that occur when the metal ions interact with the recognition elements on the sensor's surface. This capability is essential for assessing contamination levels in water sources. Electrochemical biosensors are also used for monitoring dissolved gases like oxygen, which is crucial for assessing water quality and the health of aquatic ecosystems. These sensors often utilize amperometric or potentiometric techniques to measure gas concentrations.

Both optical and electrochemical biosensors have the distinct advantage of being well-suited for in-situ and remote monitoring. They can be integrated with data transmission systems, providing real-time data, and can be deployed in field applications to assess and respond to environmental changes promptly. This makes them invaluable tools for safeguarding the environment and ensuring the health and sustainability of ecosystems.

APPLICATIONS OF BIOSENSORS IN ENVIRONMENTAL MONITORING

Water Quality Monitoring

Water quality monitoring is a critical aspect of environmental management and public health. Biosensors have emerged as indispensable tools for the assessment of water quality in a variety of settings, including natural bodies of water, wastewater treatment plants, and industrial facilities. These biosensors offer a rapid and accurate means of detecting a wide range of contaminants, ensuring compliance with environmental regulations and safeguarding the health of ecosystems and human populations (Adekunle et al., 2021), (Laad & Ghule, 2023).

Detection of Heavy Metals

Biosensors are frequently used to monitor water quality for heavy metal contaminants. Heavy metals such as lead, cadmium, and mercury can enter water sources through industrial discharges, agricultural runoff, and other sources. Biosensors designed to detect heavy metals employ specific biological recognition elements, such as enzymes or antibodies, that interact with these contaminants. When the heavy metals bind to the recognition element, they induce a change in the sensor's signal, which can be measured quantitatively. This ability to detect heavy metals is crucial for assessing water quality, ensuring regulatory compliance, and protecting aquatic ecosystems (Karthik et al., 2022), (Velusamy, et al., 2022).

Detection of Microorganisms

Water quality monitoring also involves the detection of microorganisms, including bacteria, viruses, and protozoa, which can pose health risks if present in high concentrations. Biosensors designed for microorganism detection use biological recognition elements, often antibodies or DNA probes, which are specific to the target microorganism. These biosensors can provide rapid and sensitive measurements of microbial contamination, enabling the timely response to potential outbreaks of waterborne diseases. They are essential for ensuring the safety of drinking water and recreational water sources (Nayak et al., 2009), (Wang et al., 2017).

Detection of Organic Pollutants

Organic pollutants, such as pesticides, industrial chemicals, and pharmaceuticals, can also enter water sources and impact water quality. Biosensors are well-suited for the detection of these organic contaminants. Enzymatic biosensors, for example, can be engineered to catalyze specific reactions with organic compounds, generating signals proportional to their concentration. This enables the accurate measurement of organic pollutant levels in water samples. It is crucial for assessing the impact of human activities on aquatic ecosystems and the safety of water supplies (Zhao et al., 2021).

Air Quality Monitoring

Air quality monitoring is a crucial component of environmental protection and public health. Biosensors have emerged as essential tools for monitoring air quality by enabling the detection of a wide range of airborne pollutants, including gases, particulate matter, and biological agents. Real-time data generated by these biosensors is invaluable for assessing air pollution and implementing mitigation strategies.

Detection of Gases

One of the primary applications of biosensors in air quality monitoring is the detection of gases. Various gases, including common air pollutants such as carbon monoxide (CO), nitrogen dioxide (NO2), sulfur dioxide (SO2), and volatile organic compounds (VOCs), can have adverse effects on human health and the environment. Biosensors, equipped with specific recognition elements that interact with these gases, provide rapid and sensitive measurements. When these gases bind to the recognition elements, they induce changes in the sensor's signal, which can be quantified. This real-time data allows for the timely assessment of air quality and the implementation of measures to reduce exposure to harmful gases (Sokhi et al., 2022), (Usman et al., 2023).

Particulate Matter Monitoring

Biosensors are also utilized to monitor particulate matter (PM) in the air. PM includes tiny solid particles and liquid droplets suspended in the air and is categorized based on size, with PM2.5 (particles with a diameter of 2.5 micrometers or smaller) and PM10 (particles with a diameter of 10 micrometers or smaller) being of particular concern due to their potential health impacts. Biosensors, often employing immunological recognition elements, can detect specific proteins or antigens associated with PM. This information helps in assessing the concentration of PM in the air and its potential health effects. Real-time PM data is essential for implementing air quality control measures, particularly in urban areas (Nieckarz et al., 2023).

Biological Agent Detection

In addition to chemical pollutants, biosensors can be engineered to detect biological agents in the air, such as bacteria, viruses, and allergens. These agents can have implications for public health, particularly in indoor environments or healthcare facilities. Biosensors equipped with antibodies or DNA probes specific to these agents enable the rapid identification and quantification of biological contaminants in the air. This capability is vital for implementing infection control measures and ensuring the safety of indoor air quality (Jakupciak et al., 2009).

Soil and Agriculture

In agriculture, biosensors have become invaluable tools for monitoring soil health and optimizing crop management practices. These sensors are designed to detect various parameters related to soil quality, nutrient levels, and the presence of contaminants, ultimately contributing to sustainable and environmentally friendly agricultural practices.

Soil Health Monitoring

Biosensors play a vital role in assessing soil health, which is essential for maintaining soil fertility and productivity. Soil health parameters, such as pH, electrical conductivity, and organic matter content, can be measured using biosensors (Archeka et al., 2022), (Mandal, et al., 2020). These sensors often employ enzymatic or microbial recognition elements that react with specific soil components. Monitoring these parameters helps farmers and agricultural researchers make informed decisions about soil management practices, including soil amendment and fertilization.

Nutrient Level Detection

Nutrient monitoring is a crucial aspect of agriculture, as it allows for precise nutrient management and reduces the risk of over-fertilization (Sempionatto, et al., 2020). Biosensors can detect essential nutrients such as nitrogen (N), phosphorus (P), and potassium (K) in the soil. By providing real-time data on nutrient concentrations, these sensors enable farmers to adjust their fertilizer application rates based on the specific needs of their crops. This not only maximizes crop yield but also minimizes nutrient runoff into water bodies, mitigating environmental pollution.

Contaminant Detection

Agricultural biosensors are also employed to detect contaminants in the soil, such as pesticides, heavy metals, and organic pollutants. Pesticide biosensors, for instance, utilize enzymes or antibodies to detect the presence of specific pesticides in soil samples (Zhao, et al., 2015). This information allows farmers to assess the impact of pesticide use on soil quality and make informed decisions about pesticide application (Xie et al., 2022).

FUTURE PROSPECTS AND CHALLENGES

Biosensor technology has made significant strides in various fields, from healthcare to environmental monitoring. Looking ahead, several prospects and challenges are likely to shape the future of biosensors:

Miniaturization and Integration

Miniaturization of biosensors will continue, enabling the development of portable and wearable devices for real-time monitoring. Integration with other technologies, such as microfluidics, nanomaterials, and wireless communication, will further enhance the capabilities of biosensors (Liu et al., 2020). Miniaturization raises challenges in terms of signal amplification and robustness, as smaller sensors may be more susceptible to interference and require improved signal processing techniques .

Multi-Parameter Sensing

The ability to measure multiple parameters simultaneously is a promising avenue. Multi-parameter biosensors will offer a comprehensive view of complex systems, be it in healthcare diagnostics or environmental monitoring, leading to more accurate and actionable data (Pérez-López et al., 2011). Designing biosensors that can efficiently detect and differentiate multiple analytes without cross-reactivity remains a challenge. Ensuring the reliability and specificity of multi-parameter sensors is essential (Choi et al., 2019).

Data Management and Analysis

Advanced data analysis techniques, including machine learning and artificial intelligence, will be integrated with biosensors to extract meaningful insights from complex datasets. This will enhance the predictive and diagnostic capabilities of biosensors (Hasanzadeh et al., 2017). Handling, storing, and securing large volumes of data generated by biosensors can be challenging. Data privacy and ethical concerns will also need to be addressed (Fan et al., 2023).

Standardization

Standardization in biosensor development will ensure the reproducibility and reliability of results. Internationally recognized standards can facilitate regulatory approvals and promote wider adoption of biosensor technology (Liu et al., 2021). Establishing global standards that encompass the diverse range of biosensors and applications can be complex. Coordination among regulatory agencies and research communities is needed.

CONCLUSION

Biosensors have become essential instruments for environmental monitoring, enabling us to monitor and alleviate the effects of pollutants, pollutants, and climate change on Earth. Their ongoing advancement and integration with state-of-the-art technology portend a time when we may rely on real-time, high-quality data to support biodiversity conservation, environmental protection, and the sustainability of our natural resource base. This chapter gives an extensive review of working phenomena, types and applications of biosensors for environmental applications. Future prospects and challenges are also discussed to pave the path for better, cleaner environment.

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Chapter 14
Advances in Sensor Technologies for Detecting Soil Pollution

Ranjit Singha
https://orcid.org/0000-0002-3541-8752
Christ University, India

Surjit Singha
https://orcid.org/0000-0002-5730-8677
Kristu Jayanti College (Autonomous), India

V. Muthu Ruben
https://orcid.org/0009-0006-7723-8596
Christ University, India

Alphonsa Diana Haokip
https://orcid.org/0000-0003-2578-0114
Christ King High School, India

ABSTRACT

The present chapter elucidates progressions in the surveillance of soil pollution, with a specific emphasis on integrated systems and sensor technologies. Future trends (e.g., enhanced selectivity, regulatory adoption), deployment platforms (field-deployable, wireless networks), and sensor types (electrochemical, optical, and biosensors) are discussed. Increasing sensitivity and specificity, facilitating on-site, real-time analysis, and integrating sensing with remediation strategies are priorities. The discourse highlights the revolutionary capacity that soil pollution sensors possess to propel environmental monitoring and management forward. Collaboration among stakeholders is critical for successfully implementing sensor-based approaches and driving innovation.

INTRODUCTION

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Globally, soil contamination by inorganic and organic contaminants is a significant environmental concern. Due to industrial activities and improper waste disposal, soils have become contaminated with numerous hazardous substances, such as emerging contaminants, pesticides, heavy metals, and hydrocarbons. Ingestion or direct exposure to these soil contaminants may result in severe health hazards for humans, including diminished soil fertility, groundwater and crop contamination, and accumulation in the food chain. So, quickly, cheaply, and accurately finding soil contaminants is very important for describing sites, keeping track of contamination levels, and judging how well cleanup efforts are working (He & Cai, 2021; Zaghloul et al., 2019). Gas chromatography and mass spectrometry are conventional analytical methods for measuring soil pollutants, are costly, time-consuming, and offer limited spatial information. Recent developments in sensor technologies hold significant potential for enhanced in-situ and real-time monitoring and detection of soil pollution. These sensors can identify and quantify contaminants in soil samples using sensing mechanisms, including optical, electrochemical, biological, and physical processes. These devices are well-suited for field applications and continuous monitoring due to their portability, affordability, rapid response times, and high sensitivity (Abdulraheem et al., 2023; Nadporozhskaya et al., 2022).

This chapter examines recent advancements in sensor technologies for detecting soil pollution, focusing on their operating principles, performance characteristics, applications, and challenges. This study aims to look into what could be done by connecting sensors to wireless communication networks, data acquisition systems, and geographic information systems (GIS) to make it easier to map out soil contamination and keep an eye on it from afar. Furthermore, the paper will examine the potential of sensor networks and drones to augment the resolution and spatial coverage of monitoring initiatives about soil pollution. The chapter endeavours to underscore the significance of sensor technologies in furthering our comprehension of the dynamics of soil contamination and bolstering the efficacy of environmental management approaches. Various human activities, including industrial operations, agricultural methods, and inadequate refuse management, cause substantial soil pollution, a significant global environmental issue. Soil contamination by various substances, such as organic pollutants, pesticides, and heavy metals, can harm ecosystem health, agricultural output, and human welfare. The assessment of contamination levels, identification of pollutant sources, and implementation of remediation strategies to mitigate environmental impacts all rely heavily on the efficacy of soil pollution monitoring (Cui et al., 2021). Theoretical underpinnings for soil pollution monitoring comprise engineering, chemistry, environmental science, and biology principles. It involves comprehending the mechanisms by which pollutants degrade in soil matrices, including adsorption, leaching, and microbial degradation. Theoretical models and concepts from these disciplines guide the design and development of sensor technologies, data analysis techniques, and remediation strategies to tackle soil pollution challenges.

Soil pollution monitoring integrates data analytics, sensor technologies, and environmental management strategies. Sensors equipped to identify a diverse array of contaminants in soil samples, along with data processing algorithms that decipher sensor data and pinpoint areas of high pollution, are utilized in the process. Monitoring soil contamination requires knowledge to formulate environmental management strategies, such as land use planning and remediation techniques, to alleviate environmental hazards and advance sustainable land management approaches. Monitoring soil pollution to determine the source of pollutants, identify the extent and severity of contamination in soil environments, and direct remediation efforts to safeguard human health and ecosystems. Soil pollution monitoring involves developing and deploying sensor technologies to detect pollutants, integrating sensor data with environmental models to assess risks, and implementing remediation and prevention management strategies. The objective is to develop an all-encompassing structure for proactively managing soil contamination that considers human health and environmental sustainability.

TYPES OF SOIL POLLUTANTS AND THEIR ENVIRONMENTAL IMPACTS

Soil pollution is caused by various contaminants, each with distinct environmental consequences. Industrial operations, agricultural methodologies, and urban effluent frequently contribute to the infiltration of heavy metals, including arsenic, cadmium, lead, and mercury, into the soil. These metals pose significant hazards to both ecosystems and human health. They are capable of causing soil structure degradation, fertility reduction, and microbial inhibition, all of which contribute to stunted plant growth. Moreover, the infiltration of heavy metals into groundwater can contaminate water sources and give rise to critical health concerns. Additionally, the bioaccumulation of heavy metals along the food chain elevates toxicity levels for organisms occupying higher trophic levels (Liu et al., 2022; Nnaji et al., 2023). The extensive use of pesticides for pest control in agriculture and public health exacerbates soil pollution complications. Surface waters are contaminated by runoff and leaching of pesticides, which have detrimental effects on aquatic life. In addition, using pesticides can potentially disturb the communities and biodiversity of soil microbes, impacting the cycling of nutrients and the overall functioning of ecosystems (Raffa & Chiampo, 2021; Sun et al., 2018).

Urban runoff, petroleum hydrocarbons discharged from oil accidents, and industrial operations significantly contaminate soil and groundwater. These compounds exhibit prolonged persistence in soil, thereby presenting hazards to terrestrial ecosystems and organisms. Significant implications may ensue regarding biodiversity (Chen et al., 2023; Stepanova et al., 2022).

The presence of emerging contaminants, such as pharmaceuticals and personal care products, in soil health is a growing concern due to its novelty and growing significance. These substances demonstrate ecotoxicity, can disrupt the endocrine system, and tend to accumulate and persist in the environment. Constant oversight and effective administration are imperative to confront this escalating issue (Bayabil et al., 2022; Pérez-Sirvent & Bech, 2023).

Soil pollutants induce toxicity in humans via diverse mechanisms, resulting in acute poisoning, chronic diseases, and developmental abnormalities. Furthermore, the distribution and mobility of soil pollutants are determined by their intricate fate and transport processes, which are impacted by soil properties, climate, and land use practices. Implementing comprehensive mitigation and environmental preservation strategies to tackle soil pollution is imperative. It is essential to comprehend the intricacies of soil pollution dynamics to protect the well-being of ecosystems and human populations.

CONVENTIONAL ANALYTICAL TECHNIQUES FOR SOIL POLLUTION MONITORING

Traditional analytical methods are fundamental to the surveillance of soil pollution as they provide accurate and consistent methods for identifying and measuring pollutants. The procedure commences with carefully gathering samples and employing augers or corers to guarantee that all samples are present throughout the area of interest. After that, the samples undergo a series of preparatory procedures, including dehydration, sieving, grinding, and digestion, to remove any impurities efficiently before the subsequent analysis. Chromatographic methodologies, including high-performance liquid chromatography (HPLC) and gas chromatography (GC), play a critical role in the separation and quantification of organic pollutants present in soil samples. In heavy metal analysis, spectroscopic methods such as inductively coupled plasma mass spectrometry (ICP-MS) and atomic absorption spectroscopy (AAS) are indispensable.

Soil contamination monitoring can be made more accessible with immunoassay methods like enzyme-linked immunosorbent assay (ELISA), which quickly identifies specific impurities and expands the range of tests that can be used (Eugenio et al., 2020; Singh et al., 2019). However, several obstacles impede the widespread implementation of these methodologies, including the requirement for expensive equipment, specialized expertise, and labour-intensive sample preparation processes. It frequently restricts their availability, especially in settings with limited resources where regular monitoring is critical. However, it is still imperative to utilize these traditional methods to evaluate environmental hazards precisely and devise efficient remediation approaches (Eugenio et al., 2020; Luo et al., 2023). To mitigate these constraints and improve the long-term viability of soil pollution monitoring initiatives, it is critical to expedite the development of alternative techniques that are quicker, less expensive, and easier for users to implement. Allocating resources towards developing novel technologies and methodologies guarantees the ongoing preservation of environmental health and the effectiveness and efficiency of soil pollution monitoring initiatives.

ELECTROCHEMICAL SENSORS FOR HEAVY METALS AND ORGANIC POLLUTANTS

Electrochemical sensors have become indispensable in detecting and monitoring organic pollutants and heavy metals in soil. This is due to their exceptional sensitivity, quick response times, and capability to conduct measurements on-site. Voltammetric sensors stand out among the primary categories of electrochemical sensors because they rely on measuring the current generated by redox reactions at the sensor's surface. Square wave voltammetry (SWV), cyclic voltammetry (CV), and differential pulse voltammetry (DPV) are all standard methods that can be used to measure minimal amounts of pollutants. It is because they are compassionate and have low detection limits. New developments in this field include adding nanomaterials like graphene and carbon nanotubes, which improve sensitivity and selectivity, and making sensor platforms smaller to make them easier to carry and use in the field (Baranwal et al., 2022; Venkateswara Reddy et al., 2023, p. 30). Potentiometric sensors measure potential differences between a reference electrode and an indicator electrode in response to changes in analyte concentration. It has been observed that ion-selective electrodes (ISEs) frequently detect heavy metals in soil samples. Although these sensors provide advantages such as affordability, user-friendliness, and simplicity, their detection limits may be higher than those of voltammetric sensors. Quite recently, there have been significant steps forward in creating wireless and small sensor systems designed for remote monitoring. New materials have also been used to change electrodes to make them more stable and selective (Baumbauer et al., 2022; Zhai et al., 2022).

Amplimetric biosensors are a crucial variety. Biological recognition elements on the sensor's surface selectively locate target analytes. Enzymatic biosensors have demonstrated the ability to detect organic pollutants in soil samples. The biological recognition element's affinity for the target analyte determines these sensors' substantial specificity and sensitivity. Improvements in microfabrication techniques have enabled the fabrication of more compact and stable biosensor platforms. Furthermore, incorporating nanomaterials has enhanced their sensitivity and capacity for detecting a more comprehensive range of substances (Islam et al., 2023; Kratasyuk et al., 2021). Electrochemical sensors rely on their selectivity, reproducibility, and detection limits. While most voltammetric sensors have low detection limits, some can identify pollutants at concentrations as low as sub-ppb. Surface modification techniques such as molecularly imprinted polymers or selective coatings on electrode surfaces can increase selectivity. The reliability of monitoring is contingent upon reproducibility, and recent developments in sensor fabrication and calibration techniques have enhanced the reproducibility of electrochemical measurements.

Utilizing nanomaterials and microfabrication techniques has significantly improved the functionality and practicality of electrochemical sensors. The utilization of microfabrication methods such as photolithography and microfluidics has enabled the creation of sensor platforms that are more compact, portable, and capable of seamless integration. Furthermore, incorporating nanomaterials—including graphene, metal nanoparticles, and carbon nanotubes—has improved sensors' sensitivity, selectivity, and stability. This has facilitated the advancement of multi-analyte sensor arrays, which can simultaneously detect multiple pollutants in soil samples. Electrochemical sensors offer adaptable and pragmatic solutions for monitoring soil contamination, and their effectiveness in environmental monitoring has significantly improved recently.

OPTICAL SENSORS BASED ON FLUORESCENCE, COLORIMETRY, AND SPECTROSCOPY

The advent of optical sensors utilizing fluorescence, colourimetry, and spectroscopy signifies a significant advancement in monitoring soil contamination. These sensors' remarkable sensitivity, selectivity, and portability primarily contribute to this progress. These sophisticated sensing technologies provide an array of functionalities that empower environmental agencies and researchers to identify and measure soil pollutants with unprecedented efficiency. For example, fluorescence sensors utilize the distinctive characteristic of fluorophores, which is their ability to emit light when excited. This enables the precise detection of specific analytes. Quantum dots and metal-organic frameworks (MOFs) have become frontrunners in this field because of their adaptable characteristics, which permit customized reactions to particular pollutants. Scientists can fabricate fluorescence sensors with improved sensitivity and selectivity using these materials. As a result, these instruments have become indispensable in identifying diverse contaminants present in soil samples.

In contrast, colourimetric sensors detect the presence of analytes through discernible colour changes. Researchers frequently functionalize gold nanoparticles with particular ligands to build numerous colourimetric sensing platforms. These nanoparticles enable the swift and dependable detection of target contaminants. The simplicity and user-friendliness of this method render it appropriate for on-site analysis without intricate instrumentation.

Surface-enhanced Raman spectroscopy (SERS) is an innovative technology for monitoring soil contamination. Nanostructured metal surfaces are used to boost Raman scattering signals in SERS, which gives it a great mix of sensitivity and specificity. This allows for the precise detection and measurement of trace-level contaminants present in soil samples. The attribute mentioned above renders SERS notably advantageous in identifying low-concentration pollutants, including specific organic compounds and heavy metals (Li et al., 2013; Yang et al., 2021).

This new combination of smartphone scanners and miniature spectrometers has also changed how on-site analysis is done, making it possible for scientists to quickly check for soil contamination without using expensive lab equipment. This development enables stakeholders to gather data more efficiently and cost-effectively by improving accessibility and scalability in soil pollution monitoring initiatives (Tobiszewski & Vakh, 2023). Optical sensing technologies provide adaptable and functional solutions for detecting soil pollutants, thereby making substantial strides in environmental monitoring. These technologies establish a solid groundwork for sustainable ecological stewardship by facilitating the prompt and accurate identification of contaminants, vital for protecting ecosystems and human populations. Electrochemical sensors have become indispensable in detecting and monitoring organic pollutants and heavy metals in soil. This is due to their exceptional sensitivity, quick response times, and capability to conduct measurements on-site. Voltammetric sensors stand out among the primary categories of electrochemical sensors because they rely on measuring the current generated by redox reactions at the sensor's surface. Square wave voltammetry (SWV), cyclic voltammetry (CV), and differential pulse voltammetry (DPV) are all standard methods that can be used to measure tiny amounts of pollutants. This is because they are susceptible and have low detection limits. New developments in this field include adding nanomaterials like graphene and carbon nanotubes, which improve sensitivity and selectivity, and making sensor platforms smaller to make them easier to carry and use in the field (Baranwal et al., 2022; Venkateswara Reddy et al., 2023, p. 30).

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BIOSENSORS UTILIZING BACTERIA, ENZYMES, ANTIBODIES, AND APTAMERS

The utilization of biosensors comprising microbes, enzymes, antibodies, and aptamers has significantly transformed the domain of soil pollution monitoring due to their exceptional sensitivity, specificity, and versatility attributes. (Bae et al., 2020) These cutting-edge instruments have surpassed conventional analytical techniques by offering a comprehensive method for identifying and measuring various contaminants in soil environments. To detect target analytes, whole-cell biosensors utilize the metabolic activity of living cells, such as yeast or bacteria. By integrating reporter genes, these biosensors facilitate continuous monitoring of contaminants, such as pesticides, organic compounds, and heavy metals. By capitalizing on the intrinsic biological mechanisms of microorganisms, it is possible to achieve precise and sensitive identification, even in intricate environmental matrices. Enzyme-based biosensors detect pollutants in soil by utilizing the catalytic properties of enzymes such as oxidases and dehydrogenases. Due to their remarkable sensitivity and specificity, these biosensors are essential for accurately identifying contaminants. The discernible signals generated by the enzymatic reactions of these biosensors offer valuable information regarding the concentrations and dynamics of pollutants in soil environments.

Leveraging the specific binding affinity between target analytes and antibodies, immunoassays are an additional potent instrument for monitoring soil contamination. Adaptable to contaminants, including heavy metals, pesticides, and organic pollutants, immunoassays feature exceptional specificity and breadth. Immunoassays offer dependable and robust detection capabilities by utilizing the immune system's inherent capacity to identify and bind to particular molecules. In the context of biosensors, deoxyribonucleic acid (DNA/RNA) aptamers function as recognition elements by binding with high affinity and specificity to target molecules. The aptamers provide the benefit of easy synthesis and modification, allowing for a wide range of applications in monitoring soil contamination. Aptamer-based biosensors, which take advantage of the unique characteristics of nucleic acid molecules, are an effective method for detecting contaminants in soil (Flores-Contreras et al., 2022; McConnell et al., 2020). As a group, these biosensors symbolize a fundamental change in environmental monitoring, as they permit the precise and efficient detection of soil pollutants in real-time and at the location of the incident. Their implementation signifies a substantial progression in ecological preservation and management endeavours, guaranteeing the safeguarding of ecosystems and human health while proactively mitigating soil contamination. Using the interplay between biology and technology, biosensors facilitate the establishment of a more sustainable ecological guardianship system and an improved planet for subsequent generations.

INTEGRATED SENSOR SYSTEMS AND NETWORKS FOR REAL-TIME ANALYSIS

Soil pollution monitoring has been revolutionized by implementing integrated sensor systems and networks, which provide invaluable insights and real-time analysis of environmental contamination. By precisely manipulating and analyzing small volumes of fluid, microfluidics and lab-on-a-chip devices have revolutionized the field, enabling rapid and high-throughput capabilities ideal for on-site soil pollution monitoring. These devices would allow scientists to conduct a wide range of analytical procedures in a compacted form, which decreases the amount of sample and reagent required for the analysis and improves its speed and sensitivity. Additionally, the portability of these instruments allows for immediate analysis at the collection location, eradicating the necessity for sample transportation and deployment in the field (Smolka et al., 2016). Installing wireless sensor networks (WSNs) is essential for continuously collecting data on environmental conditions across vast geographical areas. WSNs, which consist of spatially dispersed autonomous sensors, utilize wireless communication to monitor ecological parameters, soil properties, and pollutant concentrations across enormous tracts of land. Through real-time data transmission and collection, WSNs afford environmental agencies and researchers a holistic comprehension of the dynamics of soil pollution. This empowers them to implement management strategies and intervene opportunely (Le et al., 2023; Lloret et al., 2021).

Remote sensing technologies, including aerial drones and satellite imagery, are crucial in surveilling soil contamination through acquiring high-resolution spatial data. These technological advancements enable scientists to identify alterations in soil characteristics, vegetation vitality, and land utilization patterns linked to pollution. In contrast to satellite imagery, which provides a broad spatial scope, aerial drones offer precise, localized data. Abdulraheem et al. (2023) describe them as complementary instruments that monitor hotspots of soil contamination and evaluate environmental impacts on a large and small scale, respectively. Proximal soil sensing is an approach that employs sensor-equipped mobile platforms to collect comprehensive data on soil characteristics and contaminants at the surface. These platforms, which may consist of portable devices or tractors, facilitate researchers' direct data collection from the soil surface. This capability permits the accurate characterization of pollution levels and soil conditions. Proximal soil sensing techniques yield significant data that can be utilized to discern areas with high pollution concentrations, track temporal trends, and determine the order of importance for remediation endeavours. GIS is an exceptionally potent instrument that facilitates integrating and examining data derived from diverse origins, such as soil sampling, sensor networks, and remote sensing. Through the spatial visualization of soil pollution data and the superimposition of pertinent information, including topography and land use patterns, GIS enables environmental managers and researchers to precisely delineate and identify areas of high pollution. By conducting this spatial analysis, well-informed decisions can be made and targeted remediation strategies can be implemented to prevent soil pollution, protect ecosystems, and ensure human health. Integrated sensor systems and advanced analytics enable proactive soil pollution monitoring management strategies. Technology advancements such as real-time data collection, spatial visualization, and actionable insights improve environmental stewardship and significantly contribute to preserving ecosystems and human health.

TRENDS AND FUTURE OUTLOOK ON SOIL POLLUTION SENSORS

Researchers are currently focusing on critical aspects such as field deployability, selectivity, and sensitivity in the ongoing developments of soil pollution sensors, which hold great promise for their future. Advancements in materials, specifically molecularly imprinted polymers and nanomaterials, possess significant promise for enhancing the performance of sensors. Nanomaterials have unique properties, such as a high surface area to volume ratio and surface chemistry that can be changed. These properties can make sensors better at finding specific pollutants while also making it less likely that they will react with background contaminants. Instead, molecularly imprinted polymers have a recognition element that is molecularly selective and specific to a given analyte. This ensures the analyte is correctly identified even when many other things are happening around it. Advancements in signal amplification methodologies and algorithms for processing sensor signals are poised to enhance the sensitivity of soil pollution sensors. By substantially amplifying the detection signal, signal amplification techniques such as enzymatic signal amplification and nanoparticle-based signal enhancement permit the detection of pollutants at even lower concentrations. Sophisticated signal processing algorithms such as machine learning and artificial intelligence enhance the precision and dependability of pollutant detection by efficiently examining intricate sensor data.

The need for real-time, on-site soil contamination monitoring motivates the trend toward field-deployable sensor platforms, particularly in remote or resource-constrained regions. Portable and rugged sensor devices, like integrated sensor networks and mobile devices, make it easy and inexpensive for stakeholders to assess soil pollution thoroughly. These field-deployable platforms enable stakeholders, including environmental agencies, researchers, and others, to promptly collect practical data that can be utilized to make informed decisions and proactively manage pollution. In addition, endeavours to establish uniformity in sensor methodologies and technologies are vital to guaranteeing extensive implementation and regulatory approval. Standardized protocols for sensor calibration, validation, and data interpretation will ensure that measurements made with sensors are reliable, comparable, and repeatable across various platforms and applications. Regulatory bodies increasingly acknowledge the significance of sensor-based monitoring in environmental assessment and management. As a result, they have established guidelines and frameworks to streamline the incorporation of sensor data into regulatory decision-making procedures.

Integrating sensing technologies with remediation strategies is encouraging for effectively addressing soil pollution issues. Adaptive management strategies and sensor-guided remediation techniques using sensor-based feedback could help cleanup efforts by focusing on specific polluted areas and monitoring how healthy treatments are always working. An integrated approach can enhance pollution remediation efforts by executing them more efficiently and cost-effectively while reducing environmental impact and protecting ecosystems and human health. Standardization, regulatory acceptance, selectivity, sensitivity, field deployability, and integration with remediation technologies will improve proactive soil pollution monitoring and management. Regulatory agencies, industry stakeholders, and researchers will collaborate to propel the successful integration of sensor-based methodologies for soil pollution management. By applying state-of-the-art sensor technologies and interdisciplinary cooperation, it is possible to tackle soil pollution issues efficiently while positively contributing to environmental sustainability and human welfare.

DISCUSSION

When deliberating on soil pollution sensors, it is critical to recognize the complex and diverse characteristics of soil pollution and the imperative for all-encompassing monitoring approaches. Even though it is essential to make improvements in selectivity, sensitivity, and field deployability, the problem of soil contamination is very complicated and needs a whole-systems approach that looks at contaminant sources, transport mechanisms, and ecosystem interactions, among other things. An essential element to contemplate is the fluidity of soil contamination, which is susceptible to temporal and spatial fluctuations attributable to influences such as alterations in land use, weather patterns, and human activities. Hence, it is critical to establish sensor networks that can continuously monitor and collect data across extensive geographical regions to comprehensively capture the dynamics of soil pollution. By incorporating information from these networks into models, we can gain significant insights into contamination sources by predicting the pathway and destiny of pollutants. Community engagement and citizen science are essential components of soil pollution monitoring initiatives. Granting training programs and sensor technologies to local communities facilitates their active engagement in data collection and decision-making procedures, cultivating a sense of ownership and responsibility towards environmental stewardship. Citizen-generated data has the potential to supplement official monitoring endeavours by bolstering soil pollution assessments with supplementary spatial and temporal coverage.

Furthermore, as we contemplate the future, data analytics and machine learning progress presents the potential for extracting significant insights from extensive quantities of sensor data. Using these technologies, it is possible to discern correlations, patterns, and trends in soil pollution data that might need to be more readily discernible using conventional analytical techniques. This data-driven approach enables the implementation of proactive management strategies, including early warning systems for contamination events or targeted remediation efforts in high-risk areas. We can better understand ecosystem resilience and health by integrating soil pollution sensors into broader environmental monitoring systems, such as those used for monitoring air or water quality. By situating soil pollution within interconnected environmental systems, we can develop more effective strategies for promoting sustainable land management practices and mitigating pollution impacts. Soil pollution sensor technology is crucial in combating environmental issues and safeguarding ecosystems and human well-being. We can lay the foundation for a future that is more resilient and sustainable through the adoption of a holistic approach to monitoring and management, the promotion of collaboration, and the embracement of innovation.

CONCLUSION

Soil pollution is a substantial environmental issue with wide-ranging consequences for ecosystems and human well-being. Throughout this discussion, we have examined numerous facets of soil pollution monitoring, including cutting-edge sensor technologies. Various advanced instruments, including electrochemical and optical sensors and others, provide unparalleled sensitivity, selectivity, and portability levels. As a result, these tools enable stakeholders to detect and mitigate soil contamination with greater efficacy. Additionally, integrating sensor data with remediation strategies enhances the potential for proactively tackling soil pollution challenges. In anticipation of forthcoming developments, ongoing scientific inquiry, technological progress, and cooperative initiatives will be indispensable for guaranteeing environmentally responsible soil management and stewardship.

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KEY TERMS AND DEFINITIONS

Biosensors: Biological sensing devices that employ biological recognition elements, such as enzymes or antibodies, to detect and quantify target analytes, often used in environmental monitoring applications.

Electrochemical Sensors: Instruments that detect analytes by measuring changes in electrical properties, commonly used in soil pollution monitoring for their sensitivity and selectivity.

Emerging Contaminants: Previously unrecognized pollutants or chemicals of concern are becoming increasingly prevalent in the environment, posing potential risks to ecosystems and human health.

Environmental Sensors: Devices designed to detect and measure physical, chemical, or biological parameters in the environment to monitor pollution levels or environmental conditions.

Optical Sensors: Sensors that utilize light-based techniques, such as fluorescence or absorption, to detect and quantify analytes, offering advantages in sensitivity and real-time analysis.

Soil Pollution: Soil contamination by hazardous substances, such as heavy metals or pesticides, harms ecosystems and human health.

Chapter 15
Sensors for Waste Management

Ankur Bhardwaj
https://orcid.org/0000-0003-0687-8810
Department of Life Sciences, Shri Vaishnav Institute of Science, India

Surendra Prakash Gupta
https://orcid.org/0000-0002-4873-6346
Department of Life Sciences, Shri Vaishnav Institute of Science, India

ABSTRACT

The globe is becoming more and more urbanised and industrialised, making waste management an urgent worldwide challenge. Traditional waste management methods have proven to be insufficient in addressing the challenges posed by increasing waste volumes, environmental concerns, and resource scarcity. One potential answer to these problems is the use of sensor technologies in waste management (WM) systems. It explores the various types of sensors used in waste management applications, ranging from simple bin-level sensors to advanced technologies such as remote sensing and IoT-based systems. The chapter also discusses the key advantages of sensor-driven waste management, including improved efficiency, cost reduction, and enhanced environmental sustainability. As WM continues to evolve in response to the demands of the 21st century, this chapter underscores the pivotal role that sensor technologies play in revolutionizing the industry, a glimpse into a more sustainable and efficient future for WM practices worldwide.

INTRODUCTION

In an era where environmental sustainability is paramount, WM stands as a critical battleground. The burgeoning global population coupled with rapid urbanization has amplified the challenges associated with waste disposal and recycling. Traditional WM methods often fall short in effectively addressing these challenges, leading to environmental degradation, public health risks, and economic inefficiencies (Mondal et al., 2023). However, the advent of sensor technology offers a promising avenue for revolutionizing WM practices. By integrating sensors into various aspects of WM systems, we can achieve heightened efficiency, optimize resource allocation, and mitigate environmental impacts.

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Sensors play a pivotal role in modern WM by providing real-time (RT) data and insights across the entire WM cycle. From collection and sorting to processing and recycling, sensors enable precise monitoring and management, thereby optimizing each stage for maximum efficiency. One of the primary areas where sensors make a significant impact is in waste collection. Traditional waste collection methods often follow predetermined schedules, leading to inefficient routes and unnecessary fuel consumption. However, sensor-equipped waste bins can autonomously signal when they reach capacity, enabling waste collection vehicles to prioritize their routes (Szpilko et al., 2023). This dynamic approach not only reduces fuel consumption and emissions but also minimizes the likelihood of overflowing bins, thus enhancing public hygiene and aesthetics.

Moreover, sensors can facilitate waste sorting by accurately identifying recyclable materials within the waste stream. Advanced sensor technologies, such as near-infrared spectroscopy and hyperspectral imaging, can swiftly differentiate between various types of materials, allowing for automated sorting processes (Nanda and Berruti, 2021). By streamlining sorting operations, these sensors improve the efficacy of recycling facilities, thereby increasing the quantity of recyclable materials diverted from landfills.

Furthermore, sensors contribute to the optimization of waste processing facilities by monitoring factors such as temperature, humidity, and gas emissions. By continuously assessing these parameters, sensors can detect anomalies and malfunctions, enabling prompt intervention to prevent operational disruptions or environmental hazards (Mohanty et al., 2022(a)). Additionally, sensors can aid in the extraction of valuable resources from waste streams, such as methane from organic waste or metals from electronic scrap, thus promoting resource recovery and circular economy principles.

In addition to operational efficiencies, sensor technology also enhances the transparency and accountability of WM practices. By providing RT data on waste generation, collection, and disposal, sensors enable stakeholders, including government agencies, municipalities, and WM companies, to make informed decisions and track progress towards sustainability goals. Moreover, the integration of sensors with blockchain technology offers tamper-proof data integrity, ensuring the traceability and authenticity of waste-related transactions (Bahramian et al., 2023).

However, there are several obstacles standing in the way of the broad use of sensor technologies in WM, even with their promise for transformation. The most significant of these is the initial outlay of funds needed to install sensor infrastructure and integrate it with already-in-place WM systems. Additionally, concerns regarding data privacy, cybersecurity, and interoperability must be addressed to ensure the seamless operation and acceptance of sensor-equipped solutions (Martikkala et al., 2023).

Using sensor technology to its full potential throughout the WM cycle, we can move towards a future where waste is viewed not as a burden but as a valuable resource to be managed intelligently and responsibly. Through collaboration between policymakers, industry stakeholders, and technology innovators, we can realize the full potential of sensors in revolutionizing WM practices for the benefit of current and future generations.

SENSORS IN WM

Sensors are devices capable of detecting and measuring various parameters, such as fill levels, temperature, humidity, and even hazardous gas emissions, in real-time. When applied to WM, sensors have the potential to revolutionize the industry in several ways:

(a) **Fill Level Monitoring:** One of the primary applications of sensors in WM is the RT monitoring of waste container fill levels. These sensors are typically installed in trash bins, dumpsters, and recycling containers. By continuously assessing the fill levels, waste collection companies can optimize collection routes, reducing unnecessary trips to empty partially filled containers. This not only saves fuel and reduces emissions but also minimizes wear and tear on collection vehicles (Pardini et al., 2020).

(b) **Predictive Maintenance:** Sensors can also be used for the predictive maintenance of waste collection trucks and equipment. By monitoring the performance and condition of vehicles and machinery, maintenance issues can be identified early, preventing breakdowns and costly repairs (Theissler et al., 2021).

(c) **Environmental Monitoring:** Sensors can detect hazardous substances and emissions from waste sites, helping to ensure compliance with environmental regulations. This is essential for safeguarding surrounding populations and reducing the negative environmental effects of trash disposal (Fatimah et al., 2020).

(d) **Resource Recovery:** In recycling facilities, sensors play a critical role in sorting and separating recyclable materials efficiently. Advanced optical sensors can identify and sort diverse types of materials, such as plastics, metals, and paper, facilitating resource recovery and reducing landfill waste (Krechetov et al., 2019).

(e) **Data Analytics:** The data generated by sensors can be analysed to gain valuable insights into waste generation patterns, trends, and seasonal variations. This data-driven approach enables WM companies to make informed decisions, allocate resources efficiently, and implement targeted waste reduction initiatives (Jiang et al., 2020).

(f) **Smart WM Systems**: The integration of sensors into WM systems allows for the development of "smart" WM networks. These systems use data from sensors to optimize collection routes in real-time, reducing fuel consumption and greenhouse gas emissions. They can also provide residents with RT information on waste collection schedules and encourage responsible waste disposal practices (Pardini et al., 2020).

(g) **Public Engagement:** Sensors can facilitate greater public engagement in WM. Mobile apps and online platforms can provide residents with information on the nearest recycling centres, collection points, and guidelines for responsible waste disposal (Ramírez-Moreno et al., 2021).

While sensors offer numerous advantages in WM, their adoption is not without challenges. These include the initial investment cost, data management and privacy concerns, sensor maintenance, and the need for infrastructure upgrades (Joshi et al., 2022).

Sensors have the potential to revolutionize WM by making it more efficient, cost-effective, and environmentally friendly. By providing RT data and insights, sensors empower WM companies and municipalities to optimize their operations, reduce environmental impact, and engage communities in responsible waste disposal practices (Munir et al., 2023). As technology continues to advance, the integration of sensors into WM systems will likely become increasingly commonplace, contributing to a more sustainable and efficient WM ecosystem.

CHALLENGES IN WASTE MANAGEMENT: THE ROLE OF SENSORS

Waste management is a critical aspect of maintaining environmental sustainability and public health. As urban populations continue to grow and waste generation increases, the challenges in WM become more complex. One innovative solution that has gained prominence in recent years is the use of sensors to optimize waste collection and disposal processes (Martikkala et al., 2023). While sensors hold great promise in transforming WM, they also come with their own set of challenges.

(a) **Cost of Implementation:** One of the primary challenges in adopting sensor-based WM systems is the initial cost of implementation. Installing sensors in waste bins, collection trucks, and waste processing facilities can be expensive. Municipalities and WM companies often face budget constraints that may hinder their ability to invest in sensor technology (Vishnu et al., 2022; Fiorillo and Merkaj, 2024).
(b) **Data Management and Integration:** Sensor-generated data needed to be effectively managed and integrated into existing WM systems. This involves the advances in robust data infrastructure and analytics capabilities. Ensuring data security and privacy is also essential, as waste-related information can be sensitive (Arshi and Mondal, 2023).
(c) **Sensor Reliability:** Sensors are exposed to harsh environmental conditions, such as extreme temperatures and humidity, which can affect their reliability and accuracy. Regular maintenance and calibration are necessary to ensure sensors continue to function correctly. Failures or inaccuracies in sensor data can disrupt waste collection schedules and lead to inefficiencies.
(d) **Interoperability:** In many cases, WM systems involve various stakeholders, including municipalities, waste collection companies, recycling facilities, and more. Ensuring that sensors and data systems are compatible across different entities can be a challenge (Phonchi-Tshekiso et al., 2020). Lack of interoperability can lead to data silos and hinder the optimization of WM processes.
(e) **Scalability:** Implementing sensor-based WM on a small scale may be manageable, but scaling up to cover entire cities or regions is a significant challenge. It requires substantial infrastructure development, coordination among multiple parties, and the allocation of resources for widespread sensor deployment (D'Amico et al., 2020).
(f) **Community Acceptance:** The introduction of sensors in waste bins and collection trucks may raise concerns about privacy and surveillance among residents. Ensuring community acceptance and addressing privacy concerns is crucial for the successful adoption of sensor-based WM systems (Pardini et al., 2020; Pelonero et al., 2020).
(g) **Environmental Impact:** While sensor technology can improve WM efficiency, the production and disposal of sensors themselves may have environmental consequences. One issue that requires consideration is making sure that the procedures used in the fabrication of sensors are sustainable and that they are disposed of properly after their lives are over (Kundariya et al., 2021).
(h) **Technological Advancements:** Rapid advancements in sensor technology can make existing systems quickly obsolete. Staying up-to-date with the latest sensor innovations and integrating them into WM processes can be challenging for municipalities and WM companies (Das et al., 2019).
(i) **Data Analysis and Decision-Making:** Collecting vast amounts of data from sensors is only useful if it can be effectively analysed and turned into actionable insights. Developing the capability to analyse sensor data and make informed decisions based on that data is a challenge that organizations must address (Sliusar et al., 2022).

Since sensors hold tremendous potential to revolutionize WM by making it more efficient and environmentally friendly, there are several challenges that must be overcome. These challenges include cost, data management, sensor reliability, interoperability, scalability, community acceptance, environmental impact, technological advancements, and data analysis (Milson and Mehmet, 2023; Allioui and Mourdi, 2023). Addressing these challenges will be essential for the successful implementation of sensor-based WM systems and for achieving sustainable WM practices in the future.

SENSOR TECHNOLOGIES FOR WASTE MANAGEMENT

Waste management is a global challenge that requires innovative solutions to handle the ever-increasing volume of waste generated by societies. Sensor technologies have emerged as a powerful tool in modern WM, enabling more efficient and sustainable practices across the entire WM lifecycle (Bibri, 2018). These sensor technologies play a pivotal role in optimizing waste collection, improving recycling processes, and minimizing environmental impact (Table 1).

1. Fill Level Sensors

Fill level sensors are among the most widely adopted sensor technologies in WM. Installed in trash bins, dumpsters, and recycling containers, these sensors continuously monitor the fill levels of waste receptacles. By collecting RT data, waste collection companies can optimize their routes, ensuring that collection trucks only visit containers that are nearing full capacity (Premgi, 2019). This not only reduces operational costs but also cuts down on fuel consumption and greenhouse gas emissions.

2. Weight Sensors

Weight sensors are used to measure the weight of waste containers, enabling WM companies to accurately assess the amount of waste collected. This data is invaluable for billing purposes and monitoring waste generation trends (Wang et al., 2021). Weight sensors can be integrated into collection trucks, automated sorting systems, and waste compactors.

3. Environmental Sensors

Environmental sensors are employed to monitor air quality and detect hazardous substances emitted from waste sites and landfills. They help in ensuring compliance with environmental regulations and safeguarding the health of nearby communities. These sensors can detect pollutants such as methane, sulphur dioxide, and volatile organic compounds, providing early warnings in case of potential environmental hazards (Munir et al., 2019).

4. Optical and Infrared Sensors

Optical and infrared sensors are used in recycling facilities to sort and separate various types of recyclable materials efficiently. These sensors can identify and sort materials such as plastics, metals, paper, and glass based on their optical properties. By automating the sorting process, recycling facilities can enhance resource recovery and reduce contamination in recycled materials (Gundupalli et al., 2017; Senturk et al., 2021).

5. Temperature Sensors

Temperature sensors are employed to monitor the temperature within waste piles, particularly in composting and bioconversion processes. Maintaining the right temperature is crucial for the efficient decomposition of organic waste and preventing the release of harmful emissions (Duarte et al., 2017).

6. RFID and Barcode Sensors

RFID (Radio-Frequency Identification) and barcode sensors are used for tracking and identifying waste containers and their contents. These technologies facilitate better inventory management, enhance traceability, and enable more accurate tracking of waste materials from collection to disposal (Mostaccio et al., 2023).

7. GPS and Geographic Information Systems (GIS)

GPS and GIS technologies are integrated with sensors in WM to track the RT location of collection trucks, monitor routes, and optimize collection schedules. These technologies help minimize fuel consumption, reduce vehicle wear and tear, and improve overall operational efficiency (Hayat, 2023; Singh et al., 2024).

8. Smart WM Systems

Smart WM systems combine various sensor technologies with data analytics and IoT (Internet of Things) platforms. These systems provide RT insights into waste collection, enable route optimization, and enhance decision-making for WM companies (Kannan et al., 2024). They often include user-friendly interfaces for both WM professionals and residents, promoting community engagement and responsible waste disposal practices.

While sensor technologies have revolutionized WM, challenges remain, such as the initial investment cost, data security and privacy concerns, sensor maintenance, and the need for infrastructure upgrades. However, the benefits of these technologies, including reduced operational costs, minimized environmental impact, and improved resource recovery, make them a compelling choice for modern WM systems.

Sensor technologies have ushered in a new era of efficiency and sustainability in WM. By providing RT data and insights, these sensors empower WM companies to optimize their operations, reduce environmental harm, and engage communities in responsible waste disposal practices. As sensor technology continues to evolve, its integration into WM systems is expected to become increasingly prevalent, ultimately aiding more sustainable and efficient WM ecosystem (Farjana et al., 2023).

Table 1. Sensor technologies used in waste management, along with their typical applications and functions

S. No	Sensor Technology	Application	Function
1	Fill Level Sensors	Waste Containers	Monitor and report fill levels of bins for optimized collection routes.
2	Weight Sensors	Collection Trucks, Waste Bins	Measure the weight of waste materials for billing and tracking.
3	Environmental Sensors	Waste Sites, Landfills	Detect and monitor emissions, ensuring compliance with environmental regulations.
4	Optical and Infrared Sensors	Recycling Facilities	Identify and sort recyclable materials based on their optical properties.
5	Temperature Sensors	Composting, Bioconversion Sites	Monitor temperature for efficient decomposition of organic waste.
6	RFID and Barcode Sensors	Waste Containers, Materials	Track and identify waste containers and contents for inventory management.
7	GPS and GIS Technologies	Collection Trucks, Routes	Track vehicle locations, monitor routes and optimize collection schedules.
8	Smart Waste Management (SWM) Systems	Integrated Systems	Combine various sensors, data analytics and IoT for RT WM.

Source: (Bharadwaj et al., 2016; Anagnostopoulos et al., 2017; Nižetić et al., 2019; Wang et al., 2021; Sosunova and Porras, 2022).

SENSOR APPLICATIONS IN WASTE COMPOSITION ANALYSIS

Effective WM is a demanding global challenge in the 21st century, urged by the need to reduce environmental pollution, conserve resources, and promote sustainable practices (Jin et al., 2023). Waste composition analysis is a crucial component of this effort, as it helps policymakers, waste managers, and researchers understand the composition of waste streams, identify recyclable materials, and develop strategies for waste reduction and recycling. Sensors play a pivotal role in waste composition analysis, enabling accurate and efficient data collection and analysis (Piskulova and Gorbanyov, 2023).

1. Sorting and Segregation

Sensors are extensively used in automated waste sorting and segregation processes. In recycling facilities, sensors such as infrared (IR), near-infrared (NIR), and X-ray sensors are employed to identify and sort different materials based on their spectral properties. NIR sensors, for example, can distinguish between various plastics, paper, and glass, allowing for efficient separation and recycling. In addition to improving garbage sorting efficiency and accuracy, this automation also lessens the need for physical labour (Shirke et al., 2019).

2. Weight Measurement

Weight sensors are employed in waste bins and trucks to measure the weight of waste collected. These sensors provide valuable data for WM operations, enabling accurate billing for waste collection services and helping municipalities monitor waste generation trends. Weight data can also be used to optimize collection routes and reduce fuel consumption, contributing to cost savings and reduced carbon emissions (Chen et al., 2022).

3. Gas Sensors for Landfills

Landfills are a significant source of greenhouse gas emissions, primarily methane (CH_4) and carbon dioxide (CO_2). Gas sensors are utilized to monitor and control these emissions. Methane sensors can detect the presence and concentration of CH_4 in landfill gas, allowing for timely interventions to prevent gas leaks and reduce environmental impact (Dhall et al., 2021). Additionally, CO_2 sensors help assess the progress of landfill gas-to-energy projects, which convert methane into electricity.

4. pH and Temperature Sensors

In composting facilities, pH and temperature sensors are crucial for maintaining optimal conditions for the decomposition of organic waste. These sensors ensure that the composting process is efficient and produces high-quality compost, which can be used as a soil conditioner or fertilizer (Mengqi et al., 2021). Monitoring pH and temperature helps prevent issues such as odour problems and the production of harmful compounds.

5. Moisture Sensors

Moisture sensors are essential in waste composition analysis, especially for determining the moisture content of waste materials. High moisture content can make waste less suitable for recycling or energy recovery processes. These sensors help waste facilities manage moisture levels to ensure that waste is processed efficiently and effectively (Yin et al., 2021).

SENSORS FOR WASTE COLLECTION AND SORTING: REVOLUTIONIZING WASTE MANAGEMENT

Waste management is a global challenge that requires innovative solutions to reduce environmental impact, optimize resource utilization, and promote sustainability. Sensors have emerged as a game-changer in this field, offering enhanced capabilities for waste collection and sorting (Table 2). Here the pivotal role of sensors in transforming WM, from efficient waste collection to precise material sorting, ultimately contributing to a more sustainable future is explored (Szpilko et al., 2023).

1. Smart Waste Collection

Traditional waste collection methods often involve fixed schedules and routes, leading to inefficient resource allocation and increased environmental footprint due to unnecessary fuel consumption. Smart waste collection systems leverage sensors to address these challenges. These systems are equipped with various sensors, including ultrasonic level sensors, to monitor waste bin fill levels in real time (Lu et al., 2020).

Ultrasonic level sensors use sound waves to measure the depth of waste in bins. When a bin reaches a certain fill level, the sensor sends a signal to WM authorities or service providers, triggering timely collection (Silva et al., 2022). This approach minimizes the number of unnecessary collections, reducing costs and greenhouse gas discharges while optimizing resource allocation.

2. Compactor Sensors

Compactor sensors are frequently used in waste compactors, which are machines designed to compress waste materials to reduce volume. These sensors monitor the compaction process and help optimize compaction cycles for maximum efficiency. By ensuring that waste is compacted to its fullest potential, these sensors contribute to reduced transportation costs and decreased landfill usage (Kumar et al., 2023).

3. Sorting Sensors

In recycling facilities, sorting sensors are the backbone of material recovery processes. They identify and segregate recyclable materials from mixed waste streams. Common types of sorting sensors include:

(a) **Infrared (IR) and Near-Infrared (NIR) Sensors:** These sensors detect the spectral properties of materials, allowing for the identification and sorting of plastics, paper, glass, and metals based on their unique signatures. NIR sensors are highly versatile and can distinguish between various plastics, enhancing the efficiency of recycling processes (Araujo-Andrade et al., 2021).
(b) **Magnetic Sensors:** Magnetic sensors are used to separate ferrous metals (containing iron) from non-ferrous metals. They work by attracting ferrous materials with a magnetic field, while non-ferrous materials are unaffected (Brooks et al., 2019).
(c) **Eddy Current Sensors:** Eddy current sensors detect non-ferrous metals such as aluminium and copper by inducing electrical currents in these materials and measuring their response (Smith et al., 2019).
(d) **X-ray Sensors:** X-ray sensors are employed for advanced sorting applications, particularly in electronic waste recycling. They can identify different materials based on their density and atomic composition (Sterkens et al., 2021).

4. Environmental Sensors

Beyond waste collection and sorting, environmental sensors play essential role in monitoring the impact of WM operations. Gas sensors, for instance, detect and measure emissions from landfills, helping to mitigate harmful environmental effects. pH sensors and temperature sensors are used in composting facilities to maintain optimal conditions for decomposition (Ramírez-Moreno et al., 2021).

While the globe still struggles with the issues of environmental sustainability and waste generation, the role of sensors in collection and sorting will only grow in significance, contributing to more responsible and eco-friendly WM practices.

MONITORING AND CONTROL SYSTEMS: ROLE OF SENSORS

In today's rapidly urbanizing world, WM has become a serious challenge. The efficient collection, disposal, and recycling of waste are essential not only for environmental sustainability but also for public health and well-being. To address these challenges, monitoring and control systems with advanced sensor technologies are playing an increasingly pivotal role in optimizing WM processes (Yang et al., 2017).

Table 2. Sensors used in waste collection and sorting, along with potential future applications

S. No	Type of Sensor	Current Applications	Potential Future Applications
1	Ultrasonic Level	Smart waste bin fill monitoring in waste collection systems.	Intelligent waste compaction in smart cities.
2	Weight	Weighing waste in collection trucks and disposal facilities.	RT waste composition analysis for waste reduction and recycling optimization.
3	Compactor	Monitoring compaction in waste compactors to reduce volume.	Integration with AI for predictive maintenance and energy optimization.
4	Infrared (IR) and Near-Infrared (NIR)	Material sorting in recycling facilities based on spectral properties.	Enhanced recycling systems with improved material recognition and separation.
5	Magnetic	Separating ferrous metals from non-ferrous metals in recycling facilities.	Enhanced sorting of challenging waste streams, like electronic waste.
6	Eddy Current	Detecting non-ferrous metals like aluminium and copper.	Advanced resource recovery from complex waste streams.
7	X-ray	Advanced material sorting in recycling, especially electronic waste recycling.	Sorting for rare materials, trace contaminants, or hazardous materials.
8	Gas	Monitoring landfill gas emissions for environmental protection.	Early detection and prevention of gas leaks and better gas-to-energy conversion strategies.
9	pH and Temperature	Maintaining optimal conditions for composting facilities.	Precision control of compost processes for biogas production and soil improvement.
10	RFID and Barcode	Tracking and tracing waste containers and recyclable materials.	Enhanced waste tracking in circular economy systems.

Source: Araujo-Andrade et al., 2021; Brooks et al., 2019; Smith et al., 2019; Sterkens et al., 2021; Ramírez-Moreno et al., 2021.

Sensors are at the heart of modern WM systems, providing valuable RT data that enables municipalities and WM companies to make informed decisions and streamline their operations. These sensors come in various forms, from simple bin fill-level sensors to sophisticated environmental monitoring devices. Sensors revolutionizing WM are as follows:

(a) **Fill-Level Sensors:** One of the most basic yet crucial sensor applications in WM is fill-level sensors. These sensors are placed inside waste bins and containers to monitor their fill levels. By continuously measuring the waste volume, waste collection routes can be optimized. This leads to significant cost reductions in terms of fuel consumption, labour, and vehicle maintenance (Vishnu et al., 2022).

(b) **Environmental Sensors:** Beyond monitoring waste containers, environmental sensors are used to assess air quality, detect hazardous materials, and monitor emissions from waste processing facilities. These sensors help ensure compliance with environmental regulations and provide early warning (EW) systems for potential hazards, protecting both the environment and the health of nearby communities (Yekeen et al., 2020).

(c) **Sorting and Recycling Sensors**: In recycling facilities, sensors are employed to separate and classify discrete types of materials inevitably. Optical sensors, for example, can identify and sort various plastics, metals, and paper products based on their composition and characteristics. This automation not only increases the efficiency of recycling but also enhances the quality of recycled materials (Gundupalli et al., 2017).

(d) **GPS and RFID Technology:** Global Positioning System (GPS) and Radio-Frequency Identification (RFID) technology are often integrated into waste collection vehicles and bins. These technologies provide RT tracking and data collection capabilities, allowing WM companies to supervise the movement of their assets, optimize collection routes, and enhance overall operational efficiency (Arebey et al., 2010; Hannan et al., 2015).

(e) **Data Analytics and Remote Monitoring:** Sensor data is invaluable for WM companies when it is processed through advanced analytics. By analyzing historical and RT data, decision-makers can identify trends, predict maintenance needs, and optimize resource allocation. Remote monitoring systems also allow for RT visibility into WM operations, enabling rapid response to issues as they arise (Munir et al., 2023).

(f) **Smart Bins and IoT Integration:** The concept of smart bins has gained traction in recent years. These bins are equipped with sensors and IoT (Internet of Things) technology, allowing them to communicate with central systems. Smart bins can send alerts when they are full, help plan collection schedules more efficiently, and even encourage responsible waste disposal behaviour among users (Allioui and Mourdi, 2023).

(g) **Cost Savings and Sustainability:** Perhaps one of the most significant benefits of sensor-driven monitoring and control systems in WM is the promise for cost savings and environmental sustainability (Mohanty et al., 2022(b)). By reducing unnecessary collection trips, optimizing routes, and improving recycling rates, WM becomes more economically viable and environmentally friendly (Das et al., 2019).

Sensors enable RT monitoring, data collection, and informed decision-making, leading to cost savings, improved operational efficiency, and a reduced environmental footprint. As technology continues to advance, the integration of sensors and data analytics into WM processes will only become more sophisticated, helping us address the growing challenges of WM in an increasingly urbanized world.

CASE STUDIES AND EXAMPLES: TRANSFORMING THE TRASH INDUSTRY

Modern urban living requires effective trash management, and the use of sensors and technology is changing the way garbage is handled. WM techniques may be made more effective and sustainable by utilising the RT data and insights these sensors give. Here are some case studies and examples of sensors in WM:

(a) Smart Bins and Automated Collection

Barcelona, Spain: Barcelona has implemented an extensive network of smart waste bins equipped with fill-level sensors. These sensors monitor the waste levels inside the bins and communicate this information to waste collection teams. As a result, collection routes are optimized, reducing unnecessary pickups and decreasing fuel consumption (Camero et al., 2019). This smart system has led to significant cost savings and a more efficient waste collection process.

(b) Recycling Sorting Facilities

San Jose, California: The city of San Jose operates a state-of-the-art Material Recovery Facility (MRF) equipped with advanced sensor technology. Automated sorting machines use sensors to identify and separate different types of recyclables, such as paper, plastics, and metals, with remarkable precision (Cimpan et al., 2015). This technology not only reduces the need for manual labor but also ensures higher recycling rates by efficiently sorting materials.

(c) Landfill Gas Monitoring

Los Angeles County, California: The Puente Hills Landfill, one of the largest landfills in the United States, utilizes gas monitoring sensors. These sensors continuously monitor methane levels within the landfill. When methane levels exceed certain thresholds, gas extraction systems are activated to capture and convert the gas into electricity (Yadav et al., 2019). This process both reduces greenhouse gas emissions and generates renewable energy.

(d) Underground Waste Containers

Amsterdam, Netherlands: Amsterdam has adopted an underground waste container system equipped with sensors. These containers feature compaction systems and sensors that notify waste collectors when they need emptying. By eliminating the need for traditional above-ground bins, this technology enhances the city's aesthetic appeal while improving WM efficiency (Hancke and Hancke, 2013).

(e) GPS Tracking for Collection Vehicles

New York City, USA: The New York City Department of Sanitation has equipped its waste collection fleet with GPS tracking sensors. These sensors enable RT tracking of collection routes and vehicle activities. With this data, collection routes can be optimized to reduce fuel consumption, lower carbon emissions, and upgrade overall operational proficiency (Isik et al., 2021).

(f) E-Waste Recycling

Belgium: Electronic waste (e-waste) contains valuable and hazardous materials that require specialized recycling processes. Sensors are used to automatically identify and sort e-waste, ensuring the recovery of precious metals and components while safely managing toxic materials. Facilities like Recupel, a non-profit organisation that collects and processes used electrical and electronic appliances and light bulbs) in Belgium demonstrate the efficient use of sensor technology in e-waste recycling (Verstricht et al., 2022).

(g) Waste Composition Analysis

Austin, Texas: Waste composition analysis is crucial for informed waste reduction and recycling efforts. Sensors are employed to analyse the composition of waste streams, identifying types and quantities of materials present. This information helps authorities tailor recycling and waste reduction programs effectively (Sahadewa et al., 2014). The waste characterization study in Austin, Texas, relies on sensor technology to guide its WM strategies.

These case studies illustrate how sensor technology is helping cities and regions worldwide reduce costs, improve sustainability, and minimize the environmental impact of WM. As technology continues to advance, we can expect even more innovative solutions to emerge, further revolutionizing the WM industry.

FUTURE TRENDS AND EMERGING TECHNOLOGIES

Sensors embedded in waste bins, trucks, and sorting facilities will be interconnected, allowing RT data collection and analysis. This connectivity will enable predictive maintenance, route optimization, and better decision-making in waste collection.

Artificial intelligence and machine learning algorithms will become more sophisticated in predicting waste generation patterns. These technologies will help optimize collection routes, predict fill levels, and identify contamination in recycling streams. By analysing historical data, AI can help cities and WM companies make data-driven decisions.

Advancements in sensor technology will lead to smaller, more affordable sensors. These compact sensors can be deployed in various WM applications, including monitoring landfill gas emissions, detecting leaks in waste containment systems, and assessing waste composition. Miniaturization will make sensor deployment more accessible and cost-effective.

Blockchain technology can enhance transparency and traceability in WM. Each step of the waste journey, from generation to disposal or recycling, can be recorded on a blockchain. This ensures accurate tracking and reporting of waste volumes, recycling rates, and compliance with regulations.

Robotics will play a significant role in waste sorting and recycling. Advanced robotic systems equipped with sensors and computer vision technology can identify and sort various types of waste with high precision. This reduces the need for manual labour and improves recycling rates.

Sensors will be instrumental in optimizing waste-to-energy processes. The RT monitoring of waste characteristics, such as calorific value and moisture content, will enable better control of incineration and gasification processes, maximizing energy recovery and minimizing environmental impact.

The impact of WM operations on the environment will be tracked using sensors. This includes air and water quality monitoring near landfills, in addition to evaluating the environmental impact of waste processing technologies. These sensors will help ensure compliance with environmental regulations.

Smart packaging with embedded sensors will help consumers and WM organizations identify the composition and recyclability of packaging materials. This technology will promote responsible consumer choices and facilitate the recycling process.

Emerging technologies may enable decentralized WM systems. These systems could include on-site waste processing, such as small-scale recycling units or composting solutions, all equipped with sensors for monitoring and control.

Mobile apps with WM sensors will empower citizens to actively participate in waste reduction and recycling efforts. These apps can provide RT information on waste collection schedules, recycling guidelines, and nearby recycling facilities.

These innovations promise to make WM more efficient, reduce environmental impact, and encourage responsible waste disposal and recycling. As technology continues to advance, WM will become smarter, more responsive, and better equipped to address the growing challenges of waste generation in our rapidly urbanizing world.

CONCLUSION: SENSORS IN WASTE MANAGEMENT - A SMARTER, SUSTAINABLE FUTURE

The use of sensors in garbage management has brought in a new era of effectiveness, sustainability, and environmental responsibility. Throughout this chapter, we have explored the myriad ways in which sensors are transforming the WM industry, from smart bins and recycling sorting facilities to landfill gas monitoring and waste composition analysis. We have delved into case studies and examples, highlighting the tangible benefits that sensor technology has already brought to cities and regions worldwide. Furthermore, we have examined future trends and emerging technologies, providing a glimpse into the exciting developments that promise to shape the future of WM.

In the wake of unprecedented urbanization and population growth, the challenges posed by WM have grown exponentially. Traditional WM practices are no longer sufficient to meet the demands of our ever-expanding cities. This is where sensors have proven to be invaluable. They provide RT data, enhance operational efficiency, reduce environmental impact, and empower communities to take a proactive role in waste reduction and recycling.

One of the key takeaways from this chapter is the concept of "smart waste management." Smart WM systems, powered by sensors and data analytics, allow for more responsive and adaptive approaches to waste collection and disposal. For instance, smart bins equipped with fill-level sensors can optimize collection routes, minimizing unnecessary trips and reducing fuel consumption. This not only translates into cost savings for municipalities but also reduces carbon emissions, contributing to a greener, more sustainable future.

Recycling, a cornerstone of WM, has also benefited immensely from sensor technology. Automated sorting machines equipped with sensors can accurately identify and separate recyclable materials from the waste stream, increasing recycling rates and reducing contamination. This technology is vital for achieving circular economies where resources are conserved and reused efficiently.

Sensors have also proved their worth in monitoring landfill gas emissions, particularly methane, a potent greenhouse gas. By continuously tracking gas levels within landfills and triggering gas extraction systems when thresholds are exceeded, sensors mitigate the environmental impact of landfills while harnessing methane as a valuable energy source.

Looking to the future, we anticipate a profound transformation of WM practices. The emergence of the Internet of Things (IoT) will create a web of interconnected sensors, bins, vehicles, and processing facilities. This interconnectedness will enable predictive maintenance, route optimization, and data-driven decision-making on an unprecedented scale. Artificial intelligence and machine learning will refine waste generation predictions, further optimizing waste collection routes and schedules.

Sensors will also play a crucial role in ensuring the responsible disposal and recycling of electronic waste (e-waste). As technology continues to advance, e-waste will become an increasingly significant component of the waste stream. Advanced sensors will help identify and sort e-waste, recovering valuable materials while safely managing hazardous components.

Furthermore, blockchain technology will provide transparency and traceability in WM, bolstering accountability and compliance with regulations. Recycling and garbage sorting operations will be more effective thanks to robotics, automation, and smart packaging. Apps for public participation and decentralised trash management will enable communities to take an active role in waste reduction initiatives.

In conclusion, sensors in WM are not merely technological innovations; they signify a paradigm change in the direction of a more sustainable, environmentally conscious, and efficient future. In the midst of our efforts to solve the urgent problems associated with WM in an urbanising globe, sensors will continue to be at the forefront of innovation. They will enable us to reduce waste, conserve resources, lower emissions, and ultimately create cleaner, healthier communities for generations to come. By embracing sensor technology and fostering collaboration between governments, industries, and communities, we can pave the way for a smarter, more sustainable future in WM.

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KEYWORDS AND DEFINITIONS

Environmental Sensor Networks: Interconnected sensors gathering environmental data for monitoring and analysis.

IoT in Waste Management: Internet-connected systems optimizing waste collection and processing.

Real-Time Waste Analytics: Instantaneous analysis of waste data for informed decision-making.

Sensor-Enabled Waste Bins: Waste receptacles equipped with sensors for monitoring.

Smart Waste Management: Utilizing technology for efficient and optimized waste handling.

Waste Sensors: Devices detecting and measuring waste levels or compositions.

Waste Tracking Technology: Systems tracing waste from generation to disposal.

Chapter 16
Environmental Sensors:
Safeguarding the Ecosystem by Monitoring Sanitary Pad Disposal

Deepa V. Jose
Christ University, India

ABSTRACT

This chapter focuses on the applications of environmental sensors in general and their role in identifying and addressing the issues related to the improper disposal of sanitary pads, which is a growing concern. It also gives an overview of the pollutants associated with it, and the role that environmental sensors can play in mitigating this problem. By harnessing the power of advanced sensing technologies, we can gain a better understanding of the environmental impact of sanitary pad disposal and work towards sustainable solutions. This chapter aims to provide valuable insights and guidance for researchers and practitioners working to create a cleaner and healthier environment and generate self-awareness for individuals in safeguarding ecosystem.

INTRODUCTION

Sanitary hygiene is a fundamental aspect of human health and well-being. However sanitary pads, essential for women's menstrual health, have become ubiquitous in India. However, the improper disposal of these pads poses a severe environmental problem. The vast majority of sanitary pads are made from non-biodegradable materials like plastics and synthetic fibres, which can take centuries to decompose. When these pads are discarded irresponsibly, they clog waterways, litter streets, and contribute to the growing issue of plastic pollution in the environment (Qu et al.,2023) sensor.

Within the Indian landscape, critical concerns revolve around the pollution of rivers and water bodies, congestion within sewer systems, and the pressing challenges posed by open dumping sites (Ahmad,2021; Elledge et al.,2018)). These are urgent matter of concerns to be addressed seriously to ensure further complications. Wherever proper sanitary pad disposals mechanisms are not in place, it is widely observed that women dispose the used sanitary pads in rivers and other water

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bodies and even dispose them along with other waste without segregating them. This not only have adverse effects on the aquatic ecosystems but also contaminates the nearby water sources which will be depended by many communities for drinking and agriculture purposes. The polluted water can lead to various health issues for the communities relying on these sources (Patel et al.2020) in the long run. They might also create serious health concerns for the people who does the waste management. Another issue is related to the dumping of used sanitary pads in toilets. Urban and suburban areas often experience clogging of drainage systems due to the flushing of sanitary napkins into the toilets. This leads to expensive and disruptive maintenance work, which ultimately burdens municipal authorities and taxpayers. Leaving dirty napkins in public places on rural areas is a significant health risk as it draws out wandering creatures and promotes the spread of diseases (Gadekar,2023). The problem is most pronounced in groups with lower levels of proper waste disposal facilities, which are often marginalized.

In India, the issue of disposing of sanitary pads is significant due to the country's large population and potential health and hygiene issues. This requires urgent action. Improper disposal of sanitary napkins threatens public health because it can cause the spread of diseases and infections. For women and girls, access to hygienic menstrual products and safe disposal methods is integral to their well-being (Melaku et al.2023). The non-biodegradable nature of most sanitary pads means that they remain in the environment for an extended period. This contributes significantly to plastic pollution and its associated environmental degradation. The social stigma surrounding menstruation further complicates this issue. Women and girls often feel ashamed or embarrassed to discuss proper disposal methods, which perpetuates the problem. The burden of dealing with clogged sewer systems and managing open dumping sites places a strain on already stretched municipal infrastructure and resources.

This chapter endeavours to explore the contemporary landscape of sanitary pad disposal within the different context. Its aim is to ascertain prevalent challenges, anticipate future issues, and proactively devise viable solution strategies for addressing this concern. The chapter is organised into different sections which addresses various concerns. It mentions the role of environmental sensors in general and the organizations that produce these sensors and effectively use them for monitoring different aspects. Then the methods and practices of sanitary pad disposal, the environmental pollutants associated with improper disposal and statistics and facts about the scale of the problem are stated. An overview of environmental sensing technologies, the types of sensors used for monitoring environmental pollutants and the importance of real-time data collection and monitoring is mentioned. It also gives a description of the various pollutants and contaminants associated with sanitary pads and highlight the challenges of detecting these pollutants through traditional means. Section 6 present case studies and examples of how environmental sensors have been used in similar pollution monitoring scenarios and discuss the potential of these sensors in sanitary pad disposal contexts. Potential of Environmental sensors in Sanitary Pad Disposal is discussed in Section 7. Section 8 deals with the proposal for potential solutions and mitigation strategies for the issues related to sanitary pad disposal and how environmental sensors can inform and improve these solutions. Case Studies and Success Stories which showcase real-world examples of successful implementations of environmental sensors in addressing sanitary pad disposal problems is mentioned in Section 9. Section 10 discuss the Future Directions and Research Opportunities.

THE ROLE OF ENVIRONMENTAL SENSORS

Environmental sensors are devices that detect and measure various parameters in the environment. Examples include Temperature Sensor, Humidity Sensor, Air Quality Sensor, Light Sensor (Photodetector), Pressure Sensor, Gas Sensor, Sound Sensor (Microphone) etc. Temperature sensors measure the degree of hotness or coldness of an object or environment. Thermocouples, resistance temperature detectors (RTDs), and thermistors are commonly used sensors (Al Mamun et al., 2019). They work based on the principle that temperature changes affect the electrical properties of the material they are made of (e.g., resistance change in thermistors or voltage change in thermocouples). Humidity sensors measure the amount of moisture present in the air. Capacitive, resistive, and thermal conductivity sensors are used for humidity measurement. They operate by detecting changes in electrical conductivity, capacitance, or thermal properties due to the presence of moisture. The air quality sensors measure various pollutants present in the air, such as particulate matter, volatile organic compounds (VOCs), carbon monoxide (CO), nitrogen dioxide (NO_2), etc. Different technologies like electrochemical cells, metal oxide semiconductors, optical detection, and particulate matter sensors are used to detect and quantify these pollutants. Light sensors measure the intensity of light in an environment. Photodiodes, phototransistors, and photoresistors (LDR - Light Dependent Resistor) are commonly used. They work by converting light energy into electrical signals, where the electrical output is proportional to the intensity of incident light. Pressure sensors measure force applied by a fluid (liquid or gas) on its surface. Various types include piezoelectric, capacitive, and strain gauge sensors (Rhouati et al.,2022;Riza et al.2020). They operate by detecting changes in capacitance, resistance, or mechanical deformation due to pressure changes. Gas sensors detect the presence and concentration of specific gases in the environment (Burgués et al.,2022). Electrochemical, semiconductor, and infrared sensors are common types. They work based on interactions between gases and the sensing material, which causes changes in electrical conductivity, optical properties, or chemical reactions. Sound sensors capture sound waves and convert them into electrical signals. Microphones, which are a type of sound sensor, use diaphragms or other elements that vibrate in response to sound waves, generating corresponding electrical signals. Figures 1 depicts a temperature and humidity tracking box which is commonly used for environmental monitoring green houses, smart homes etc.

These sensors are integral to various applications like weather monitoring, indoor air quality assessment, industrial automation, smart homes, healthcare, and more, enabling the collection of data crucial for decision-making and understanding the environment's conditions. Environmental sensors have the potential to play a pivotal role in addressing the challenge of sanitary pad disposal in India. These sensors can be integrated into waste collection systems, sewage networks, and public spaces to monitor and manage the issue effectively. For real-time monitoring the environmental sensors can detect the presence of non-biodegradable waste in sewer systems, enabling immediate action to prevent clogs and overflows. Smart bins equipped with sensors can identify and sort sanitary waste, directing it to appropriate disposal channels and ensuring responsible disposal (Mor & Ravindra, 2023;Naher & Ahsan, 2023). Environmental sensors can also be used to monitor public spaces for littering and illegal dumping, providing data to raise awareness and enforce regulations (Joe et al.2018;Javaid et al.,2021). The data collected by these sensors can help local authorities make informed decisions about waste management, allowing for more efficient and sustainable solutions.

Figure 1. AEM1000 environmental monitoring box

Environmental sensors are devices designed to detect and measure various environmental parameters (Chapman et al., 2020). Table 1 gives the examples of the same, including the name of the integrated circuit (IC), their use, and type. These sensors are widely used in various applications like weather stations, environmental monitoring, home automation, and industrial control systems (Demrozi et al.2020). Each sensor has its specific application based on its sensing capability and the parameter it measures (De Sousa et al.,2023).

Several Indian companies specialize in the production and development of environmental sensors, catering to a wide range of applications such as air quality monitoring, weather forecasting, agriculture, and industrial automation. Table 2 gives an overview of some of the major Indian companies in this field. These companies are involved in either the direct production of environmental sensors or the development of systems that incorporate these sensors. Their products are used in a variety of sectors including industrial, commercial, healthcare, and agriculture.

Environmental sensors are used in various aspects of our daily lives. Table 3 gives some examples of specific organizations and locations where environmental sensors are prominently used. These organizations are leaders in their respective fields and utilize environmental sensors to enhance their operations, research, and services in specific locations around the world.

The global environmental sensor market is experiencing significant growth and is influenced by a variety of factors, including the increasing use of these sensors in various sectors, advancements in technology, and governmental regulations on pollution control. However, the market also faces challenges such as lack of awareness and budgetary constraints. As of 2023, the global environmental sensor market is expected to grow from \$1.59 billion in 2022 to \$1.77 billion in 2023, demonstrating a compound annual growth rate (CAGR) of 11.2%. Looking ahead, the market is projected to reach around \$2.59 billion by 2027, maintaining a CAGR of approximately 10.1%. The surge is fuelled by various factors, including the growth of smart cities, rising demand in different industries, and the development of IoT and cloud-based services.

Table 1. Examples for environmental sensors

Sl No	Sensor	IC Name	Use	Type
1	DHT22 (AM2302) - Temperature and Humidity Sensor	DHT22 or AM2302	Measures ambient temperature and humidity.	Capacitive humidity sensing and thermistor-based temperature sensing
2	BMP280 - Barometric Pressure Sensor	BMP280	Measures atmospheric pressure, useful in weather forecasting and altitude estimation	Piezoresistive pressure sensor
3	MQ-135 - Air Quality Sensor	MQ-135	Detects various gases like ammonia, nitrogen oxides, alcohols, aromatic compounds, sulphide, and smoke	Gas sensor, chemoreceptor
4	DS18B20 - Waterproof Temperature Sensor	DS18B20	Measures temperature in wet or underwater environments	Digital temperature sensor, one-wire interface
5	TSL2561 - Luminosity Sensor	TSL2561	Measures ambient light intensity, mimicking the human eye response	Digital light sensor
6	MPU-6050 - Gyroscope and Accelerometer	MPU-6050	Measures angular rate and acceleration. Useful in orientation and motion detection	MEMS (Micro-Electro-Mechanical Systems) sensor
7	CCS811 - VOC and CO2 Sensor	CCS811	Measures indoor air quality by detecting volatile organic compounds (VOCs) and equivalent CO2 levels	Metal oxide gas sensor
8	Rain Sensor Module	Often a simple conductive board without a specific IC	Detects rainwater or water level presence	Conductive sensor
9	Soil Moisture Sensor	Often generic, with no specific IC	Measures the moisture level in soil, aiding in agriculture and gardening	Capacitive or resistive soil moisture sensor
10	MAX6675 - Thermocouple Temperature Sensor	MAX6675	Measures high temperatures, often used in conjunction with a K-type thermocouple	Thermocouple-to-digital converter

The global market is mainly concentrated in Asia Pacific, which is an industrial hub with China as its largest producer. The market in this region is expected to grow significantly, fuelled by factors such as industrialization, water scarcity, and air pollution control. However, the North American market is expected to surpass the Asia-Pacific region in terms of market share during the forecast period due to the technological development of the local countries. Government-led environmental initiatives are expected to drive the market's expansion in Europe, the Middle East, and Africa.

The main applications of these sensors are the monitoring and recording of environmental parameters such as humidity, temperature and air quality, which are important in industry, smart homes, consumer electronics and other devices. The main types of environmental sensors are temperature, humidity, air quality, water quality, integral, gas, chemical, smoke, ultraviolet (UV), and soil moisture sensors. Major players in the market are making product innovations and strategic acquisitions to maintain and strengthen their market position. For example, Zebra Technologies Corporation launched a new line of environmental sensors in April 2023 focused on the food, pharmaceutical and health sectors. Similarly, Interlink Electronics Inc. acquired SPEC Sensors and KWJ Engineering in December 2022, expanding its product range in gas and ambient air quality sensors. These developments show a vibrant and evolving market where environmental sensors are an increasingly important part of various aspects of modern life, from smart city development to industrial and agricultural applications. The Market Data Forecast report discussed the growing concern for environmental protection across the

Table 2. Indian companies using environmental sensors

Sl No	Company Name	Focus Area
1	Eureka Forbes Ltd	Known for their air quality monitoring products, Eureka Forbes offers a range of sensors and systems for detecting various air pollutants
2	Samriddhi Automation Pvt. Ltd. (Sparsh CCTV)	While primarily known for security and surveillance products, they also provide environmental sensors, particularly for industrial applications
3	Ambetronics Engineers Pvt. Ltd	They manufacture and export a wide array of electronic instruments and systems, including gas detection and environmental monitoring systems
4	Phoenix Sensors	Specializes in producing a variety of sensors including those for environmental monitoring, such as temperature, humidity, and pressure sensors
5	Oizom Instruments Pvt. Ltd	Focuses on smart environmental monitoring. They offer solutions like air quality monitors, dust monitors, odor monitors, and weather monitoring systems
6	Napino Auto & Electronics Ltd	While they are primarily focused on automotive electronics, they also venture into the development of sensors, including environmental sensors.
7	Robert Bosch Engineering and Business Solutions Private Limited	Part of the global Bosch group, this Indian subsidiary is involved in the development of various sensors, possibly including environmental sensors, as part of their wide range of electronic and technical services
8	Sensinova	Known for a range of sensor solutions, including motion sensors and environmental sensors for smart and automated systems
9	SEDEMAC Mechatronics	Specializes in mechatronics solutions and may include environmental sensors in their product range, particularly for automotive and industrial applications
10	Ripples IOT Pvt Ltd	Provides IoT solutions which include environmental monitoring for industries and healthcare facilities

Table 3. Organizations using environmental sensors

Sl No	Purpose	Organisation	Place
1	Weather Monitoring and Forecasting	National Oceanic and Atmospheric Administration (NOAA)	United States, with weather monitoring stations and equipment deployed nationwide
2	Air Quality Monitoring	Central Pollution Control Board (CPCB) in India	Major cities across India, including Delhi, Mumbai, and Bangalore, where air quality monitoring stations are installed
3	Smart Agriculture and Soil Monitoring	The United States Department of Agriculture (USDA)	Across various agricultural research sites and farms in the United States, particularly in the Midwest, known for its extensive agricultural activities
4	Home Automation and Smart Buildings	Siemens Building Technologies	Implemented in smart buildings and modern housing complexes worldwide, particularly in urban areas like New York City, London, and Singapore
5	Environmental Research and Conservation	World Wide Fund for Nature (WWF)	In various ecological conservation areas globally, notably in the Amazon Rainforest, the Arctic, and the Great Barrier Reef.
6	Industrial Emission Monitoring	Environmental Protection Agency (EPA) in the United States	Industrial zones across the United States, particularly in areas with high industrial activity like Texas and California
7	Water Quality Monitoring	European Environment Agency (EEA)	Across various water bodies in Europe, including the Danube River and the Baltic Sea
8	Healthcare and Hospital Environments	National Health Service (NHS) in the United Kingdom	In hospitals and healthcare facilities across the UK, particularly in major cities like London and Manchester
9	Urban Planning and Development	Urban Redevelopment Authority (URA) of Singapore	In urban areas of Singapore for monitoring environmental conditions and planning urban development projects

globe, the impact of IoT on the development of environmentally sensitive technology and the impact of government initiatives on market growth. Challenges faced by the market such as lack of awareness and budget constraints were also discussed. Allied Market Research has provided detailed statistics on the environmental sensors market, including its size, share and industry forecast to 2030. This resource highlighted the widespread use of environmental sensors in various sectors, market value in 2020 and forecasts to 2030. Research and Markets provided a comprehensive overview of the environmental sensors market, including its expected growth from 2022-2023 and forecasts to 2027. The source also presented the types of environmental sensors and their applications in various industries and the strategic movements of the most important market participants. Disposal of sanitary napkins in India is not only a public health problem, but also a major environmental problem. It is important to understand the urgency of solving this problem and the potential of environmental sensors to manage it. Sustainable solutions and awareness are critical to mitigating environmental impacts and promoting responsible disposal practices (Kaur et al., 2018), which ultimately improve women's well-being and the health of the planet. It is high time India took collective action to tackle this problem and create a more hygienic and sustainable future for all.

SANITARY PADS: AN ENVIRONMENTAL CHALLENGE

Indispensable for women and hygiene, sanitary napkins have had a significant impact on the lives of women and people around the world. However, the improper disposal of sanitary napkins has become a growing environmental problem, along with the many benefits they provide. Awareness of sanitary pad methods and practices, environmental contamination associated with improper disposal (Ghosh et al., 2020; Harrison and Tyson, 2022) and statistics and facts about the extent of this problem are mandatory to address emerging issues. With these sanitary napkins are traditionally disposed of by wrapping them in paper or plastic and throwing them in the trash. However, this method is not without problems. Sanitary napkins are often non-biodegradable and can take hundreds of years to decompose, adding to landfill and posing a serious environmental threat. Moreover, the lack of proper waste management infrastructure in many areas means that sanitary napkins are often discarded in open areas, rivers or even flushed toilets, clogging drainage systems and further degrading the environment. Improper disposal of sanitary napkins results in many environmental pollutants that negatively affect both terrestrial and aquatic ecosystems. The main environmental problems associated with improper disposal are soil, water, air pollution and related health risks. Sanitary napkins contain plastic parts and other non-biodegradable materials that remain in the environment for a long time. When deposited in landfills or open areas, they add to soil and soil pollution. Flushing sanitary napkins in the toilet can cause blockages in drainage systems, which can lead to contamination of overflow channels and waterways. Plastic and synthetic materials in pillows can release harmful chemicals and microplastics into the water, which harms aquatic life. Incineration of sanitary napkins as a disposal method can release toxic fumes and airborne pollutants into the atmosphere, further degrading air quality. Improper disposal practices can also endanger the health of waste collectors and sanitation workers who come into contact with contaminated materials. The scale of the problem of inappropriate disposal of sanitary napkins is significant and alarming. Problems related to the disposal of sanitary napkins are not limited to developing countries. Even in countries with advanced waste management systems, there are still problems in ensuring proper disposal. Here are some statistics and facts that highlight the importance of this environmental problem: According to a study by the Menstrual Hygiene Association, about 80% of India's sanitary waste is disposed of improperly, causing environmental pollution. According to a UK study, more than 4.6 billion single-use sanitary products are used each year, placing a significant burden on the environment. The Ellen MacArthur Foundation reports that plastics used in sanitary napkins and tampons, which are often disposed of incorrectly, contribute to plastic pollution in the oceans.Sanitary napkins are an environmental problem that can no longer be ignored. To reduce the environmental damage of these important hygiene products, it is necessary to adopt responsible waste management practices. Recommending the use of biodegradable and environmentally friendly hygiene products, improving waste management systems and raising awareness about the correct disposal of sanitary napkins are important steps towards a more sustainable and environmentally friendly future. By solving this problem, we can protect both the health of our planet and the well-being of women around the world.

ENVIRONMENTAL SENSORS: TECHNOLOGY AND CHARACTERISTICS

Environmental sensing technologies have advanced significantly in recent years (Tajik et al., 2021; Thakur and Kumar, 2022), providing invaluable tools for monitoring and managing our planet and health. These technologies include a wide range of sensors and data collection methods designed to measure various environmental parameters. They play an important role in understanding, mitigating and preventing the negative effects of pollution, climate change and other environmental problems. One of the key components of environmental sensing technology is the array of sensors used to monitor environmental contaminants. These sensors are designed to detect and measure a wide range of pollutants such as air pollution, water quality parameters, soil pollutants, and more (Khanmohammadi et al., 2020). They come in many forms, from simple handheld devices to sophisticated automated systems. For example, air quality sensors can measure levels of gases such as carbon dioxide and ozone (Dhall et al., 2021), while water quality sensors can detect parameters such as pH, turbidity, and chemical concentrations. These sensors provide important information that informs decision makers, scientists and the public about the state of the environment.Real-time data collection and monitoring has become increasingly critical in our efforts to effectively address environmental issues. Timely availability of environmental data enables a rapid response to pollution incidents and evaluation of the effectiveness of environmental policies and measures. For example, using real-time air quality sensors, cities can provide health information during fog or forest fires. In addition, they contribute to the development of early warning systems for natural disasters and can help monitor the movement of pollutants, such as oil spills, to minimize their impact on ecosystems and human health. This immediate access to information improves our ability to make informed decisions and take proactive measures to protect the environment (Kumunda et al., 2021; Lazarević et al., 2023). Environmentally sensitive technologies not only provide important information to solve current problems, but also support long-term environmental monitoring and research. By collecting continuous and reliable data over long periods of time, scientists can identify trends and patterns that aid our understanding of environmental change. This information is essential to develop sustainable policies and strategies to address emerging challenges such as climate change. Continuous monitoring also serves as a valuable learning tool, raising awareness of environmental issues and encouraging responsible behaviour by individuals, industries and governments. Environmental sensors and sensor technologies are essential to keeping our planet safe. These technologies use a variety of sensors to monitor environmental pollutants (Du et al. 2023), which provide real-time data collection and monitoring capabilities. Such advances are critical to mitigating the effects of pollution and climate change because they provide information needed for informed decision-making and long-term environmental research. As we constantly face environmental challenges, the development and application of environmental sensors remains at the forefront of our efforts to protect our environment and ensure a sustainable future.

IDENTIFYING POLLUTANTS IN SANITARY PAD DISPOSAL

Sanitary pads, essential for women's health and hygiene worldwide, present significant environmental and health challenges attributable to the non-biodegradable materials employed in their production and disposal. A critical step in addressing these concerns involves the identification of pollutants associated with sanitary pad disposal. Common contaminants encompass non-biodegradable plastics like polyethylene and polypropylene, superabsorbent polymers such as sodium polyacrylate, and chemical additives like synthetic fragrances, dyes, and adhesives containing volatile organic compounds. Furthermore, used sanitary pads may host harmful bacteria and microorganisms, elevating health risks for individuals managing the waste. Recognizing and comprehending these pollutants is indispensable for formulating effective strategies to mitigate the environmental and health impacts of sanitary pad disposal (Peter & Abhitha, 2021; Aguilar et al., 2020).

In light of these challenges, it becomes evident that a comprehensive approach is required to address the multifaceted issues associated with sanitary pad disposal. This involves not only acknowledging the ecological consequences of non-biodegradable materials but also considering the potential health risks posed by chemical additives and microbial contaminants. By fostering awareness and promoting sustainable alternatives, society can contribute to the development of environmentally friendly menstrual hygiene practices, thus mitigating the adverse impacts of sanitary pad disposal on both ecological systems and human health.

CHALLENGES OF DETECTING POLLUTANTS IN SANITARY PADS

Analysing the environmental impact of sanitary pads poses several challenges due to their complex composition, characterized by a combination of multiple materials. Identifying and quantifying pollutants becomes a daunting task as traditional chemical analysis methods are often time-consuming and necessitate intricate sample preparation. Compounding the issue, pollutants may be present in low concentrations, rendering conventional techniques optimized for higher concentrations less effective. The heterogeneous nature of the waste stream generated by the varied usage and disposal conditions of sanitary pads further complicates the detection of pollutants in this matrix. Moreover, certain pollutants, such as microorganisms or volatile organic compounds (VOCs), may demand non-destructive analysis methods to preserve sample integrity, contrasting with traditional methods that involve destructive sample preparation. Additionally, the absence of standardized testing protocols hampers the assessment of environmental impacts, making it challenging to compare results across different studies and regions. Many advanced analytical methods for detecting pollutants are expensive and may not be readily available, especially in resource-constrained settings. The disposal of sanitary pads can be a sensitive issue, and obtaining samples for analysis may raise privacy and ethical concerns, particularly if personal information is involved.

To address these challenges, ongoing research is focused on developing more efficient and sensitive analytical methods, as well as promoting the development and use of eco-friendly materials in menstrual hygiene products to mitigate their environmental and health impacts.

The critical concern of environmental pollution, emphasizing its potential irreversible harm to genetic, nervous, and circulatory systems was highlighted by Yang (2023). Luminescent metal-organic frameworks (LMOFs) are spotlighted for their selectivity, sensitivity, and recyclability in detecting pollutants. The paper provides a systematic overview of MOF-based luminescent sensors, addressing the gap in their application to detect various environmental pollutants, including radioactive and heavy metal ions. Another study by Yuan et al. (2023) discuss the pervasive spread of emerging contaminants due to human industrial practices, posing threats to health and ecology. They introduce optical fiber microfluidic coupled sensors as a promising solution, offering controlled microfluidics for precise and stable detection of environmental contaminants. The paper comprehensively reviews sensor characteristics, methodological principles, and applications, envisioning the future role of these sensors in environmental detection. Zhang et al. (2021) examine the promise of sensors in addressing global environmental challenges through pollutant detection, emphasizing the need for advancements in sensitivity, efficiency, simplicity, and miniaturization. The review critically analyses current sensing strategies to guide the future evolution of sensor technology for environmental applications. Zhou et al. (2023) focus on the reproductive toxicity of Per- and polyfluoroalkyl substances (PFAS) in personal hygiene products. Their study reveals the presence of PFAS in products such as paper diapers, sanitary pads, and menstrual cups. Paper diapers exhibit the highest concentrations, raising concerns about potential exposure and environmental emissions of PFAS from these products. The study emphasizes a previously undisclosed exposure pathway of PFAS through personal hygiene items and underscores potential health implications. Additionally, raising awareness about proper disposal and recycling methods is essential to reduce the environmental footprint of sanitary pads.

APPLICATIONS OF ENVIRONMENTAL SENSORS

Environmental sensors (Liang et al.,2020; Liu et al.,2022; Li et al,2022) play a crucial role in monitoring and mitigating pollution across various scenarios. Exploring diverse realms of environmental monitoring, several case studies showcase the practical applications of sensor technologies. In the realm of air quality, urban areas leverage sensors to track pollutants like PM2.5, PM10, NO2, SO2, and O3. A notable example is Beijing, where a sensor network provides real-time air quality data, empowering the government's pollution control measures and enhancing public awareness. Transitioning to water quality, the Chesapeake Bay Program in the U.S. deploys sensors to continuously monitor parameters such as dissolved oxygen, pH, turbidity, and nutrient levels. This approach facilitates the evaluation of water pollution levels, identification of pollution sources, and the implementation of targeted corrective actions (Pooja et al., 2020).

Expanding the scope to industrial emissions, companies employ sensors to ensure compliance with environmental regulations. The Sulphur Dioxide Emission Reduction Project in India exemplifies this, utilizing continuous emission monitoring systems (CEMS) to track SO2 emissions from power plants, thereby contributing to efforts aimed at reducing air pollution. Shifting focus to noise pollution, urban areas benefit from sensors that measure noise levels and identify noisy zones. London's "The Noise App" illustrates this concept, allowing residents to use smartphones for recording and reporting noise pollution incidents, actively participating in collective noise control initiatives. Lastly, in the agricultural domain, soil sensors play a pivotal role in monitoring moisture content, temperature, and nutrient levels. These sensors empower farmers to optimize irrigation and fertilization practices, effectively mitigating soil pollution arising from excess nutrients.

POTENTIAL OF ENVIRONMENTAL SENSORS IN SANITARY PAD DISPOSAL

Environmental sensors play a crucial role in addressing the environmental challenges associated with sanitary pad disposal, contributing to pollution in water bodies and landfills. In various pollution monitoring scenarios, these sensors have demonstrated success by providing real-time data for decision-making and pollution control. In the context of sanitary pad disposal, they offer potential improvements in waste management, compliance monitoring, and reducing the environmental impact of sanitary pad waste.

One application of environmental sensors is bin level monitoring, where sensors placed in sanitary pad disposal bins can track fill levels. Alerts can be sent to waste management teams when bins reach capacity, ensuring timely collection and preventing overflowing bins, which can lead to littering and environmental pollution. Additionally, sensors combined with RFID or barcoding technology facilitate waste sorting and tracking, aiding in proper disposal, recycling, or safe incineration, thus reducing the environmental impact.

Compliance monitoring is another key application, as sensors can ensure adherence to sanitary waste disposal regulations. For instance, in public restrooms, sensors can monitor disposal practices, providing data for awareness campaigns or enforcement measures. Environmental sensors also contribute to the Environmental Impact Assessment (EIA) process by strategically placed measurements near disposal sites, including landfills and incinerators. These sensors assess air quality, soil composition, and water quality, providing essential information for making informed decisions regarding the environmental impact of sanitary pad disposal.

Environmental sensors are instrumental in air quality assessment, measuring pollutants released during disposal and incineration, such as VOCs and particulate matter. This accurate data helps understand the impact of emissions on nearby ecosystems and public health, informing assessments and protective measures. Similarly, sensors in water bodies detect changes in water quality due to leachate or runoff, offering critical data for safeguarding aquatic ecosystems and community water supplies.

Soil analysis near disposal sites is facilitated by sensors, providing crucial data for assessing the impact on soil ecosystems. This includes potential harm to plant life, disruptions to nutrient cycles, and impacts on soil organism health. Biodiversity and habitat monitoring benefit from environmental sensors, offering comprehensive data on how sanitary pad disposal affects local ecosystems, informing conservation efforts.

Moreover, environmental sensors contribute to assessing public health implications by measuring pollutants in the air, water, and soil. This data helps understand exposure pathways and health hazards, enabling the formulation of protective measures and regulations. Data-driven decision-making is empowered by environmental sensors, providing accurate and comprehensive information essential for developing effective regulations and minimizing negative impacts on ecosystems and human populations.

The continuous collection of long-term data is emphasized, as some consequences may only become apparent years after disposal activities cease. In conclusion, the data collected by environmental sensors are critical for conducting an EIA of sanitary pad disposal, enabling informed decisions and actions for the well-being of ecosystems and human populations.

SOLUTIONS AND MITIGATION

Proper disposal of sanitary pads is a significant environmental and public health concern, involving waste management, hygiene, and environmental impact. Solutions and mitigation strategies that can be considered are mentioned below.

Promoting awareness and education on proper disposal through community programs, schools, and social media campaigns. Environmental sensors can monitor changes in disposal habits, assessing the success of awareness initiatives.

Encouraging the use of biodegradable sanitary pads to reduce environmental impact. Sensors can monitor decomposition rates in landfills or compost facilities, providing insights into their sustainability.

Ensuring waste management facilities, such as incinerators and sanitary landfill sites, are available and equipped to handle sanitary pad disposal safely. Sensors monitor facility efficiency and capacity, preventing overloading and ensuring safe operation.

Installing dedicated disposal bins for sanitary pads in public and private spaces, with sensors monitoring fill levels. Real-time data helps schedule timely disposal and prevent overflow.

Investing in waste-to-energy conversion technologies for safe incineration. Sensors monitor emissions to ensure compliance with environmental standards and prevent harmful pollutants.

Promoting recycling programs for specific components of sanitary pads, such as plastic backings. Sensors track the recycling process, ensuring efficiency and eco-friendly use of recycled materials.

Encouraging the development and use of environmentally friendly materials for sanitary pads. Sensors monitor the environmental impact, aiding the transition to more sustainable practices.

Empowering communities to use environmental sensors for monitoring and reporting improper disposal. Community-driven sensors provide real-time data, enabling authorities to respond promptly.

Implementing and enforcing regulations on manufacturers and distributors, including labeling requirements and extended producer responsibility. Sensors help monitor compliance and track the environmental impact of regulations. Environmental sensors, including air quality sensors, landfill gas detectors, and waste monitoring systems, play a crucial role in informing and improving solutions to sanitary pad disposal issues. They provide essential data for making informed decisions, optimizing waste management processes, and assessing environmental impact, ultimately leading to more sustainable practices.

FUTURE DIRECTIONS AND RESEARCH OPPORTUNITIES

The field of environmental observations developed rapidly in response to concerns about climate change, pollution, and the sustainable management of natural resources. Technological innovations enable accurate and scalable data collection on various environmental parameters. Future R&D opportunities in this area include:Miniaturization and Sensor Networks: Development of smaller, cost-effective, and energy-efficient sensors for large-scale use in sensor networks. These networks can provide high-resolution data on air quality, temperature, humidity and soil conditions.Advanced Data Analytics: Process increasing environmental sensor data using advanced analytics, including machine learning and artificial intelligence, to efficiently process, analyze and interpret data and identify trends, anomalies and patterns.Integration with the Internet of Things and Smart Cities: Explore the seamless integration of environmentally sensitive technology into urban infrastructure for real-time monitoring and adaptive resource management as smart cities and the Internet of Things (IoT) evolve. Improved environmental forecasts: Improve models and tools for predicting environmental change, including weather forecasting, long-term climate modelling, and prediction of natural disasters such as hurricanes, fires, and floods. Ocean and Space Research: Extend environmental monitoring beyond Earth by exploring innovations in underwater sensor technology to monitor ocean health and study extreme environments, and space-based sensors to study Earth's atmosphere and beyond. Biodiversity Monitoring: Develop sensors and data collection methods for biodiversity monitoring and conservation, including acoustic sensors for wildlife monitoring, cameras for wildlife monitoring, and environmental DNA (eDNA) technologies for species identification and tracking. Environmental Health and Epidemiology: Explore how environmental monitoring can contribute to public health, such as using sensors to detect air and water quality to control the spread of diseases and epidemics. Environmental Ethics and Policy: Explore the ethical implications of large-scale environmental control, addressing privacy, data ownership and potential abuse. Develop rules and regulations that balance the benefits of surveillance with the protection of individual rights and privacy. Renewable energy and sustainable development: Sensor technology research to improve the efficiency and sustainability of renewable energy sources, to optimize energy production and storage, and to support the development of environmentally friendly technologies. Interdisciplinary Collaboration: Encourages collaboration among environmental scientists, engineers, data scientists, and social scientists for multidisciplinary research that addresses complex environmental problems and develops comprehensive solutions. Community Engagement and Citizen Science: Engaging the public in environmental monitoring through citizen science initiatives using crowdsourced data to improve the reach and accuracy of environmental monitoring efforts. Carbon Sequestration and Mitigation Technologies: Develop sensors and monitoring systems to track carbon sequestration efforts and evaluate their effectiveness in mitigating climate change.

CONCLUSION

The field of environmental sensing is ripe with opportunities for innovation and research. As technology continues to advance, there is enormous potential for environmental sensors to play a pivotal role in our efforts to understand, mitigate, and adapt to environmental changes. These innovations are crucial for achieving a sustainable and resilient future.

This book chapter aims to shed light on the critical issue of sanitary pad disposal and the role of environmental sensors in identifying and mitigating the associated problems. By providing a comprehensive overview of the topic, including case studies and potential solutions, it will serve as a valuable resource for researchers, practitioners, and policymakers working towards a cleaner and more sustainable environment.

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Chapter 17
Bioindicators of Environmental Pollution With Emphasis to Wetlands of Kashmir

Kounsar Jan
Government Degree College Thindim Kreeri, India

Javid Majeed Wani
Government Degree College Dangiwacha, India

ABSTRACT

The use of bioindicators has grown in recent years, and they have provided a wealth of valuable data that has improved water resource management. One way to measure the quality of an environment is by looking at how well a species (or group of species) can adapt to different kinds of chemical, physical, and biological stresses. A further benefit of bioindicators is their capacity to detect the indirect biotic impacts of contaminants, a feat that is not accomplished by many physical or chemical tests. When used as bioindicators, the varying degrees of stress that various aquatic species can withstand might provide light on the nature of a given environmental problem. Zooplankton species such as Branchionus sp., Molina sp., Keratella cochlearis, Daphnia sp., and Cyclopus sp., as well as phytoplankton species such as Euglena viridis, Oscillatoria limosa, Nitzschia palea, and Scenedesmus quadricauda, are indicators of water pollution. The goal of this study is to showcase some new plankton research that focuses on their potential and uses as bioindicators of water quality.

INTRODUCTION

One way to measure environmental quality and its changes over time is via bioindicators, which might be biological processes, species, or communities. Anthropogenic stressors are the main focus of bioindicator study, while natural stressors like as drought and late spring freeze are also considered contributors to environmental change. Anthropogenic disturbances include things like pollution and changes in land use. Since the 1960s, bioindicators have been extensively studied and used. Using all the main taxonomic

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groupings, we have expanded our bioindicator repertoire throughout the years to help us investigate both aquatic and terrestrial habitat (Cairns et al., 1993).

To be sure, not every living thing, ecosystem, or biological activity can be used as a bioindicator. Different settings have different physical, chemical, and biological elements, such as substrate, light, temperature, and competition. Over time, populations adapt to their environments by developing strategies that maximise fitness, which is defined as the rate of growth and reproduction. Because they can withstand environmental change to a reasonable degree, bioindicator species are able to accurately reflect environmental conditions. Contrarily, the overall biotic reaction is not always reflected in the sensitivity or frequency of encounters with uncommon species (or assemblages of species) with low tolerances for environmental change. Similarly, animals that are present everywhere and have a wide range of tolerances are less affected by changes in their environment that might otherwise affect other members of the community. Nevertheless, bioindicators aren't confined to a single species with low environmental tolerance. A "biotic index" or "multimetric" technique may evaluate environmental state using whole communities as bioindicators. These communities cover a wide range of environmental tolerances (Carignan et al., 2001).

In addition, bioindicators might be individual biological activities. One example is the coldwater streams found in the western United States, where you may find cutthroat trout. Since the highest temperature tolerance range for most people is 20–25°C, their temperature sensitivity provides a useful bioindicator for measuring water temperature. When cutthroat encounters thermal pollution, it reacts instantly on a cellular level. In order to safeguard critical cellular processes against heat stress, there is an increase in the production of heat shock protein (HSP). By measuring hsp levels, we can gauge thermal stress in cutthroat trout and evaluate the impact of environmental changes. When heat stress lasts too long, people may usually control their own physiological changes by adjusting their behaviour and slowing down their development. Large and sustained temperature changes, on the other hand, might cause compositional shifts to warmwater fisheries, which in the worst case scenario can lower population numbers or even cause local extinctions (Elphick et al.2000).

Worldwide, changes in land use, rising populations, and more urban, agricultural, and industrial uses have all contributed to a greater need for potable freshwater. The daily water consumption in the US is around 1.5 billion cubic metres. One of the most significant problems that human civilizations have encountered in the last half-century is water contamination, says the UNDESA. The quality of water is declining as a result of an increase in human activity. Human health, sanitation, and biodiversity are all impacted by water-quality concerns. Water contamination is still a major issue on a worldwide scale, even though there has been significant success in cleaning up rivers in many regions. Water contamination poses risks to human health, reduces agricultural yields, diminishes ecological services, and slows economic development. Keep people's lives, ecosystems healthy, and economies strong by ensuring a sustainable supply of clean water. Both the water supply and its distribution networks face several obstacles, one of which is the presence of biological and chemical pollutants. The security and longevity of several water supplies are also jeopardised by the deteriorating infrastructure of water systems. Natural and human-made factors, including reservoir retention, water diversion via channelization, and variations in precipitation and melting, influence the dynamics of water quality (Fjerdingstad et al.,1964). Subtle variations in soil temperature, atmospheric deposition, and changing patterns of vegetation may also affect changes in water quality, and these impacts are complicated and interrelated. In situations like chemical spills or wastewater lagoon discharges after heavy rains, the ability to detect short-term changes in water quality is crucial. For effective resource management, it is crucial to track trends over the long term. There is now a better chance to monitor and manage large-scale water systems thanks to new technology that include in-situ sensors, data platforms, and analysis (Vasconcelos et al., 1999).

Many different things, including chemical, physical, and microbiological components, contribute to water contamination. Legacy and developing pollutants of various forms remain a worry in the majority of industrialised nations. Nonetheless, there has been a dramatic change in the pollution balance across time (Uttah et al., 2008). Reducing discharges of untreated sewage and industrial contaminants to rivers has improved their quality. The UN Environment Programme (UNEP) conducted a research on lake water and found four major issues that pollute freshwater lakes and water. Organic stuff (including plant nutrients from agricultural runoff, such as nitrogen or phosphorus), chemical contaminants, pathogens (from human and animal waste), and salt (from irrigation, residential wastewater, and mining runoff into rivers) are all examples of this (Turner and Dale, 1998). A combination of factors, including rising populations, improved farming practices, and more industrialization, has led to a rise in nonpoint source pollutions, particularly in developing nations. To measure biochemical signals, an analytical instrument called a biosensor brings immobilised biological material into close proximity with a transducer that is compatible with the substance. The biomolecules are in charge of the analyte's particular recognition, and the electrical output signal is amplified by the electronic component of the physicochemical converter. A wide range of fields may benefit from biosensors, including agriculture, food quality control, medicine, the military, and environmental process control. For effective environmental management and monitoring, biosensors are essential because they can quickly pinpoint the location of contamination. The portability of biosensors also gives them an edge over other analytical techniques; researchers can use them to detect pollutant concentrations in real time, and they don't need to prepare samples beforehand to do so. Additionally, they may provide information on the biological impact of compounds (such as a compound's toxicity) in addition to determining the compounds themselves.

Biosensors have emerged as a valuable tool for identifying and tracking biological and chemical components for nutritional, ecological, and clinical purposes because of their remarkable performances, which include high sensitivity and specificity, quick response, cheap cost, relatively small size, and easy operation. As a consequence of an ecosystem's nutrient enrichment, eutrophication has become the most common water-quality concern. Phosphorus and nitrogen, which originate in urban and agricultural areas, make up a large portion of nutrient loads. Eugenication was also a problem for big bodies of water. According to the World Wildlife Fund, the quantity of phosphorus in the Baltic Sea has grown tenfold in the last hundred years (Rosenzweig, 1995). According to research conducted by the United Nations Environmental Programme (UNEP), nutrient enrichment on coastal hypoxia has led to eutrophication in around 40% of the world's lakes and reservoirs, resulting in algal blooms that pose a health risk to humans. Although the exact process of eutrophication remains a mystery, nitrogen and phosphorus are widely believed to be the principal nutrients responsible. Due to nonpoint pollution from farming and urbanisation as well as increasing discharge of household waste, nutrient levels in many rivers and lakes have risen dramatically over the last half-century (Pandey and Verma. 2004). Marine biotopes are at risk of air loss or quality decrease due to eutrophication, pollution, uncontrolled fishing operations, and human settlements; this is especially true in shallow bodies of water that are surrounded by land, like the Baltic Sea. An growth in the usage of wastewater treatment technology caused a halt or slowdown in water-quality deterioration in several lakes of industrialised nations by the year 2000. Nevertheless, in many nations where agricultural fertiliser application is very high and in areas where pollution removal is economically unfeasible, eutrophication of water bodies is rapidly increasing. Human waste, agricultural effluent, and very harmful industrial effluent make up over 80% of untreated sewage released in underdeveloped nations. Rivers, lakes, and shorelines have been contaminated by sewage flows. According to Hallegraeff (2003), harmful algal blooms (HABs) are caused by changes in the type and amount of nutrients. Episodic or chronic low-level nutrition supply from outside sources may induce and maintain HAB. As a result, managing water quality now requires the ability to identify and forecast HABs and associated pollutants.

Wildlife and aquatic life are negatively affected by the degradation of freshwater habitats caused by pollution. Drinking, bathing, and agricultural water quality are all affected by the kinds and amounts of pollutants in the water. It is frequently impossible, very expensive, and a laborious process to remove contaminants from water. Because smaller towns sometimes lack the financial resources to invest in costly treatment technology, pollution has a greater effect on drinking water supplies in these places. Lake Dianchi and Lake Taihu in China are two examples of drinking water supplies that have become very or hyper-eutrophicated, which has caused problems for both the environment and human health. Because of the severity of the situation, several fish species and natural water plants in these lakes died off. Deadly low oxygen levels at the ocean floor kill snails. Supplying water for household use that satisfies legal criteria has been hard due to the water's low quality. Industries that produce harmful substances, such those involved in tanning leather and making chemicals, are increasingly relocating from industrialised to developing nations. There have been isolated areas with better water quality, but overall, water contamination is becoming worse over the world. A change in native plant and animal life is occurring in the Florida Everglades as a result of eutrophication. A total of 69 µg/L of phosphorus was found in Lake Okeechobee in 2007, according to Richardson et al., even though more than 17,000 hectares of stormwater treatment sites have been used since 2004 (Oberholster et al., 2009).

Concerns about water pollution from livestock activities in agriculture have persisted for a long time. Concentrated animal feeding operations (CAFOs) have been more common in the last 30 years, and the increased waste volume and toxins in this waste pose a bigger threat to water quality. It is found that manure and sludge from increased agriculture may contaminate surface and groundwater, which can lead to health issues. The fact that CAFOs may act as a "point source" for many different kinds of pollutants has caused some worry. Nutrients, growth hormones, antibiotics, chemical additives in manure or equipment cleansers, infectious diseases like Escherichia coli, blood, silage leachate from maize feed, and copper sulphate used in cow footbaths are all part of the waste streams. For instance, compared to the yearly sanitary waste generated by the city of Philadelphia, Pennsylvania, which is home to over 1.5 million people, a huge pig farm with 800,000 pigs might create over 1.6 million tonnes of trash (Mittal, 2009). Because of this, CAFOs need a sizable waste treatment facility next to the farm. Lagoons are often used to hold wastewater before treatment. Landfill lagoons have the potential to overflow during rainstorms, releasing massive amounts of wastewater into neighbouring bodies of water. Surface drainage systems, adjacent streams, and man-made ditches provide additional pathways for contaminants to migrate.

Accidental pollution of groundwaters, rivers, and lakes—sources of raw drinking water—occurs often. There is serious worry that dangerous bacteria and other microbes may contaminate water sources used for drinking. Aeromonads may be easily extracted from both nutrient-rich and nutrient-poor settings, and they are present in every aquatic habitat. Many types of Aeromonas bacteria are known to cause gastroenteritis and other gastrointestinal illnesses. They may be found in both unprocessed and treated water for human consumption. There has been growing concern in recent years over the occurrence of mesophilic Aeromonas in public drinking water sources. A drinking water distribution system has been contaminated in several regions of the globe as a result of mixing with sewage water and other contaminants. As a result, mesophilic Aeromonas have contaminated drinking water in Finland and Scotland (Noss, 1990).

While there are several potential entry points for contaminants into groundwater, the most common ones are floods, incorrect disposal of pollutants, nonpoint sources, and issues with well integrity. As an example, in 2015, the Texas Commission on Environmental Quality recorded 276 more instances of groundwater pollution, adding to the more than 3,400 total cases they were handling. Authorities were compelled to inform private well owners that their drinking water might be polluted, with one-third of these contaminations originating from petroleum storage tanks (Nkwoji et al, 2010). Another incident that occurred in February 2018 at Clean Harbours Colfax, Grant Parish, Louisiana, USA, included the spillage of around 400,000-450,000 gal of water from a containment vessel. A 45-foot-wide sinkhole leaked water contaminated with low-level radiation and other contaminants into a key drinking water aquifer in 2016 in rural Polk County, central Florida, near a fertiliser company.

Biosensing cells—whether naturally occurring or engineered—from many sources, including microbes, plants, algae, fungus, protozoa, etc.—form the basis of whole cell-based biosensors. Whole cells provide several benefits when used as biological components of recognition. Since whole cells are more amenable to cultivation, isolation, and purification than enzymes, whole cell-based biosensors are often more cost-effective than enzyme-based biosensors. A large shift in temperature, ionic strength, or pH is less of an issue for whole cells. One cell may house all the enzymes and cofactors required to detect the analyte, allowing for a multistep reaction to be performed. Allowing cells to regenerate while functioning in situ makes it easy to repair or maintain these biosensors. Sample preparation is often unnecessary. One drawback of these devices is that they are more likely to be interfered with by pollutants that aren't targeted analytes, unlike enzyme-based biosensors. Furthermore, in comparison to other biosensor kinds, their reaction time is somewhat sluggish.

Ammoniacal copper zinc arsenate (ACZA), a water-based wood preservative, has also contributed to environmental arsenic pollution. Wood goods that are allowed to be labelled as having been treated with chromium arsenate include commercial wood shakes, shingles, and permanent foundation support beams. Pressure treatment of timber has used copper-chromated arsenicals (CCA), a water-based wood preservative, since the 1930s. Timber has traditionally been pressure treated to prevent termites, fungus and other pests from destroying wood goods. Heavy metals may be released into the environment unintentionally from CCA-treated wood at several stages of its life cycle, including production, handling, use, and disposal (Khan et al., 2006). The solubility of arsenic salts varies greatly with pH and the ionic environment in water, despite the fact that elemental arsenic is insoluble in water. The most common form of arsenate in oxygenated settings, such surface waters, is arsenate [As(V)], while arsenite [As(III)] is more prevalent under reducing circumstances.

Biomonitoring

Essentially, the traits of a biosphere are defined by the bio-organisms that inhabit it. The term "bioindicators" may refer to these creatures, and the definitions of "biomonitors" might vary widely (Purdy 1926; Mohapatra & Mohanty 1992; Gaston 2000; Gaston (2000), and Chakrabortty and Paratkar (2006), bioindicators can be used to determine the quality of changes in the environment, while biomonitors can get quantitative information on the quality of the environment through biological monitoring. The latter also incorporates data regarding past aggravating factors and the impacts of various variables. According to several studies (Burger & Gochfeld 2001; Mahadev & Hosmani 2004), monitoring can be carried out for a variety of biological processes or systems in order to observe changes in health status over time and space, determine the effects of certain environmental or human-made stressors, and evaluate the success of anthropogenic measures. Biological monitoring relies heavily on species variety as a key component in order to ascertain the state of the ecosystem (Marques 2001; Joanna 2006). Biomonitoring has grown in importance as a tool for studying water contamination and is a crucial part of water quality assessment (Vitousek et al., 1997; Butterworth et al., 2001). All living things have the potential to operate as biomonitors, however when it comes to water contamination, the points mentioned above are particularly relevant to planktons and related species (Singh et al. 2013).

Planktons

Plankton perform a crucial role in the biological production of many aquatic environments, including lakes, streams, swamps, and oceans. Phytoplankton and animals like zooplanktons are the two main groups of organisms that make up planktons. Communities of plankton float on the water's surface, yet they fusing and cycling vast amounts of energy that are subsequently transferred to higher trophic levels (Walsh 1978). Plankton studies in Indian lentic habitats began in the middle of the twentieth century. Based on factors such as supplement status, age, morphometry, and location, these investigations showed that the predominate planktons and their regularity vary greatly across different bodies of water. According to Thakur et al. (2013), they may also be utilised to determine the trophic level of lakes. Because of their short lifespan and high reproductive rate, planktons are considered good indicators of water quality and trophic conditions, and they respond quickly to changes in the environment. with their native habitat, planktonic organisms are defined by their resistance range with respect to biotic linkages among organisms and abiotic ecological components (such as temperature, oxygen fixation, and pH). The trophic status of bodies of water may be inferred from changes in plankton populations (Pradhan et al., 2008). As a measure of water contamination, planktons The greatest indicators of water quality, and in particular lake conditions, are planktons because of their extreme sensitivity to environmental changes. Planktons are being investigated for use in lakes as a means of monitoring water quality, particularly in cases of high phosphate and nitrogen concentrations, which may be signalled by an increase in the reproductive rate of certain planktons. This indicates that the water quality is low, which might have an effect on the aquatic life there. You can tell the lake is healthy just by looking at the planktons; they're also the main source of food for a lot of bigger creatures. Being an indication of water quality and the primary food supply for many species, plankton plays a crucial role for marine creatures (Thakur et al. 2013). Although plankton are essential for biological decomposition of organic materials, excessive plankton populations provide additional challenges to water body management. Grazing planktons is a crucial ecological function, and fish play a key part in this. Fish do an essential double-duty by regulating the number of planktons in the pond and by transforming the nutrients in wastewater into a form that people can eat. Also, certain planktons, including cyanobacteria, create poisons that inhibit fish development. According to Pradhan et al. (2008), planktons may be classified as either beneficial or detrimental when it comes to the generation of fish using wastewater.

Phytoplankton

Phytoplanktons, sometimes called microalgae, have many characteristics with terrestrial plants, including chlorophyll and the need for sunlight for photosynthesis and other life processes. Since most of them are nocturnal, they spend their time swimming in the upper ocean, where more light reaches. Photosynthesis and development go hand in hand since they are both dependent on the absorption of light and the incorporation of nutrients. Indicators of how vulnerable algae are to pollution include changes in population size and/or the rate of photosynthesis. In general, contaminants have the same effect on algae as they do on other species, whether it's on population growth or photosynthesis. Phytoplankton species diversity changes may be an indicator of marine ecosystem contamination (Hosmani 2014).

Zooplanktons

Microscopic creatures that inhabit the water's surface are known as zooplanktons. Because of their lack of swimming ability, they must depend on the ebb and flow of the ocean for transportation. Phytoplanktons, bacterioplanktons, and debris (such marine snow) are their food sources. For fish, zooplankton are an essential component of their diet. In addition to their usefulness as bioindicators, they contribute to the assessment of water contamination levels. Along with fish, they are the primary source of nutrition for a number of marine species in freshwater ecosystems (Walsh 1978). Their role in a body of freshwater's production, eutrophication, and water quality indicators is widely believed to be crucial. Seasonal changes and the abundance of zooplanktons are two indicators of a body of freshwater's health (Zannatul & Muktadir 2009). An indicator of a biological system's robustness can be the variety of species present, the variety of biomass, and the abundance of zooplankton groups. Zooplankton have great promise as a bioindicator species because their growth and migration are affected by both biotic (e.g., food scarcity, predators, and competition) and abiotic (e.g., temperature, salinity, stratification, and pollutants) factors (Ramchandra et al. 2006). What we know about zooplanktons as the pH dropped from 7.0 to 3.8, mechanical fermentation reduced the number of species and altered the potency of those that remained. The zooplankton of Darjeeling, Himalayan Lake Mirik was the subject of a study by Jha and Barat. Toxins introduced into the lake from outside sources caused its pH to drop and its acidity level to rise, so polluting the lake (Jha and Barat 2003). Examination of other physiochemical measures and planktons corroborated this. *Bosmina, Moina,* and Daphnia were among the cladocerans discovered in this state, along with the most widespread copepods, Phyllodiaptomus and cylops. Since these species acted as a bioindicator to draw attention to the health of this aquatic body, the study's underlying assumption was that the lake could not be used as a water supply shortage. Since *Trichotria tetrat* were found in the lake, which was abundant in phosphorus and other heavy metal particles, Siddiqi and Chandrasekhar concluded that they may be used as pollution indicators. The original source of this species was tanks that had been polluted with sewage (Zannatul & Muktadir 2009). The growth of zooplankton was hindered by the lake's phosphorus and metal particles, high aggregate alkanity, hardness, and conductivity (130 ms m^{-1}) (Ramchandra et al. 2006). In a wide range of habitats, zooplankton may be found. Limiting factors include, but are not limited to, depleted oxygen, temperature, salinity, and pH. The presence of three different species of Brachionussp in the lake suggests that it is being naturally polluted and is experiencing eutrophication. Seasonal studies of zooplanktons revealed that their density was greatest during the rainy season and declined during the summers owing to high temperatures; this suggests that the population of copepods varies across different water bodies in India. The zooplankton kingdom is dominated by copepods, with cladocera, rotifers, and ostrocoda following closely after. As a result, zooplankton is a great bioindicator for gauging the level of pollution in seawater and other marine bodies (Zannatul & Muktadir 2009).

Fish

The sensitivity of fish to pollution has led to their extensive documentation as indicators of water quality. An important topic in ecology is estimating the number of species in a given region. Species diversity is associated with ecological system functioning and provides insight into the causes and consequences of environmental disturbances like pollution. Quantifying the danger of extinction and, by extension, prioritising the protection of regions rich in biodiversity, is another important application of species diversity estimates. Unfortunately, comprehensive surveys that detail the species richness and diversity in great detail are rather uncommon. Important data may be derived via surveys or biota sampling instead (Hall et al., 2004; Plafkin et al., 1989).

MACROPHYTES IN NORTHERN HIMALAYAN DAL LAKE OF KASHMIR

Depending on their location, macrophytes may be either submerged, floating, or free-floating. Heavy metals may be absorbed by submerged macrophytes. There are many different kinds of phenolics and flavonoids in the floating macrophyte Nymphaea, which gives it a strong antioxidant potential. Some are medicinal, some are consumable by humans, and a great number of them have strong antioxidant capabilities. To ease gastrointestinal problems, people turn to the marginal emergent species Polygonum. Flowers, leaves, roots, and rhizomes are only a few plant parts that have a wide range of pharmacological effects. Diabetes, fever, liver issues, and jaundice are among the many diseases that they alleviate. The main lake in Srinagar is Dal Lake, a valley lake located in the centre of the Kashmir valley. Some 1,586 metres above sea level is where it sits. Its probable fluvial origin is supported by the fact that it is an oxbow of the Jhelum River. The lake's surface size has been reduced to 10.4km2 due to construction of a floating garden, land surfaces, and marsh-lands. The lake's surface area is decreasing, which means less water overall and clearer water. Maltchik et al. (2002), Bertoluci et al. (2004), Rolon et al. (2004), and Rolon et al. (2008) were among the latest studies conducted in the Kashmir Valley's wetlands that documented the presence of around 250 aquatic macrophytes. The investigations included a range of geographical scales. According to Irgang and Galstal (1996), the Rio Grande do Sul is home to a diverse array of aquatic macrophytes, with an estimated 500 species. Nonetheless, a wider variety of habitats, such as coastal plain lakes and estuary wetlands, formed the basis of the estimate. Aquatic life in the Kashmir valleys includes a wide range of taxonomic groupings, from macroalgae to angiosperm, and a wide diversity of biological kinds, including submerged, fluted, emergent, and amphibious organisms. New species predominate in the marshes of the Kashmir Valley, and among these groups, Cyperaceae, Poaceae, and Asteraceae are particularly noteworthy. It is believed that low-lying wetlands and the sporadic nature of those forms are responsible for the larger superiority of emergent species compared to the number of hydrophyte species (both floating and submerged) in wetlands. *Nymphaea stellata, Juncus articulate, Ceratophyllumdemersum, Utricularia aurea, Nymphaya, Menthasp*, or any form of water *Batrachium riomi, Nymphoides Peltata, Potamogetionlucus, Ranunculus aquatilis, Polygonumamphibium, or Carexphacot*a Despite this, most species have had low occurrence rates, suggesting that the macrophyte community is quite variable in terms of space. Wetland conservation relies on this kind of spatial variability, also known as ß-diversity. The most notable species of this species found in Dal Lake include *Ceratophyllumdemersum, Hydrocharisdobia, Myriophyllum spicatum, Nulembonucifera, Nymphaea alba, Nymogetoncrispus,* *Trapanatans, Potamogetonlucens, Salvinianatans, and Typhaangustata*. Both macro- and micro-scale environmental factors, such as changes in elevation, habitat size, hydroperiod, communication, and the environmental matrix, can influence the diversity of water macrophytes in wetlands. Micro-scale factors, on the other hand, include things like water and sediment physic-chemical conditions and habitat diversity (Maltchik et al., 2002; Bertoluci et al., 2004 and Rolon et al., 2008).

ENVIRONMENTAL GRADIENTS AND MACROPHYTE DIVERSITY IN FRAGMENTED WETLANDS OF KASHMIR VALLEY

According to many studies (Oertli et al., 2002; Jones and Maberly, 2003; Dahlgren and Ehrlén, 2005), the area is a crucial environmental element determining the abundance of aquatic macrophytes. In Kashmir, the abundance of macrophytes is often influenced by the relative humidity in different regions (Maltchik et al., 2002; Rolon and Maltchik, 2006; Rolon et al., 2008). The area effect (Kohn and Walsh, 1994; Ricklefs and Lovette, 1999) is a direct cause of the high species wealth in big regions, because there is a proliferation of possible colonisation sites. It is also hypothesised that species wealth and area will rise together. Kohn and Walsh (1994) and Ricklefs and Lovette (1999) put forward the idea of habitat diversity, which states that the number of species grows as the habitat rises. Nevertheless, due to their strong correlation, it is difficult to assess the separate effects of habitat diversity and area on wealth (Ricklefs and Lovette, 1999). Coastal Plain wetland macrophyte richness was shown to be habitat diversity and per se area (Rolon et al., 2008).

According to Rolon and Maltchik (2006), the macrophyte of Kashmir's wetlands was mostly affected by elevation. It became difficult to determine the relative contributions of each of these factors on species richness due to the correlation between the area effects and the impact of altitude on macrophyte wealth (Rolon and Maltchik, 2006). The linking of the wetlands is another contributor to the Kashmir Valley's altitude fluctuation, which is likely crucial for the macrophyte community's structure. The most notable species of this species found in Dal Lake include *Ceratophyllumdemersum, Hydrocharisdobia, Myriophyllum spicatum, Nulembonucifera, Nymphaea alba, Nymogetoncrispus, Trapanatans, Potamogetonlucens, Salvinianatans, and Typhaangustata.*

Macrophytes rely on stable and dynamic water environments (Rolon and Maltchik, 2006; Maltchik et al., 2007). There found a far greater abundance of macrophytes in permanent wetlands compared to intermittent ones. Also, the times of least and greatest rainfall occurred simultaneously with the smallest and greatest species wealth, respectively. Although Brose expected a longer hydroperiod for macrophytes in permanent wetlands, this may not be the case in intermittent wetlands, where water scarcity leads to local extinction and/or hydrographies that remain dormant (2001). However, once the water table is restored, the species variety in intermittent wetlands recovers quite quickly, which might indicate that dormancy is a useful strategy for plants in these environments.

Numerous environmental factors, including site, variety of ecosystems, height, water conductivity, nutrient content, and macrophyte richness in aquatic environments, have been computed (Rolon and Maltchik, 2006; Rolon et al., 2008). Additional research conducted in the coastal wetlands of Rio Grande do Sul has shown that the composition of the water macrophytes is influenced by both surface and habitat diversity, which are landscape structural features, and chemical factors in the water, which have additive effects (Rolon et al., 2008). According to Roland et al. (2008), the macrophyte composition was also impacted by the humid hydroperiod.

Identifying the primary environmental variables impacting the composition of the aquatic macrophyte population is crucial for formulating conservation criteria for the Kashmir Valley. Policies pertaining to biodiversity management often give precedence to regions that have a high concentration of endangered species, a high degree of connectedness, and a robust plant abundance. It was recommended that the preservation of wetlands in the Kashmir Valley be given attention, since the area had a significant impact on the variety and composition of the macrophyte in the valley. However, other factors like elevation, hydropower, and ecological variety may also be taken into account.

Macrophyte Community Dynamics in Valley Wetlands

There are large wetland systems in the Kashmir valley's floodplains. According to Junk et al. (1989), the idea of flood pulses implies that the flood plays a significant role in the community's structure and functioning within the river flood system. A complicated variable, the flood event may affect biota in different ways depending on its length, frequency, amplitude, and timing, among other characteristics. Brock and Casanova (2000) state that the new plants' capacity to reach the surface and absorb light was impaired by the flood, which caused them to sink farther into the water. Thus, aquatic plants may be transported throughout the river system by the flood pulse.

Wetland systems rely on the length of floods as a bio stability agent (Turner and Dale, 1998). While some studies have examined the impact of long-term floods on aquatic floods in major river-floor-plain systems (Junk, 1989; Ferreira, 2000; Padial et al., 2009), data on the structure of aquatic macrophytes pertaining to short-term floods is still rare in the literature. The structure of macrophyte communities may be altered by long-term changes in environmental circumstances, which can alter species richness, biomass, and relative abundance. There were changes in wealth and total macrophyte biomass following a long-term flux (38 days) in a shallow lake linked with the river flat, which challenged the stability of the macrophytic community (Maltchik et al., 2004). There was no change in species wealth, but there was a shift in biomass in water macrophyte assemblies during flows of one to three days (Schott et al., 2005; Maltchik et al., 2007).

Another crucial characteristic of flood disturbance in maintaining the stability of community aquatic ecosystems is the frequency of floods. Even in the short run, the macrophyte community in the Kashmir valley has become much less resistant due to the increased flood rate (Maltchik et al., 2005). Maltchik et al. (2005) also found that dominance was not present in the small lake that had the most flood occurrences. Floods happening again and again are reducing the community's resiliency since the macrophyte can't expand because it recovers too quickly between floods (Maltchik et al., 2005, 2007). The number of macrophyte species with changed biomass increased due to the frequent flood episodes in the Kashmir Valley's floodplain palustrins (Maltchik et al., 2007). One to three macrophyte species had their biomass altered after future floods, even though no species had altered its biomass following the first flood (Maltchik et al., 2007).

Macrophyte diversity is impacted by flood-related changes in hydrology and connectivity (Santos and Thomaz, 2007). Furthermore, aquatic plant growth and survival are directly impacted by drainage and flooding episodes (Blanch et al., 1999; Seabloom et al., 2001). The organisation of macrophyte communities is determined by the species' resistance to severe events and floods. Maltchik et al. (2005), Schott et al. (2005), and the Kashmir valley wetland types were impacted by the richness, biomass, and composition of aquatic macrophytes as a result of the change in water-producing phases (flood, no flood, and drainage). According to Maltchik et al. (2005), Schott et al. (2005), and others, the abundance of aquatic macrophyte was often lower during floods. As to Gopal and Junk (2000), a high biodiversity is attributed, in part, to the hydrological variability in inland rivers. A palustrine subtropical wetland's increased species diversity led to a variety of resistances, including those to hydrological extremes (drought and flood) and to the drawdown phase of newly-arrived species (Maltchik et al., 2007).

During the hydrological period, there was a change in the macrophyte biomass of the Kashmir Valley's different kinds of wetlands. at flooded times, biomass was lower in some installations (Malchik et al., 2005); however, in systems that did not have surface water at that time, biomass was higher (Schott et al., 2005). While the biomass peak of several macrophyte species occurs during the flooding season, some species have high values at low water levels, according to Neiff (1975). Community biomass dynamics in flood-affected systems are determined by these shifts in species biomass maxima. The average macrophyte biomass was maintained in both hydrological phases throughout the drawdown phase, according to Maltchik et al. (2007), which was driven by the *Eichhornia azurea* peak during the flood and the Peruvian Luziola and *Eleocharisinters tincta* biomass peaks during the drawdown phases.

FUTURE PERSPECTIVES

The potential for biosensors to detect several contaminants at once is another way they work. That goal has been adequately addressed by many studies. The feasibility of using carbon screen-printed electrodes for the simultaneous detection of estradiol, paracetamol, and hydroquinone in municipal water supplies was shown by Raymundo-Pereira et al. Their research may provide significant insights for the field of wastewater analysis. A luminous sensor made from a stable europium(III) metal-organic framework also showed promising results for water quality measurement. Antibiotic identification testing was performed on it (Li et al, 2022). Additionally, Martins et al. showed interest in the potential of biosensors to detect contaminants in water. Their analysis of the water samples revealed the presence of trimethoprim and sulfamethoxazole.

Biosensors demonstrated encouraging potential for the simultaneous detection of pesticides in water samples using their electrochemical and optical detection biosensors, which are based on various reactions from algae. A mimetic biosensor that can detect several contaminants was also designed in response to these results. Biosensors built for EQ monitoring will keep getting better with the help of new functionalization techniques and innovative nanocomposites and nanomaterials, but new sensing systems, including those that can be coupled with aircraft systems, will have to be developed to meet the need for in-situ and real-time monitoring of contaminants. The key obstacle in meeting the present need for affordable, sensitive, quick, and dependable environmental monitoring devices is closing the gap between the findings of academic research and the commercialization of these biosensors.

CONCLUSION

Biosensors can meet the demand for rapid, reliable, and stable devices to detect environmental toxins, according to this assessment. When applied to complex, unpredictable, and chemically dynamic environmental samples, nevertheless, they ought to satisfy the needs of sensitivity and selectivity. Considerations such as portability, cost, automation, and integration into professional devices should be prioritised when designing biosensors for environmental pollutant detection, regardless of the sensing element or transducer. Continuous use, on the other hand, would necessitate rapid renewal of the biological activity during detection cycles. Standardised laboratory samples are often used to evaluate the biosensor's performance in most studies.

While stability, interference, and ideal operating circumstances may be obstacles for biological sensing components like enzymes, aptamers, DNA, antibodies, and microbes, they nonetheless provide the potential benefit of being amenable to enhancements in selectivity and specificity.

When several physical or chemical measures fail to reveal the indirect biotic consequences of pollution, bio indicators step in to fill the void. The environment will undoubtedly suffer from a conduit that releases phosphorus-rich sewage into a lake. We may assume that certain species' development and reproduction will be enhanced by higher phosphorus concentrations since phosphorus often restricts primary output in freshwater habitats. When species variety decreases or when other species' development and reproduction slow down as a result of competitive exclusion, chemical measurements may not be reliable indicators of these changes. When it comes to bioaccumulation, it is very challenging to determine indirect pollutant impacts using chemical or physical tests. Metals and other pollutants build up in living things, which in turn increases metal concentrations in food webs. Pollutant concentrations at higher trophic levels may therefore be underestimated by chemical and physical methods.

Finally, scientists have realised that biota is the greatest indicator of how ecosystems react to disturbance or stressor presence, even if there are hundreds of chemicals and elements to track. In very speciose settings, there may be issues with using whole communities (and the reactions of all species within them) for informational purposes. It is obviously impossible to determine how every single species in a tropical rainforest will react to a disturbance, given that there may be 300 tree species per hectare on average. In addition, if there are too many different species' reactions (e.g., some may rise and others decrease), it can be difficult to discern a distinct bioindication signal. Scientists often isolate a specific group of organisms or even a single species in these instances in order to account for the full range of impacts caused by a disturbance. Because of this reduction in scope, monitoring is both more cost-effective and more relevant to biology. Furthermore, chemical and physical measures sometimes oversimplify a complex reaction that is typical to these environments with a high concentration of species. To provide a real-time image of the state of the environment, bioindicators utilise a representative or aggregated response that is dependent on the complex complexity of ecosystems. Compared to biosensors based on enzymes, biomimetic sensors have superior kinetic performances, according to current scientific study. But its primary drawbacks, namely lack of specificity and selectivity, persist. The many benefits of bio indicators have exceeded the limitations of these tools. Helpful, objective, simple, and repeatable these are the qualities of the bio indicator. Bio indicators are useful for monitoring the evolution of a particular biological community at different scales, from the molecular to the ecological. One key component of assessing the health of bodies of water is planktonic monitors, which include physical, chemical, and biological aspects. The use of bio indication and biomonitoring has the potential to distinguish between polluted and unpolluted regions, and to research the effects of human activities on ecosystems and their growth.

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Chapter 18
Catharanthus roseus L. and Ocimum sanctum L. as Sensors for Air Pollution

Ab Qayoom Mir
Government Degree College Hajin, India

Javid Manzoor
Shri JJT University, India

ABSTRACT

The expansion of urban areas, the acceleration of traffic, the acceleration of economic growth, and the excessive use of energy are all characteristics of industrialized nations that have contributed to the worsening of air pollution. The integrity of the natural world is compromised by all these elements, which have a domino effect on one another and work together to harm it. A major ecological problem is the regional effects of air pollution on various plant species. Unlike animal populations, plant populations are constantly (24/7) and directly exposed to the danger of pollution. Biochemical, physiological, morphological, and anatomical reactions are among the many ways in which these organisms take in, store, and process contaminants that land on their surfaces. This research aims to find out how two possible therapeutic plant species Catharanthus roseus L. and Ocimum sanctum L. react to different levels of air pollution (vehicular pollution) in terms of their morphology, physiology, biochemistry, and pharmacognosy.

INTRODUCTION

The expansion of urban areas, the acceleration of traffic, the acceleration of economic growth, and the excessive use of energy are all characteristics of industrialized nations that have contributed to the worsening of air pollution. The integrity of the natural world is compromised by all these elements, which have a domino effect on one another and work together to harm it. A study conducted by Kumar and Bhattacharya (1999) compared the rates of economic growth, industrial pollution, and vehicular

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pollution in India from 1975 to 1995. The results showed that when the Indian economy grew 2.5 times, industrial pollution increased by 3.5 times, and vehicular pollution by 7.5 times. Due to the emigration of rural Indians seeking employment opportunities in urban centers, most Indian cities are seeing faster-than-average population growth. Cities are growing and merging with one another because of this. The issue of air pollution has arisen as a result of significant population influxes to metropolitan regions, rising consumption habits, and uncontrolled industrial and urban expansion. Point sources, mobile sources, and interior sources are the three main categories of human-caused air pollution. The use of open fires for cooking and heating may cause significant indoor air pollution in developing nations, particularly in rural regions. Distant sources of air pollution include factories, power plants, and other industrial facilities. However, in both wealthy and developing nations, mobile sources, especially pollution from cars, are the main culprits when it comes to poor air quality in metropolitan areas. Automobile use is expanding rapidly over the world, especially in developing nations (Yunus et al., 1996). India has also seen a surge in car sales in recent years. In India, air pollution is a serious problem in cities, where vehicles constitute a big part of the problem, and in other places where thermal power plants and industrial facilities are concentrated. Increasing levels of air pollution in metropolitan areas throughout the globe have been linked to motor vehicles (Mage et al., 1996; Mayer, 1999). When compared to other cities across the globe, the pollution level in Indian cities is increasing owing to the emissions from cars running all the time, according to the National Environmental Engineering Research Institute (NEERI). Sixty to seventy percent of the pollution in metropolitan areas is caused by vehicles, which considerably adds to the air pollution load (Singh et al., 1995). In India's major cities, air pollution from cars is a major and quickly expanding issue (UNEP/WHO, 1992; CSE, 1996), as it is in many other regions of the world. A number of India's largest cities have severe air pollution problems, with vehicle exhausts being named as a key source of this issue (CPCB, 1999, 2000). The problem has been made worse by the high concentration of automobiles and the relatively high ratio of motor vehicles to inhabitants in these cities (CRRI, 1998; CSE, 2001). Concerns about energy security and global warming are heightened by the fast increase in the use of motor vehicles. Nearly half of the world's oil is currently used by transportation. In the ten years after the 1990s, transportation related energy consumption and carbon dioxide emissions increased by almost one third; low income nations accounted for over half of this growth (Grubler, 1994). The use of petroleum products in India has almost quadrupled in the last ten years, with transportation accounting for half of this increase. The road industry alone consumes 25% of India's total energy, with 98% of it coming from oil. Diesel usage is six times higher than gasoline consumption, despite the fact that gasoline cars constitute the vast majority of vehicles (around 85%). Also contributing to the dramatic rise in fuel usage is the steady transition of freight and passengers away from rail and onto roads (CRRI, 1998). Approximately one million tons of pollutants are discharged into the atmosphere daily in all of the country's major cities, with 75% of that amount coming from vehicles (Chauhan et al., 2004). Hydrocarbons (including aldehydes, single and poly aromatic hydrocarbons, alcohols, olefins, alkylnitrites), carbon particles, heavy metals, water vapour, and oxides of sulfur (SO_2), carbon (CO_2), and nitrogen (NO_2) are the primary pollutants from exhaust, while a variety of secondary pollutants, including ozone, contribute to harmful environmental and health effects (Pandey et al., 1999; Kammerbauer and Dick, 2000). Incomplete combustion of fossil fuels produces polycyclic aromatic hydrocarbons (PAHs), a type of ubiquitous organic chemicals in the environment. Some of these PAHs are very concerning due to their mutagenic and carcinogenic properties (IARC, 1983). It is believed that car exhausts are the primary source of these persistent organic pollutants in large metropolitan conurbations. It is estimated that in the main metros of India, automobiles are responsible for 70% of CO, 50% of HC, 30-40% of NO_2, 30% of SPM, and 10% of SO_2 pollution. Out of this total, two-wheelers contribute two thirds. Respiratory and other air pollution related illnesses, such as lung cancer, asthma, etc., are mostly caused by these elevated amounts of contaminants (CPCB, 2002; Sengupta et al., 2001).

Vulnerability to emissions from vehicles is a result of a complex interplay of variables, including but not limited to: vehicle age, maintenance history, fuel quality, traffic conditions, driving habits, and road conditions. Vehicle maintenance is a major contributor to emissions, according to studies conducted all over the world. For example, using low quality lubricating oils in two-stroke and three-wheeled motorized vehicles can increase particulate pollution by ten times, and diesels with damaged fuel injection systems can increase it by twenty times (Faiz et al., 1996; Shah and Nagpal, 1997). Vehicles are often neglected due to a lack of efficient monitoring and enforcement. Due to insufficient road infrastructure and traffic regulation, congestion has been steadily worsening in Indian cities. The engines used in most conventional cars are either compression ignition (CI) or spark ignition (SI), which run on gasoline or diesel, respectively. Many nations, India included, are also making use of alternative fuels such as LPG and CNG. But in India, the service is only available in the larger cities.

The hydrocarbon molecules that make up gasoline and diesel are a combination of carbon and hydrogen atoms. In a perfect world, all the hydrogen in the fuel would be converted to water and all the carbon into carbon dioxide when these fuels were completely burned in the presence of airborne oxygen. However, this process would have no effect on the nitrogen in the air. Car engines really do release a number of pollutants due to the imperfect nature of the combustion process.

Two main varieties of gasoline engines are the 4 stroke and the 2 stroke. Spark Ignition (SI) gasoline engines, used in most passenger vehicles and light trucks, utilize a spark plug to ignite a combination of fuel and air at the very end of the compression stroke. Pollutants are released when fuel air mixtures may not be burned completely. A number of variables, including fuel quality, driving patterns, road conditions, vehicle maintenance, and other vehicle-related issues, regulate emissions from gasoline-powered engines. Carbon monoxide, hydrocarbons, oxides of nitrogen, particulate matter, and other harmful pollutants including benzene, 1,3-butadiene, and aldehydes, in addition to a few heavy metals, are the most often released pollutants by gasoline fed cars and engines. While aldehydes are byproducts of hydrocarbon partial oxidation, oxides of nitrogen (NO_x) are created when combustion chamber oxygen and nitrogen levels are high. Most of the pollution in cities comes from gasoline powered vehicles, particularly two and three wheelers with mostly two stroke engines.

Lubricating the engine with 2T oil, which may be done by an oil injection system or a premixing mode, is necessary for two stroke and three wheelers. Because mineral based lubricating oil has such a low burning quality compared to gasoline, a significant portion of it that makes it into the engine either doesn't burn at all or burns only partially. This causes smoke and suspended particulate matters (SPM) to be released into the air through the exhaust. In reality, 2 stroke engines need a 2% concentration of 2 stroke oil, or 20 milliliters per litter of gasoline. A little increase of only one percent in oil content may result in a fifteen percent spike in SPM, in addition to the appearance of smoke (CPCB, 1999). Research has shown that between fifteen and twenty-five percent of the oil in a two-stroke engine's exhaust remains unburned (Pundir, 2001). Engines powered by diesel power the most majority of medium- and heavy-duty trucks, buses, and even some passenger cars and light-duty vehicles. Instead of mixing fuel and air before it enters the cylinder, diesel engines inject the fuel at high pressure toward the conclusion of the compression stroke, unlike Spark Ignition (SI) engines. Compressed air in the cylinder ignites the fuel after it has been injected. Because diesel engines run on surplus air and combustion happens largely around a stoichiometric mixture, they produce less hydrocarbons and carbon monoxide than gasoline engines. As a result of the high compression ratio and the combustion occurring near the stoichiometric area, which is at a high temperature, diesel engines produce a great deal of NO_x and other pollutants. When engines run on diesel, they release a lot of diesel particulate matter (DPM). Adding extra fuel causes it to not burn entirely, which causes cracking to occur without oxygen and eventually leads to soot development. Solid, dry carbon particles, heavy hydrocarbons adsorbed and condensed on the carbon particles (soluble organic fraction), or hydrated sulphuric acid (sulfate fraction) may all contribute to the formation of soot. Other harmful pollutants emitted by diesel engines include sulfur oxides, particulate matter, visible smoke, and a host of others, including formaldehyde, benzene, polynuclear aromatic hydrocarbons, and so on. It has been noted that SPM and SO_2 emissions are directly related to diesel's sulphur content (CPCB, 1999). Because of the alarming rise in car exhaust-related illnesses like hypertension, bronchial asthma, malignancies, and more, it is quite concerning that SPM levels in cities over the threshold limits are on the rise. The following factors may contribute to the presence of heavy metals in vehicle exhaust: i) slower vehicles experience more engine wear and tear and produce more particulate matter, including dust, than faster vehicles; ii) vehicles that stop at traffic signals contribute to air pollution; and iii) streets near high rise buildings have less effective ventilation and more pollutant dispersion. There has been a significant uptick in research on the elemental makeup of airborne particulate matter. High concentrations of metals in gasoline and diesel exhaust have been detected, which may be related to traffic (Que Hee, 1994). Zn mostly comes from worn tires, Cu from brake dust, and Fe and Zn from vehicle separation and fluid leaks (Ball et al., 1991). Particulate matter often enters Earth's atmosphere from two sources: first, vehicle exhaust, and second, the Earth's crust. Their ability to float in the air for extended periods of time makes them ideal vehicles for transporting and redistributing metals across the Earth's ecosystem. Their final removal from Earth's system is due to either dry or wet deposition. This means that the atmospheric cycling of the vast majority of metals, irrespective of their source, is closely tied to the destiny of SPMs (Kim et al., 2002). While several researchers from other parts of the globe have collected enough data on environmental trace element distributions (Kretzs Chamar et al., 1980; Carreras and Pignata, 2001), very little is known about India's metropolitan regions.

The locally detrimental air pollution consequences of the rapidly expanding motor vehicle and other energy intensive activities in Indian cities are significant for both regional and global reasons. Air pollution from cars may have consequences on a local, regional, and worldwide scale. Local affects include smoke influencing visibility, ambient air, noise, and other similar factors. Regional effects include smog and acidification. Finally, global warming is an example of a global problem. Soil, water, and air are all directly affected by pollution, along with all the biotic and abiotic characteristics of the ecosystem, including plants and animals. People in urban areas and the surrounding regions are more likely to experience a range of health issues due to air pollution. Because of this, it has gained a lot of attention from scientists and the general public. The fact that vehicle emissions are so close to ground level, where humans breathe, makes it very difficult, if not impossible, to escape vehicular pollution. The symptoms of automobile pollution, which include coughing, nausea, eye irritation, headache, bronchial issues, and impaired vision, contribute to the increased mortality and morbidity rates. An alarming surge in cases of respiratory allergies has been linked to the fast and noticeable worsening of air pollution in metropolitan areas (Hill, 1996). Diesel exhaust has a strong cancer causing potential, according to scientific data from worldwide research. Long term exposure to 1 $\mu g\ m^{-3}$ of diesel exhaust has the potential to cause 300 more incidences of lung cancer per million individuals (CARB, 1998). Living close to heavily populated roads is linked to more asthma hospitalizations, worse lung function, more wheezing episodes, and more severe allergic rhinitis, according to similar research (Diaz-Sanchez et al., 2003). Because air pollution may harm sperm, it can cause mutations, which in turn can cause birth abnormalities or miscarriages, in addition to bronchial or respiratory problems. A higher incidence of heart attacks may be seen among populations living in highly polluted regions.

Air pollution impacts not just people and other animals, but also plants. A major ecological problem is the regional effects of air pollution on various plant species. Unlike animal populations, plant populations are constantly (24/7) and directly exposed to the danger of pollution. Their morphological, biochemical, anatomical, physiological, and other reactions are varied, and they soak up, store, and incorporate the contaminants that hit their surfaces. Despite the fact that a great deal of work has been done in recent decades to establish how air pollution affects plants (Sharma and Tyre, 1973; Yunus et al., 1982; Khan et al., 1990; Jahan and Iqbal, 1992; Sheu, 1994; Carreres et al., 1996; Kammerbauer and Dick, 2000; Li, 2003; Hijano, 2005; Pandey, 2005; Rajput and Agrawal, 2005; Agarwal et al., 2006; Verma and Singh, 2006; Wahid, 2006), most of these studies have been conducted in vitro or to a lesser degree on avenue trees. Specifically, there has been very little research on the effects of vehicle pollution on medicinal plants, despite the fact that these plants are a major supply of medicines for both traditional medicine and modern pharmaceuticals. Air pollution is one of the elements that control the therapeutic efficacy of crude pharmaceuticals.

Additionally, a number of techniques have been used to evaluate the degree of damage to vegetation in its natural habitat and to investigate the interactions between plants and pollutants. To measure the quantifiable effects of contaminants on plants while they develop in their native environments, in situ approaches are often used. While conducting such experiments in natural settings has its benefits (Pandey and Pandey, 1994), there are also several drawbacks, such as the fact that plant material is heterogeneous and environmental conditions can vary greatly, making it hard to pinpoint exactly which environmental factor(s) govern plant responses. Particularly important among the many elements are edaphic (Farley and Fitter, 1999) and biotic (Narayan et al., 1994) regulation. Transplant studies, also known as "Transfer Experiment Studies," provide a more straightforward method by planting uniformly sized seedlings of the same age group in similar edaphic circumstances and irrigating them in the same way. It is important to maintain genetic consistency while propagating plants, hence common stock is used (Chaphekar, 1995). One way to influence the root environment and biotic variables is by using pot cultured transplants (Chaphekar, 2000). It offers a more realistic experience with the air around us, which improves our ability to measure the impact of the atmosphere and makes it easier to compare different locations. (Pandey and Pandey, 1996).

This is the background against which the current investigation into the effects of urban air pollution on medicinal plants in Lucknow was planned and executed. The environmental quality of Lucknow has been negatively impacted by the vehicular population, which grew from 6,79,326 in March 2004 to 9,04,831 in March 2007, a growth rate of 24.92%. *Catharanthus roseus L. and Ocimum sanctum L.* were chosen as the study's plant subjects because of their widespread distribution in Lucknow and their immense therapeutic value.

Invisible, flavorless, and odorless air is a gas mixture that includes 78% nitrogen and 21% oxygen. The remaining 1% is made up of nitrogen and sulfur oxides as well as water vapors, as well as trace quantities of ammonia, ozone, organic matter, salts, and suspended solid particles. This vast expanse of air is thought to be about 1018 kg in total mass. This distinctive atmospheric composition, which makes the planet livable and able to sustain life in its current form, was supposedly created some 4.5 billion years ago, according to evolutionary theory. The atmosphere has played a significant role in shaping plant and animal life on Earth from the dawn of life itself. A number of atmospheric chemical components and other physical variables have become manifestations of this impact, which may have both positive and negative effects (Posthumus, 1998). The chemical climatology of our planet is controlled by both natural and human made phenomena. The second one is a major worry on a global, national, and even regional scale since, unless humans drastically modify our atmosphere, it will be able to maintain a stable equilibrium (Lovelock, 1987). The atmospheric composition and complexity have been altered due to the addition of several contaminants brought about by human activity, which is regrettable and stems from a variety of technological breakthroughs. The growth and wellbeing of people are promoted by these activities, but at the cost of environmental contamination caused by the creation and discharge of undesired chemicals and substances.

The problem of air pollution has been there since the beginning of time, impacting both industrialized and developing nations. Since emissions from man-made sources first appeared, the existence of man-made air pollution has been well-documented. Numerous industrial processes, the biodegradation of waste products, some agricultural and forestry activities, and the combustion of fossil fuels in power plants and engines all contribute to the atmospheric emission of hundreds of distinct chemicals. Because of their low concentrations or lack of toxicity to biological systems, the majority of these substances have little to no impact on the environment. On the other hand, there are a few that are known to cause serious harm to humans, as well as to ecosystems in both their natural and manipulated forms (Barnes et al., 1996). But for quite some time, natural air pollution from things like swamps, lightning, forest fires, and volcanoes has been affecting weather patterns and plant life. Researchers have been looking at how air pollution affects plants for about 160 years (Stockhardt, 1850). Objecting to the soot damage inflicted on the old Roman temples, the Roman poet Horace records the first concerns about atmosphere in his works (Brimblecombe, 1982).

As far as the urban ecology is concerned, air pollution is one of the most detrimental effects of human operations. As a result of chemical reactions triggered by sunlight and a wide range of weather circumstances, gaseous and particle emissions into the atmosphere may cause harm to a wide range of organisms, including humans. There are a lot of different types of air pollutants in cities. The most common ones include sulfur oxides, nitrogen oxides, carbon oxides, carbon particles, heavy metals, hydrocarbons, and a host of secondary pollutants like ozone and peroxyacylnitrate (PAN). Pollutants have a wide range of negative effects on plants, and scientists have made incredible strides in documenting these effects in recent years (Sharma and Tyree, 1975; Yunus et al., 1979, 1982; Khan et al., 1990; Jahan and Iqbal, 1992; Marth, 1995; Singh et al., 1995; Carreras et al., 1996; Altaf, 1997; Shchberbakov et al., 2001; Li, 2003; Hijano et al., 2005; Pandey, 2005; Rajput and Agrawal, 2005; Verma and Singh, 2006; Wahid, 2006). Symptoms, changes in photosynthesis, metabolic and gaseous exchange activities, and tissue damage are all outcomes of the varied ways in which these pollutants impact plants, even at low concentrations (Posthumus, 1983). Numerous variables, including exposure duration, genetic composition, phenological phases, and dosage (pollutant concentration), determine the extent of the effect (Heck et al., 1965). Light, humidity, temperature, water availability, and mineral content are among environmental factors that might influence plant responses to harmful gasses. Several elements, like the source's proportion of emissions, wind direction and speed, geography, etc., affect the quantities of pollutants in the air, which in turn define the impact's intensity.

Pollutant Infusion

The process by which air contaminants are efficiently taken up by plants via their stomata goes like this: (1) Gas enters the leaf through stomata in its gas-phase; (2) Gas within the leaf's air space dissolves in the water on the surface of the plant cell; (3) Gas within the cell, in its liquid-phase, diffuses into the cells according to its concentration gradient; and (4) Gas within the cell undergoes metabolism or decomposition, thus sustaining a gas concentration gradient between the atmosphere and the interior of the plant cell (Omasa and Endo, 2001). According to Yunus et al. (1979), stomata size, quantity, and degree of opening significantly affect the entrance and effect of pollutants on plants. The sensitivity of plants to air pollution is thought to be significantly impacted by stomata, which control the entrance of contaminants into the plant. The cuticle is another potential entry point for contaminants entering plants, alongside the stomatal pathway (Omasa and Endo, 2001).

Oxides of sulfur, which include sulfur monoxide (SO), sulfur dioxide (SO_2), sulfur trioxide (SO_3), sulfur tetra oxide (SO_4), sulfur sesquioxide (S_2O_3), and sulfur heptoxide (S_2O_7), are the most abundant air pollutants. These compounds are primarily formed when inorganic sulphides and sulfur-containing organic compounds found in coal and oil are burned. When it comes to sulfur oxides, SO_2 is by far the most prevalent air pollutant (Gupta and Prakash, 1994). Plants are able to absorb sulfur dioxide from the air because they act as sinks. Because SO_2 is highly soluble and rapidly dissociates in the cell sap, its internal (mesophyll) resistance is low, which means that its diffusion via the stomata determines the foliar absorption. The process of oxidation to SO_4 may be either enzymatic or non-enzymatic. After that, it is moved into the vacuole, where its remobilization seems to be difficult (De Kok, 1990; De Kok and Tausz, 2001). In addition to the dissociation of ingested SO2 and the subsequent reactivity of the generated sulfite with cellular components, acidification of tissue and cells may also contribute to SO_2 toxicity. The effect of sulphur dioxide on plant activity is puzzling since plants may absorb and utilize the gas for both harmful and nutritional purposes (De Kok, 1990; De Kok et al., 1998; De Kok and Tausz, 2001; Deepak and Agrawal, 2001). The sulfur assimilation pathway may take in foliarly absorbed SO_2 either directly or after oxidation to SO_4. From there, it can be reduced to sulfite, which can be used as a nutrient, or it can be integrated into cysteine and organic sulfur compounds. (The works of De Kok (1990), Tausz et al. (1998), and De Kok and Tausz (2001)). Nevertheless, when the quantity of sulfur dioxide in the air reaches levels that are harmful to plants, the aforementioned processes are overwhelmed, and distinctive symptoms manifest, which may be either obvious (morphological) or subtle (biochemical or physiological). various environmental elements, such as the time of year, the availability of nutrients and water, and the presence of various contaminants in gaseous, particulate, and soluble forms, may have either complementary or antagonistic impacts on the development of any kind of injury. When compared to NO_x, sulfur dioxide may pose a greater danger to ecosystems and plant life. The relative phytotoxicity of SO_2 was found to be 2.0 to 2.6 times greater than an equally high concentration of NO_2 in the air, according to a quantitative study of the effects of SO_2 and NO_x on Norway Spruce conducted by Slovik (1996).

Even though nitrogen in the air is a gas with no discernible chemical properties, it undergoes a significant atmospheric event when fossil fuels and biomass are burned: the thermogenic oxidation of nitrogen to form nitrogen oxides (NO_x) ($NO + NO_2$). Products with negative impacts on biological systems are considered pollutants in addition to being chemically active. Several in situ and ex situ experiments have investigated the phytotoxic reactions of these gases and other nitrogenous compounds in the environment, including N_2O_5, HNO_3, HNO_2, NO_3-, and peroxyacylnitrate (PAN), sometimes known as odd nitrogen compounds (NOy) (Roberts, 1995). However, NO_2 has been the most investigated NO component, perhaps due to its role as a precursor molecule for the majority of NO components and O_3, another oxidant that is harmful to plants. Additionally, NO_2 is thought to be more hazardous to plants than NO. Because it forms nitrate and nitrite ions when dissolved in water, it is easily absorbed and transported across the moist interstitial spaces of cells. Comparable to SO_2 entrance, NO_2 enters leaves via the cuticle at a greater rate due to reduced cuticular resistance to NO_2 compared to SO_2 and O_3. Most nitrogen oxides (NOx) in the air come from burning fuels. Direct foliar depositions of NO_2 or indirect depositions in rainfall or soil are two ways in which this gas might enter the plant system. Species of plant, genes, concentration of NO_2, and other variables regulate its entry into the leaf via the stomata (Srivastava et al., 1975). When this happens, it's called translocation, and it happens all across the plant (Yoneyma et al., 1980). Whether it's via the leaves or the roots, plants may take NO_2 from the air or the soil when it dissolves in rainwater as HNO_3 and HNO_2.

Despite the discovery of many pathways by which NO_2 may potentially disrupt typical plant processes, the core mechanism of NO_2 phytotoxicity remains unknown. Several pieces of evidence point to a correlation between NO_{2-} accumulation and the obvious damage (Nouchi, 2002). According to Shimazaki et al. (1992), NO_2- accumulated in leaves from air NO_2 inhibited photosynthesis and produced reactive oxygen species (ROS), which may have contributed to the visual damage caused by NO_2. By altering lipid composition, inactivating enzymes, damaging DNA, and even triggering cell death, these species and free radicals may modify the functioning of membranes. But plants have developed a complex antioxidant defense system that includes low-molecular-weight components like glutathione and ascorbate as well as enzymatic components like SOD, POD, and CAT. These components detoxify O_{2-} and H_2O_2, respectively, and prevent the formation of HO radicals (Mittler, 2002). Plants, particularly those growing in soils lacking in nitrogen, may benefit from a low concentration of NO_2 in terms of their physiological and growth traits. Reason being, ambient NO_2 undergoes a series of reductions in the cell, beginning with NR in the cytosol, followed by nitrite reductase in the chloroplasts, and eventually, amino acids are formed from NH^{4+} (Kondo and Saji, 1992). Since NO_2 and SO_2 often coexist in urban settings, it would be prudent to investigate the combined impact of these two pollutants on plants there.

EFFECTS ON VEGETATION

Morphological Aspects

Air pollution is known to have negative impacts on plants, and the key components that contribute to this problem, such as ozone, sulfur dioxide, and nitrogen dioxide, are well known. The impact of pollutant gas mixtures on various plant species' growth and development may be additive, synergistic, or antagonistic, according to studies. A number of studies have examined the cumulative and sequential impacts of different pollutant combinations. It has long been known that plants are negatively impacted by air pollution, which in turn reduces their development and production (Ashmore and Marshall, 1999; Ashmore et al., 1988). There is consensus that higher plants can experience damage in polluted atmospheres with SO_2 concentrations above 25 pphm (parts per million hundred by volume) (Thomas, 1961; Daines, 1968; Guderian and Van Haut, 1970), and that even four weeks of exposure to 11 pphm SO_2 can reduce yields by half (Ashenden and Mansfield, 1977; Ashenden, 1978). Pollutants can cause a broad range of morphological, physiological, and biochemical changes in plants.

Researchers have shown that some species may experience noticeable leaf damage after being exposed to SO_2 and NO_2 for as little as four hours. It is possible that these gases have an additive or synergistic effect (Tingey et al., 1971). When studying the effects of SO_2 and NO_2 on pea seedlings' enzymatic and physiological levels, Wellburn et al. (1976) discovered that the two compounds worked together. At concentrations ranging from 10 to 25 parts per million of both gases, Bull and Mansfield (1974) found that net photosynthesis was additively inhibited. Ashenden (1979b) conducted an intriguing twenty-week study to find out how different concentrations of SO2 and NO_2 affected the growth of two species: *Dactylis glomerata L. and Poa pratensis L.* The results showed that both the SO_2 + NO_2 and SO_2 alone treatments significantly reduced the leaf area and all the dry weight fractions of the plants. Both species showed decreased tiller and leaf production in the SO_2 + NO_2 treatment, but only *P. pratensis* showed this effect when SO_2 was the only ingredient. Nevertheless, when sprayed alone, NO_2 had no impact on D. glomerata growth but significantly decreased *P. pratensis* leaf area and all assessed dry weight fractions. The same holds true for *Phaseolus vulgaris L.*; when applied separately, 10 pphm SO_2 and 10 pphm NO_2 increased transpiration rates for a short duration, but when applied together, they reduced (Ashenden, 1979a). In a separate investigation, Ashenden and Williams (1980) subjected *Phleum pratense L.* and *Lolium multifolium L* 6.8 pphm (194 $\mu g\ m^{-3}$) of SO_2 and 6.8 pphm (139 $\mu g\ m^{-3}$) of NO_2, which were treated individually and together. Both species yields of leaves and tillers, as well as their leaf area and all dry weight fractions, were drastically reduced when exposed to SO_2 and NO_2. Applying SO_2 alone had minimal effect on both species, but significantly reduced the amount of leaves and tillers produced by *Phleum pratense* and all dry weight fractions measured for *Lolium multifolium*, except for the green leaves dry weight fraction. To confirm the impact on development and growth, reddish *Raphanus sativus L*.cv. *cherry Belle* plants were subjected to 0.8 $\mu l\ l^{-1}$ NO_2 and 0.8 $\mu l\ l^{-1}$ SO_2 in both day and nighttime exposures. When compared to controls exposed to charcoal filtered air, growth was unaffected by sequential exposure to the two pollutants, but growth was significantly reduced when exposed to both pollutants at once (Hogsett, 1984). The cumulative impact of SO_2, NO_2, O_3, and other environmental conditions affecting the performance of four wheat cultivars was investigated experimentally by Ashmore et al. (1988). They found that SO_2, NO_2, and, to a lesser degree, O_3 significantly affected vegetative and reproductive development parameters according to a multiple regression analysis. The impact of low levels of O_3, SO_2, and NO_2 on the development and yield of spring rape plants in containers was studied by Adaros et al. (1991) both individually and in all potential combinations. It is supported by the fact that environmental conditions dictate the degree of impact since the single impacts of O_3 on growth and yield metrics were largely negative and the size of these effects varied with season. O_3 decreased plant dry weight by 11.3% to 18.6% and seed output by 11.4% to 26.9%, but a medium level of SO_2 increased pod weight by 33%. The yield decreased by 12.3% due to the higher concentrations (88 $\mu g\ m^{-3}$). Based on the observed substantial interactive effects, it can be concluded that SO_2 and NO_2 had largely good benefits when used alone, but had antagonistic interactions when combined and, in particular, when combined with O_3, since these pollutants reduced the negative impacts of O_3. The yield was significantly affected by the antagonistic impact of SO_2 on O_3 or NO_2. Even while 56 $\mu g\ m^{-3}$ SO_2 improved yield by 9.9% when compared to the control group, it worsened yield loss due to O_3 by 16.18% to 21.4 percent and decreased yield stimulation from NO_2 by 11.8 percent to 4.2 percent. Using ambient and charcoal filtered air, Wahid et al. (1995) showed that two winter wheat cultivars had a 46% and 38% decrease in grain production, respectively, in an open top chamber research in Lahore, Pakistan. In addition, Maggs et al. (1995) demonstrated that wheat and rice yield metrics in Lahore were significantly reduced at yearly mean concentrations of 20–25 ppb of nitrogen dioxide (NO_2) and 6 hrs. mean concentrations of ozone (O_3) that reached 60 ppb in specific months. *Lolium perenne L.* (Perennial rye grass) and *Agrostis capillaries L.* (common bent-grass) were subjected to mixtures of gaseous contaminants and acid mists during 18 weeks and 22 weeks, respectively, by Ashenden et al. (1996). For the gaseous treatments, we had (a) air filtered through charcoal, (b) 40 ppb SO_2 + 40 ppb NO_2, (c) 40 ppb O_3 with peaks of 2x3 h at 80 ppb and 1x1 h at 110 ppb O_3, and (d) a mixture of (b) and (c) as well as 6 mm per week of solution at pH 2.5, 3.5, 4.5, and 5.6 for the mist treatments. The dry weight of *L. perenne* plants was significantly reduced by all gaseous treatments, with the exception of the SO_2 + NO_2 + O_3 treatment, which had a smaller impact than the additive effects of O_3 and SO_2 + NO_2. The development of *L. perenne* subjected to a pH of 2.5 did not differ in the charcoal filtered air and O_3 treatments compared to the less acidic mist, but this was not the case with SO_2 + NO_2 and SO_2 + NO_2 + O_3 gas treatments. The gas x mist treatments were more effective against A. capillaris plants, and the total shoot weights of plants cultivated in the gas exposure treatments were not significantly different from those grown in the charcoal filtered air. A. capillaris plants were simulated to grow in an environment with a pH of 2.5 and a lower concentration of acid mist in comparison to other gas treatments. For both species, exposure to any gaseous pollution treatment reduced the number of healthy shoots while increasing the number of dead ones. Another research found that Agrostis capillaris plants exposed to gaseous pollutants alone or in conjunction with wet nitrogen mist had leaves that progressively aged. Consistent with the trend of increasing damage over time, this matched up well with leaf dry weights. After 11, 13, and 15 weeks of exposure to pollutants, growth analysis showed that both the 20 ppb SO_2 + 20 ppb NO_2 and 40 ppb SO_2 + 40 ppb NO_2 treatments significantly reduced the leaf areas and dry weight of A. capillaris compared to the charcoal filtered controls and the 10 ppb SO_{2+} 10 ppb NO_2 treatment. According to Kupeinskiene (1997), the gaseous contaminants had a more detrimental impact on the shoots than the roots. These results show that the combined impacts of SO_{2+} NO_2 + O_3 or acid mist may be more harmful to plants than the sum of their separate components would indicate. Research by Shamsi et al. (2000) on the effects of several urban environmental factors, including SO2, NO_2, and O_3, on two crops wheat and rice found that both crops' yields were significantly reduced. Nevertheless, they attribute these decreased yields to the combined effects of NO_2 and O_3, as the concentrations of SO_2 were found to be very low during the research period. Agrawal (2003) found that when exposed to different levels of SO_2, NO_2, and O_3 at different urban sites, *Beta vulgaris, Triticum aestivum, Brassica compestris*, and *Vigna radiate* showed significantly reduced physiological characteristics, pigment content, and above-ground biomass compared to the least polluted sites. The development and production features of Helianthus annuus were shown to be significantly reduced as the dosage of SO_2 increased, when exposed to varied concentrations (142, 285, and 571 μg m^{-3}) of the pollutant (Siddiqui et al., 2004). While conducting a transplant research with wheat, Rajput and Agrawal (2005) found significant changes in a number of growth metrics, suggesting that urban air pollution affects sub-urban agriculture. Air pollution levels at various locations were positively correlated with the physiological traits, growth, and yield of transplanted wheat. Because of the significant impact on production, this research also demonstrated how urban air pollution impacts sub-urban agriculture. The same thing happened to three distinct wheat types in Pakistan when exposed to varying levels of urban air pollution, according to Wahid (2006). In a study conducted by Agrawal et al. (2006), mung beans were cultivated from seed to maturity in several regions of Varanasi, each with its unique pollution load. The results indicated a significant decrease in biomass accumulation and yield, which was strongly correlated with the pollution gradients. Using open top chambers, Rai et al. assessed the impacts of ambient gaseous air pollution on wheat (*Triticum aestivum L.*) grown in a suburban area located in the eastern Gangetic plain of India (2007). Filtered chambers (FCs), non-filtered chambers (NFCs), and open plots (OPs) were monitored for ambient concentrations of SO_2, NO_2, and O_3 every eight hours. We measured yield parameters at harvest after evaluating morphological, physiological, and biochemical characteristics throughout development. In the NFCs, the average SO_2 concentration was 8.4 ppb, NO_2 was 39.9 ppb, and O_3 was 40.1 ppb. As compared to NFCs, FCs had a 74.6% decrease in SO_2 concentrations, an 84.7% decrease in NO_2 concentrations, and a 90.4% decrease in O_3 concentrations. Photosynthetic rate, stomatal conductance, chlorophyll content, and Fv/Fm ratio were all greater in FC grown plants than in NFC and OP grown plants. Plants grown in FCs showed an improvement in morphological characteristics when compared to NFCs and OPs. There was a considerable improvement in plant yield in FCs as compared to NFCs (ventilated with ambient air) and OPs (grown in open spaces). Compared to FCs, NFCs significantly reduced plant development and biomass accumulation due to the detrimental impacts of NO_2 and O_3 on plant physiological and biochemical traits. Lower net assimilation per unit ground surface may result from less radiation absorption if leaf area is reduced.

Physio-Biochemical Aspects

The photosynthetic machinery of all phototropic organisms relies on several photosynthetic pigments. There are many kinds of chlorophyll found in higher plants, including chlorophyll a (the main pigment, which is yellow-green), chlorophyll b (blue-green), and accessory pigments. Light harvesting is linked to both the a and b pigments of chlorophyll. Also, according to Procházka et al. (1998), chlorophyll an is involved in the process of electric charge separation. Chlorophyll is protected from photo-oxidative degradation inside the chloroplast by carotenoids, which also function as antioxidants (Siefermann-Harms, 1987; Polle et al., 1992). However, when our bodies are under a lot of pressure, their usual defense mechanisms can't keep up, leading to cellular death and pigment deterioration (Senser et al., 1990). Many environmental conditions, including light intensity, water scarcity, pollution, and other pressures, have a significant impact on the concentrations of these pigments. Because air pollution is one of the external elements that might affect the levels of chlorophyll and carotenoids, many authors have shown that these compounds react to both internal and exterior stimuli. Chlorophyll depletion precedes carotenoids depletion (Sakaki et al., 1983), and an increase in chlorophyllase enzyme activity may be to blame for this decline in plant chlorophyll concentration (Mandal and Mukherji, 2000). According to Mandloi and Dubey (1988) and Rao and Dubey (1985), SO_2 is a key factor in lowering chlorophyll concentration. Acidic pollutants, such as SO_2, reduce chlorophyll concentration and lead to the synthesis of phaeophythin by acidification, as previously described by Rao and Leblance (1966). Metabolically active tissue of plants, mesophyll, receives sulfur dioxide via stomata diffusion and oxidizes it to sulfate ions. Mesophyll cell pigments are immediately affected by these ions in high concentrations, which may cause photo-oxidation, destruction, or pheophytinization (Rao and Leblance, 1966; Malhotra, 1977). According to Rao and Leblance (1966), when SO2 concentrations were greater, chlorophyll a was degraded into phaeophytin by exchanging Mg^{2+} ions in chlorophyll molecules, while chlorophyll b was degraded into chlorphyllide b by removing the phytol group. On the other hand, others claim that when chloroplasts are exposed to SO_2 in light, superoxide radicals are produced on the thylakoid membranes. These radicals then cause the chloroplasts to enlarge (Wellburn et al., 1972) or even disintegrate (Malhotra, 1976). Light catalyzes processes that oxidize carotenoids, producing epoxide, which is then reduced in the dark by an enzyme catalyzed reaction (Calvin, 1955). Such epoxide cycles indeed occur, and Krinsky (1966) verified their function in preventing photo-oxidation of chlorophylls. Several studies that have been conducted periodically have provided more evidence of this. In addition, Agrawal (1985) found that exposure to SO_2 and O_3 reduced the chlorophyll levels of some agricultural plants. According to Singh et al. (1988), when Dahlia rosea Cav. was exposed to SO_2, its photosynthetic pigments degraded. The most critical plant pigment for photosynthesis, chlorophyll a, is very sensitive to sulfur dioxide (SO_2), making it a negative influence on CO_2 fixation and ultimately stunting the plant's growth and development. Chlorophyll b is about two times as vulnerable to SO_2 while carotenoids are four times more so. The amount of chlorophyll in the air may be used as a measure of air pollution since it is a key component of photosynthetic activity (Pawar and Dubey, 1985). Khan et al. (1990) demonstrated a significant decrease in chlorophyll pigment in locations with greater air pollution compared to their control groups, in an experiment designed to confirm the impact of thermal power plant emissions on *Catharanthus roseus L.* They went on to say that this decrease was because chlorophyll was converted to phaeophytin, which altered its light spectrum properties, due to the SO_2 driven removal of Mg^{2+} ions by two hydrogen atoms from chlorophyll molecules. If *Catharanthus roseus L.* shows no outward signs of chlorophyll deficiency, it may be because its chlorophyll pigment production has slowed down (Shimazaki et al., 1980). Subsequently, Sharma et al. (1994) investigated how *Brassica campestris var*. responded to varying SO_2 concentrations. There was a marked drop in the chlorophyll concentration, as Krishna noticed. Chlorophyll an is more vulnerable to SO_2 pollution than the other photosynthetic pigments, and their findings reinforce this fact. Tripathi et al. (1999) found that compared to their control groups, *F.relegiosa, S. jambolana, A. indica, C. fistula,* and *M. indica* had significantly lower chlorophyll content and carotenoids due to NO_x pollution in the areas around silver refineries. Nighat *et al.* (2000) During research on how thermal power plant emissions affect some foliar features of *Ruellia tuberose L.*, it was found that plants grown in polluted areas had significantly less chlorophyll throughout the whole life cycle, from pre-flowering to blooming and beyond. For 20 days in a row, at an intensity of 8 hours per day, plants of Bel-W3 and seven commercial tobacco cultivars (*Nicotiana tabacum L.*) were subjected to two comparatively low ozone concentrations (90 or 135 ppb). Ozone has several negative effects on plants, including the development of necrotic and chlorotic patches, a quickening of the aging process in leaves, a decrease in chlorophyll, and a more severe degradation of chlorophyll a than chlorophyll b. Test tube experiments exposing leaf segments to high ozone concentrations (>1000 ppb) and in vitro ozone bubbling in chlorophyll extracts further corroborated chlorophyll a's greater sensitivity (Saitanis et al., 2001).

Reducing the photosynthetic pigment level of the plant correlates with the pollution load, according to Raina and Sharma (2003), who studied the effects of vehicle pollution on the micro morphological, anatomical, and chlorophyll contents of *Syzygium cumini L.* leaves. Similarly, in the suburbs of Varanasi, Agrawal et al. (2003) found that potted wheat plants exposed to ambient air containing mostly O_3 and NO_2 had a lower total chlorophyll content. Similarly, Siddiqui et al. (2004) found that varying doses of SO_2 significantly reduced the photosynthetic pigment (chl. a, chl. b, total chl., and carotenoids) in *Helianthus annuus*. Hemavathi and Jagannath (2004) also found that when grown in environments with varying levels of urban air pollution, the photosynthetic pigment content of *Peltophorum inerme* and *Azadaricta indica* decreased. Research by Kumari et al. (2005) examined the effects of vehicle exhaust pollution on various biochemical traits of roadside vegetation. They found that photosynthetic pigments in *Ficus relegiosa, Ricinus communis,* and *Carica papaya* were significantly lower in the roadside vegetation compared to the control group. Under increasing pollution loads, the chlorophyll content was reduced in *Carissa canadas L., Cassia fistula L.*, and *Psidium guajava L.* as well (Pandey, 2005). According to Verma et al. (2006), *Ipomea pes-tigridis L.* shows a substantial decrease in chlorophyll and carotenoid concentration when exposed to air pollution. Verma and Singh (2006) also found that when auto-pollution levels increased, the chlorophyll and carotenoid contents of roadside plants (*Ficus relegiosa L.* and *Thevetia nerefolia L.*) degraded. Using open top chambers, Rai et al. (2007) examined the effects of gaseous air pollution on wheat (*Triticum aestivum L.* var. HUW-234) grown in a suburban area in India's eastern Gangetic plain. Photosynthetic rate, stomatal conductance, chlorophyll content, and Fv/Fm ratio were all greater in FC-grown plants than in NFC and OP grown plants. Following this, Joshi and Swami (2007) used physiological markers such as chlorophyll a and b, total chlorophyll, carotenoids, ascorbic acid, pH, and relative water content to examine how four economically significant tree species Mango (*Mangifera indica*), Eucalyptus citriodora, Sagon (*Tectona grandis*), and Sal (*Shorea robusta*) reacted to pollution from cars on roadside. Leaf samples taken from trees along roadsides that were exposed to vehicle exhausts showed a significant change in all of these characteristics when compared to the control group. At the same time, Wali et al. (2007) found that field-grown marigold (*Calendula officinalis L.)* plants react differently to different concentrations of SO_2 (0.5, 1.0, and 2.0 ppm) stress during pre-flowering, flowering, and post-flowering stages of plant development. Under high SO_2 stress, chlorophyll and carotenoids are significantly reduced at all stages, but the lowest dose of SO_2 actually stimulates growth.

It is well-known that air pollution cause proteins and other physiologically significant molecules to degrade, leading to the production of malondialdehyde (Mudd, 1982). According to Foyer et al. (1994), plants that are exposed to SO_2 produce more free radicals, which can lead to impaired protein metabolism. This is because activated oxygen species change the structure of cellular proteins (Pacifici and Davies, 1990) and make them more vulnerable to proteolysis (Stadtmann and Oliver, 1991). Multiple researchers have found evidence of a decline in plant foliar protein content. The protein concentration of *Catharanthus roseus L.* has decreased significantly, but the free amino acid content has increased. published in the year 1990 by Khan et al. Some researchers have proposed that reduced photosynthesis (Constantinidou and Kozlowiski, 1979), blocked protein synthesis, or increased protein breakdown (Robe and Kreeb, 1980) might be responsible for the lower protein concentration. Degradation of existing protein molecules or enhanced de novo protein synthesis is shown by the reduction in protein content followed by an increase in free amino acid content. Thirty days after exposure to 99 ppb O_3 for two hours, Agrawal and Agrawal (1990) found a 39% decrease in Vicia faba and a 6.8% decrease in Cicer arietinum, respectively. every day. The protein content of soybean cv. was found to drop by 23% according to Verma and Agrawal (1996). for four hours with JS-72–44 treated at 0.15 ppm SO_2. for six weeks, five days a week. Protein hydrolysis or a reduction in protein synthesis have been proposed as the mechanisms by which SO_2 reduces protein content (Carlson and Bazzaz, 1985). Over the course of eight hours, Deepak and Agrawal (2001) exposed two soybean cultivars, Glycine max cv. Bragg and PK 472, to high levels of CO_2 (600 μl l^{-1}) and/or SO_2 (0.06 μl l^{-1}), respectively. under field circumstances to evaluate the response to SO_2 exposure resulting from CO_2 enrichment, from germination to grain maturity in open top chambers. Plant growth, biomass, yield, foliar starch, and protein content were all negatively affected in both soybean cultivars when exposed to SO_2 alone. A decrease in protein content was seen exclusively in PK 472 when subjected to CO_2 enrichment. It has been shown that plants grown in environments with increased CO_2 levels have a lower concentration of soluble proteins (Webber et al., 1994). Soybean cv. foliar protein content did not very much. There has also been a report of Kent at 700 µl l^{-1} CO_2 (Havelka et al., 1984). It seems that protein damage caused by SO_2 is considerably reduced in a CO_2 enriched environment, as protein maintenance under combined therapy is comparable to the control. It has been shown that wheat plants treated with O_3 exhibit CO_2 induced protein protection (Rao et al., 1995). *Ricinus communis L.* plants were studied by Kammerbauer and Dick (2000). was compared with controls maintained in a location free of direct motor vehicle emissions after being exposed to urban traffic exhaust emissions for 5 months. There were no outward signs of injury, but there were notable variations in terms of a number of physiological variables. After 2 months and 5 months, respectively, soluble leaf protein levels in the plants exposed to pollution were 32% and 14% lower than in the control plants. The increased levels of nitrogen oxides, carbon monoxide, and carbon dioxide in city air are likely to stimulate protein synthesis. Plants can tolerate low levels of CO_2 in the air. According to Bidwell and Bebee (1974), CO that leaves may absorb is transformed into CO_2, which is then added to serine, glycine, and eventually sucrose. Zeevart (1976) found that tomato plants increased their protein content and amino acid synthesis from CO_2 when given gaseous NO_2. Fluckiger et al. (1978b) also discovered that juvenile birches exposed to highway exhaust pollution stimulated amino acid production. Previous research by Kammerbauer et al. (1987) found that spruce trees along highway borders had reduced CO_2 absorption via stomatal conductance and photosynthetic capability. Thus, it is reasonable to assume that exhaust fumes are inhibiting protein production, however this does not rule out protein breakdown. Urban air pollution also causes protein breakdown in wheat transplants (Rajput and Agrawal, 2005). In their study, Tiwari et al. (2006) examined the effects of air pollution on carrot plants. The plants in the non-filtered chambers showed a significant decrease in protein concentration, while the plants in the filtered chambers were grown in open top chambers (OTCs) ventilated with either ambient air or charcoal filtered air. The experiment was conducted at a suburban site in Varanasi, India. The foliar protein content was found to be significantly lower at sites that received the highest amounts of pollution, according to a subsequent study by Verma and Singh (2006). They attributed this to either the breakdown of existing protein molecules or reduced de novo protein synthesis, building on previous work by Iqbal et al. (2000). The plants studied in this study were *Ficus relegiosa L.* and *Thevetia nerefolia L.*, which are found along roadsides.

According to Darrall (1989), Foyer et al. (1994), and Sandermann (1996), among other major and widely-spread air pollutants, SO_2, NO_2, and O_3 may cause oxidative stress in plants and negatively impact several physiological processes. When plants are exposed to oxidative stressors, they undergo a cascade of physiological and biochemical changes that contribute to their antioxidant defense mechanisms, some of which include enzymes and others that do not (Sharma and Davis, 1997). All cells, whether they are under stress or not, create reactive oxygen species (ROS). Plants have elaborate defensive mechanisms that deal with reactive oxygen species (ROS), which include mitigating their production and eliminating them when necessary. Oxygen production and removal are equal in relaxed circumstances. On the other hand, the immune system might become overwhelmed when faced with elevated ROS production during times of stress. However, plants have developed a sophisticated defense mechanism against free radicals called an antioxidant defense system. This system includes both low molecular weight components like glutathione and ascorbate and enzymatic components like SOD, POD, and CAT. The former two components detoxify oxygen radicals and H_2O_2, respectively, and the latter three prevent the formation of HO radicals (Mittler, 2002). According to Alscher et al. (2002), the superoxide dismutases (SODs) are the first defensive mechanisms that cells have against reactive oxygen species (ROS). Research indicates that SOD has the potential to shield cells from ROS-induced harm. H_2O_2 may diffuse quickly across cell membranes and is the most persistent ROS. Plants use hydrogen peroxide for two purposes: first, at low concentrations it triggers adaptive signaling, which in turn builds tolerance to different abiotic stresses (Karpinski et al., 1999; Dat et al., 2000). Second, at high concentrations it orchestrates programmed cell death (Lamb and Dixon, 1997; Alvarez et al., 1998). Superoxide dismutases, catalases, and peroxidases all have their activity amplified in response to oxidative stress (Hippeli and Elstner, 1996; Sharma and Davis, 1997). Peroxidase activity in plants has been proposed as a marker to assess urban air pollution (Puccinelli et al., 1998; Kammerbauer and Dick, 2000) and has been discovered to be a sensitive indicator of pollutant exposure (Keller, 1974; Curtis et al., 1976; Sarkar et al., 1986) among these antioxidant enzymes. Also, superoxide dismutase's conflicting function in plants' reactions to air pollution needs further investigation. Pollutant exposure increased superoxide dismutase activity in sugar beets (Dixon et al., 1995), pine and spruce (Tandy et al., 1989), and snap beans (Lee and Bennett, 1982). Chloroplasts and mitochondria in plants often create O_2 and H_2O_2 as part of their aerobic metabolism and in response to ambient oxidative stress (Sharma and Davis, 1997). To protect themselves against reactive oxygen species, plants have developed a number of molecular defensive mechanisms. Superoxide dismutases, for instance, convert O^{2-} to H_2O_2 and O_2. According to Harris (1992) and Sharma and Davis (1997), peroxidases and catalases proceed to further degrade H_2O_2 into water and oxygen. Hence, it is suggested that plants respond to oxidative stress caused by air pollutants by increasing the activity of antioxidant enzymes (Hippeli and Elstner, 1996; Sharma and Davis, 1997). The effects of acute levels of nitrogen dioxide (NO_2) on *Brassica campestris* seedlings were studied by Chun-yan et al. (2007) in a plant development chamber. The researchers also looked at whether plants might be pretreated with hydrogen peroxide (H_2O_2) to reduce the damage caused by NO_2. In a controlled setting, *B. campestris* plants that were 28 days old were subjected to varying concentrations of NO2 (0.25, 0.5, 1.0, and 2.0µl l^{-1}, respectively) during 24 hours after being sprayed with a 10 mmol l-1 H_2O_2 aqueous solution (equivalent to around 1.0 mg H_2O_2 per plant). The air that was filtered using charcoal was used as a control. Immediate post-exposure measurements were taken of ascorbate (ASA), malondialdehyde (MDA), total chlorophyll, photosynthetic rate, stomatal conductance, nitrate, nitrate reductase (NR), and plant biomass. Compared to the control, plants exposed to moderate doses of NO_2 (e.g., 0.25 µl l^{-1}) benefited from the exposure and had an increase in the dry weight of the aboveground part. However, plants exposed to high concentrations of NO_2 (e.g., 0.5 µl l^{-1} or higher) had a decrease in plant biomass and total chlorophyll. Furthermore, significant increases in the activity of superoxide dismutase (SOD) and NR were seen at NO_2 concentrations of 0.5 µl l^{-1} or above.

Pharmacognostic Aspects

Alkaloids, terpenes, cyanogenic glycosides, phenolics, and countless other secondary metabolites are produced by vascular plants. It is believed that many of these chemicals have no role in either the energy release mechanisms or the construction of structural components of cells. When it comes to protecting plants against herbivores, pests, and diseases, several secondary metabolites play crucial roles. Furthermore, their accumulation and synthesis differ between plant taxonomies (Harborne, 1999; Bourgaud et al., 2001; Ossipov et al., 2001). When it comes to the connections between plants and their environments, secondary metabolites specifically phenolic chemicals like flavonoids and phenols are very important (Haslam, 1989; Rhodes, 1994). Phenolic chemicals have a multi-functional role in terrestrial plants and are found all over the place (Harborne, 1997). Among their many roles, phenolics aid in wound healing after injury, are involved in plants' defensive responses to air pollution (Fluckiger et al., 1978a; Karolewski and Giertych, 1995), and protect plants from herbivorous insects and diseases (Hahlbroch and Scheel, 1989; Nicholson and Hammerschmidt, 1992; Dixion and Paiva, 1995; Hartley and Jones, 1997). Everything with an aromatic ring and one or more hydroxyls is considered a phenolic chemical (Waterman and Mole, 1994). There are a number of internal and external elements that influence foliar phenolic concentrations; one of the most important external ones is air pollution. According to Zobel (1996), Kanoun et al. (2001), and Loponen et al. (2001), secondary metabolite composition may be altered by air pollution, both quantitatively and qualitatively. According to Giertych et al. (1999), plants exposed to various harmful contaminants showed an increase in the levels of phenolic compounds. Researchers Kanoun et al. (2001) found that fumigating *Phaseolus vulgaris* cv. *Nerina* with ozone at 65-85 ppb significantly altered the accumulation of foliar phenolics in plants subjected to chronic stress. Glucose, fructose, and soluble phenol levels were shown to be lowered in *Pinus sylvestris* and *Picea abies* seedlings exposed to SO_2, according to Kainulainen et al. (1995). Agrawal and Deepak (2003) found that total soluble sugars, starch, and total phenolics were significantly higher under CO_2 and $CO_2 + SO_2$ exposures in an open top chamber study that evaluated the physiological and biochemical effects of two wheat cultivars (*Triticum aestivum L.* cv. *Malviya* 234 and HP1209). The foliar phenol contents of Aleppo pine (*Pinus halepensis Mill.*) needles were studied by Pasqualini et al. (2003). The needles were gathered from six different locations that were impacted by different types of air pollutants, including NO, NO_2, NO_x, O_3, and SO_2. Exposure to sulfur dioxide increased total phenol content, but exposure to nitrogen oxide pollution decreased it. One possible explanation for the negative connection between total phenolics and nitrogen oxides is that these pollutants have a favorable effect on nitrate reductase activity (Krywult et al., 1996). Several investigations have shown that there is a negative link between the quantities of nitrogen and phenolic compounds in the needles or leaves of different Pinus species, and this enzyme helps with nitrogen assimilation (Giertych et al., 1999). While sulphur dioxide and ozone reduced quantities of gallic acid and vanillin, respectively, exposure to nitrogen oxide pollution raised concentrations of p-coumaric acid, syringic acid, and 4-hydroxybenzoic acid. All phenolic compounds begin with cinnamic acid, which is produced by the shikimic acid pathway. P-Coumaric acid is produced via aromatic hydroxylation of cinnamic acid. One of the primary pathways to benzoic acids is the b-oxydation and aromatic hydroxylation of cinnamic acid side chains. Protocatechuic acid and vanillic acid are the products of a second aromatic hydroxylation followed by methylation. The p-coumaric acid routes may also lead to vanillic acid. According to Torssell (1981), syringic acid may be produced by methylating vanillic acid. There may be a hierarchy of sensitivity among the enzymes involved in these biosynthetic pathways with respect to certain contaminants (Loponen et al., 2001). Consequently, the effects of pollutants on secondary metabolism in plants are species-specific and chemically dependent. This is due to the fact that different plants have different metabolic routes for secondary chemicals. The enzymes chalcone synthetase and phenylalanine ammonia lyase, which control the production of phenolic compounds, are known to have their activity changed by exposure to ozone. O_3 fumigation did not affect the amounts of phenolic compounds in *Populus tremuloides* and *Betula papyrifera*, according to Lindroth et al. (2001). When *P. halepensis* needles accumulate both total and simple phenols, it indicates that the shikimate pathway is activated due to air pollution. Agrawal et al. (2005) conducted a field research in the suburbs of Allahabad, a city in a dry tropical region of India, to determine the effect of O_3 on mung bean plants (*Vigna radiata L.* var. *Malviya Jyoti*). The purpose of the evaluation was to determine if ethylene diurea (EDU) was suitable for this purpose. EDU has anti-ozonant properties and is a synthetic compound. Throughout the course of the experiment, the average monthly concentration of O_3 ranged from 64 to 69 μgm^{-3}. When it came to photosynthetic pigments, soluble proteins, ascorbic acid, and phenol levels, EDU application had a significant positive impact. The levels of pigments, protein, and ascorbic acid in the leaf of plants that were treated with EDU were greater than those of plants that were not, whereas the opposite was true for the phenol content. This would imply that by mitigating the detrimental effects of O_3 on proteins, its use decreased the production of phenolic chemicals. According to Tiwari et al. (2006), who used open top chambers (OTCs) to study the effects of air pollution on carrot (Dacus carota var. Pusa Kesar) plants, total phenolics increased significantly when the plants were stressed by air pollution. Previous research has also shown that exposure to pollutants may stimulate total phenolics (Howell, 1974). A study conducted by Rai et al. (2007) attempted to assess the effects of ambient gaseous air pollution on wheat (*Triticum aestivum L.*) using open top chambers. They found that total phenolic contents increased under air pollution stress, which could lead to a decrease in carbon fixation and ATP synthesis as well as an increase in respiration and chloroplast disintegration (Howell, 1974). The effect of ozone on phenols has been the subject of very few investigations (Howell, 1970; Louguet et al., 1989; Langebartels et al., 1990; Kainulainen et al., 1994). The enzyme activity that intervenes in phenol metabolism is affected by high ozone levels, as stated by Howell (1970). The presence of more phenolic compounds in plants exposed to ozone was shown by Langebartels et al. (1990). High levels of ozone were not associated with total phenol concentrations, however, as shown by Kainulainen et al. (1994). There are conflicting findings about the effect of ozone on total phenol concentrations, which may vary by species. In a study conducted by Katoh et al. (1989), it was shown that when *Cryptomeria japonica* was exposed to O_3, the quantities of soluble phenols, glucose, and shikimic acid all dropped. Wheat transplants stored in various locations exposed to varied concentrations of pollutants showed a considerable decrease in phenolic content, according to research by Rajput and Agrawal (2005).

Flavonoids, a type of low molecular weight phenolic chemicals found in many different plant species, have many different biological activities, and are essential in many ways in which plants interact with their environments (Shirley, 1996). Plant organs, tissues, and developmental variables all affect the content of phenolic chemicals such flavonoids (Bohm, 1987). Phytochemical adaptation to both biotic and abiotic conditions is what Dixon and Pavia mean when they say that flavonoid changes occur (1995). Bohm (1987), Tomas-Barberan et al. (1988), Midiwo et al. (1990), Cuadra et al. (1997), Cooper-Driver and Bhattacharya (1998), Lalova (1998), Markham et al. (1998), Penuelas et al. (1996), Simmonds (1998), Chaves et al. (2001), Sallem et al. (2001), and Robles et al. (2003) provide extensive data demonstrating that various biotic and abiotic factors, such as drought, atmospheric pollutants, phytopathogens, and insect deterrent, affect flavonoid synthesis. In spite of the abundance of literature documenting intraspecific flavonoid variation, very little is known about how flavonoids react to different levels of environmental pollution (Loponen et al., 1998; Robles et al., 2003; Nikolova and Ivancheva, 2005). The effect of an altitude gradient and environmental pollution on flavonoid aglycones that have accumulated from the outside was studied by Nikolova and Ivancheva (2005). Apigenin and quercetin 3,7,3'-trimethyl ether contents in *Artemisia vulgaris L.* and *Veronica chamaedrys L.,* respectively, were determined. There were significant variations in the quantity of quercetin 3,7,3'-trimethyl across *A. vulgaris* populations collected from environments with various types of contamination. Populations in environments contaminated by industry had a high quercetin 3, 7, 3'-trimethyl ether concentration. Pollution has been shown to raise levels of phenolic compounds and flavonoids in trees, while the exact mechanisms behind this phenomenon remain unknown (Loponen et al., 1997, 1998; Giertych et al., 1999). Accumulation of methylated flavonoids, according to Chaves et al. (1997), increases plants' overall stress tolerance and prevents water loss.

With a wide variety of structural forms, biosynthesis processes, and pharmacological actions, alkaloids are among the most varied groups of secondary metabolites identified in living organisms. These days, most people agree that secondary metabolites are important for an organism's continued existence. It is believed that alkaloids are an intricate chemical defense mechanism in plants. (Harborne, 1999; Bourgaud et al., 2001; Ossipov et al., 2001) The production and accumulation of secondary metabolites differ among plant taxonomies. External and internal stressors both have an impact on their concentrations (Senoussi et al., 2007; Jaleel et al., 2007; Misra and Gupta, 2006; Qureshi et al., 2004). The composition of secondary metabolites may undergo both qualitative and quantitative changes as a result of air pollution (Zobel, 1996; Kanoun et al., 2001; Lopanen et al., 2001). The production and accumulation of alkaloids in plants are thought to be heavily influenced by the availability of nitrogen, given that alkaloids are nitrogenous molecules. Tobacco, lupines, barley, Datura, Atropa, and Papaver are among the medicinal and non-medicinal plants whose alkaloids are amplified when nitrogen is added (Waller and Nowacki, 1979). It has been shown that indole alkaloid synthesis may be stimulated in cultures of Catharanthus roseus cell suspensions by nitric oxide (Xu and Dong, 2005).

CONCLUSION

The problem of air pollution has been there since the beginning of time, impacting both industrialized and developing nations. Since emissions from man-made sources first appeared, the existence of man-made air pollution has been well documented. Numerous industrial processes, the biodegradation of waste products, some agricultural and forestry activities, and the combustion of fossil fuels in power plants and engines all contribute to the atmospheric emission of hundreds of distinct chemicals. Low quantities or lack of toxicity to biological systems mean that most of these chemicals have little to no impact on the environment. On the other hand, there are a few that are known to have devastating impacts on human health and on flora and fauna in both wild and cultivated environments. A major ecological problem is the regional effects of air pollution on various plant species. Unlike animal populations, plant populations are constantly (24/7) and directly exposed to the danger of pollution. Their morphological, biochemical, anatomical, physiological, and other reactions are varied, and they soak up, store, and incorporate the contaminants that hit their surfaces.

According to the majority of research, there is a positive correlation between pollution load and the majority of morphological traits of various plant proteins and enzymes (Gavrila et al., 2022) Plants such as *Ocimum sanctum* and *Catharanthus roseus* have also shown this behavior. Exposure to vehicle pollution was shown to decrease the height, girth, and number of leaves of both plants. Both plants' chlorophyll, carotenoids, and protein contents dropped sharply as pollution levels rose. Both plants' carotenoids content decreased significantly when pollution levels rose, but *O. sanctum's* dropped the most.

While both plants' color and protein content increased due to vehicle pollution, their cysteine and proline levels increased significantly. The non-protein thiol content of both plants increased significantly in response to traffic pollution, with *O. sanctum* exhibiting the highest accumulation. Therefore, by observing the aforementioned characteristics, researchers may use these two plants as air pollution monitors.

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Chapter 19

Harnessing Nature:
Whole Cell Biosensors for Environmental Monitoring

Naseema Banu A.
Ethiraj College for Women, India

Sangeetha Vani G.
https://orcid.org/0000-0003-4462-0730
Ethiraj College for Women, India

Sarah Grace P.
Ethiraj College for Women, India

ABSTRACT

This chapter discusses the role of whole-cell biosensors in monitoring the impact of human advancements on the environment, leading to an imbalance that threatens ecosystems. Biosensors are cost-effective devices known for their specificity, sensitivity, and portability. The advancement in biosensors includes using genetically engineered microbial cells as whole-cell biosensors. These manipulated cells respond to external stresses, making them effective tools for detecting pollutants. The stress-response mechanisms of bacterial species are harnessed for environmental monitoring. The customizable nature of whole-cell biosensors is displayed in the text, and it also discusses applications such as water contamination detection and the design of engineered bacterial cells. The chapter aims to provide a comprehensive understanding of whole-cell biosensors, their principles, and their applications in addressing environmental issues in air, water, and soil pollution.

INTRODUCTION

The advent of human development, socially and economically, has taken a major toll on the surrounding environment and its health, affecting not only plants and animals but humans too. With mass production strategies to meet the needs of a growing population, comes the ill effects of waste accumulation and

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toxicity. This needs immediate and effective measures to detect, sense, and mitigate the harm. There are numerous ways to monitor the pollution by accumulating contaminants. Some examples include pesticides, heavy metals, and human wastes that cause soil pollution, and unchecked contamination leads to water pollution (Prabhakaran et al., 2017).

Sensors are used to monitor the levels of analytes. A sensor is a device that has wide applications and of many types. One of them is a biosensor, which is an analytical device meant to detect analytes of biological importance. They have a recognition component and a physical layer that conducts the signal and converts it into a measurable value. Novel microbial biosensors for the detection of environmental samples, food processing, and biomedical purposes have been developed, based on a wide range of principles (Su et al., 2011).

The sensing element for these biosensors comprises enzymes, microorganisms, antibodies, cells, tissues, and organelles. Enzymes possess the properties of sensitivity and specificity, making them an ideal choice for the recognition element. However, the synthesis and purification process is time-consuming and expensive. The microbial cell as such is a better alternative to specific enzymes, given their ease of culture and manipulative abilities. These cells also provide the ambient microenvironment for the enzymes or other recognition elements to act without losing their ability.

Microbes have a non-specific metabolic activity, except for a few species. However, these cells can be easily manipulated using selective culture techniques or by blocking the undesired trait or enhancing the desired expression via genetic engineering (Su et al., 2011).

In this chapter, we delve into the fascinating domain of whole-cell biosensors, exploring how live microorganisms can be harnessed as powerful tools for environmental monitoring. This innovative approach not only reflects nature's complexity but also offers a dynamic and responsive solution to the ever-growing challenges of environmental surveillance.

Understanding Whole-Cell Biosensors

Whole-cell biosensors differ significantly from traditional sensing methods in their approach to environmental monitoring. Unlike conventional sensors that rely on chemical reactions or physical changes to detect pollutants, whole-cell biosensors utilize living cells, typically bacteria, as the sensing element. These genetically engineered microbial cells possess inherent stress-response mechanisms, which are leveraged to detect changes in the environment. The genetic manipulation allows these cells to exhibit distinct responses, such as the overproduction of specific enzymes or proteins, in the presence of pollutants. This biological approach offers advantages in terms of specificity, sensitivity, and adaptability. Unlike chemical sensors, whole-cell biosensors can be customized for different pollutants, making them versatile tools for environmental monitoring. Moreover, these biosensors provide real-time information about the biological impact of pollutants, offering a more holistic understanding of environmental conditions. Overall, the use of living cells in whole-cell biosensors represents a paradigm shift from traditional methods, providing a more dynamic and responsive approach to detecting and monitoring environmental changes.

Why Use Microorganisms?

Microorganisms, particularly bacteria, are commonly used for whole-cell biosensors due to their unique characteristics and versatility. There are several reasons why microorganisms are preferred for this purpose:

- **Genetic Manipulation:** Microorganisms can be easily genetically engineered to express specific genes or respond to stimuli. This allows for the creation of customized biosensors with tailored responses to environmental changes.
- **Inherent Stress Responses:** Many microorganisms naturally exhibit stress responses when exposed to various environmental conditions, such as the presence of pollutants. These stress responses can be harnessed and engineered to serve as indicators in biosensors.
- **Sensitivity**: Microorganisms often show high sensitivity to changes in their surroundings. This sensitivity allows for the detection of pollutants even in low concentrations, making microorganism-based biosensors effective in monitoring environmental conditions.
- **Rapid Response:** Microorganisms can provide rapid and real-time responses to environmental changes. This quick response is crucial for timely detection and monitoring of pollutants.
- **Versatility:** Microorganisms offer a wide range of species with diverse characteristics. This diversity allows for the selection of microorganisms that are well-suited for specific applications or pollutants, enhancing the versatility of whole-cell biosensors.
- **Cost-Effectiveness:** Using microorganisms is often more cost-effective than synthetic alternatives. Microorganisms can be easily cultivated and maintained, contributing to the affordability of whole-cell biosensors.
- **Biocompatibility:** Microorganisms are generally biocompatible and pose minimal risk to the environment. This makes them suitable for applications in ecological sciences without causing harm to the surroundings.
- **Living Systems:** Unlike traditional sensors that rely on chemical reactions, microorganisms are living systems. This living nature allows for continuous monitoring and adaptation to changing environmental conditions.

BIOSENSOR DESIGN

A biosensor typically consists of three main components: a biorecognition element, a transducer, and a signal processing system. Each component plays a crucial role in the biosensor's functionality.

Biorecognition Element

The biorecognition element is responsible for selectively interacting with the target analyte, initiating a biochemical response. This element can be an enzyme, antibody, DNA, whole cells, or other molecules capable of recognizing and binding to the target (Prabhakaran et al., 2017). It facilitates the specific recognition and binding of the target analyte, leading to a measurable change.

Transducer

The transducer is a component that converts the biochemical response generated by the biorecognition element into a quantifiable and often electrical signal. Various types of transducers include electrochemical (e.g., amperometric, potentiometric), optical (e.g., fluorescence, absorbance), and piezoelectric devices. It transforms the biological signal into a readable and interpretable output, providing a measurable response proportional to the concentration of the target analyte.

Signal Processing System

The signal processing system is responsible for amplifying, conditioning, and interpreting the signal generated by the transducer. This may involve electronic circuits, amplifiers, and microprocessors to enhance the signal quality and extract relevant information. It ensures accurate and reliable detection by processing the raw signal into a meaningful output, such as concentration or presence/absence of the target analyte.

In addition to these main components, biosensors may also include other elements, depending on the specific design and application:

Interface and Housing

The interface connects the biosensor to the sample or measurement environment, while the housing protects the sensitive components from external factors. It ensures proper interaction with the sample and provides a protective environment for the biorecognition element and transducer.

Calibration and Control Systems

Calibration systems and controls are mechanisms to standardize and verify the biosensor's performance over time. They enable the biosensor to provide accurate and reliable measurements by compensating for changes in environmental conditions and sensor properties.

CHEMICAL METHODS

Microbe immobilization chemically involves covalent binding and cross-linking. Covalent binding forms stable bonds between microbial cell wall components and the transducer, but harsh chemical reactions may damage cell membranes, reducing biological viability. Overcoming this challenge is a practical concern. In contrast, cross-linking uses multifunctional reagents like glutaraldehyde to bridge functional groups on the cell membrane, forming a network. This technique is widely accepted due to its speed and simplicity. Cells may be cross-linked directly onto the transducer or on a removable support membrane. While cross-linking offers advantages over covalent bonding, it may affect cell viability. Therefore, cross-linking is suitable for microbial biosensors where cell viability is less critical, and only intracellular enzymes are involved in detection.

GENETICALLY ENGINEERED READOUTS OF MICROBIAL SENSORS

In the field of whole-cell biosensing, various approaches have been employed to quantify changes in cellular metabolism, pH, and gene expression as responses to the presence of target molecules. One strategy involves utilizing microbial auxotrophy to monitor growth-limiting small molecules. For instance, an autotrophic *Escherichia coli* strain was constructed to detect and quantify mevalonate, an intermediate in the biosynthesis of industrially important isoprenoids. The biosensor employed the deletion of the native pathway for isopentenyl pyrophosphate (IPP) and dimethylallyl pyrophosphate (DMAPP) production, replacing it with a mevalonate-utilizing pathway.

Additionally, by-products generated from target compounds can serve as biosensor readouts. Examples include the conversion of α-naphthyl acetate to α-naphthol and acetate, resulting in a pH change, and the hydrolysis of paraoxon, a pesticide, to p-nitrophenol. A whole-cell electrochemical biosensor for detecting the organochlorine pesticide lindane was developed by expressing the enzyme γ-hexachlorocyclohexane (HCH) dehydrochlorinase in *E. coli*, monitoring conductivity changes using pulsed amperometry.

Reporter gene expression, controlled by specific regulatory networks, is another powerful readout method. Commonly used reporter genes include *β-galactosidase* (*β-gal*) and *luciferase*, offering colourimetric, fluorescent, or luminescent readouts. *β-gal* provides simple and rapid detection, with ultrahigh sensitivity and a wide dynamic range. Bacterial and firefly luciferases offer sensitivity, a broad dynamic range, and simplicity. Fluorescent proteins, such as green fluorescent protein (GFP), provide autofluorescence without the need for substrates, enabling the measurement of gene expression and cell trafficking mechanisms. Genetically modified fluorescent proteins of different colours allow simultaneous detection of multiple targets and fluorescence resonance energy transfer (FRET) for conformational changes triggered by ligand binding. Overall, these biosensing approaches offer versatility for detecting a wide range of target compounds (Park et al., 2013).

WHOLE-CELL SENSOR BASED ON INTRACELLULAR SYSTEM

Regulator-Promoter System

Intracellular sensing mechanisms often involve coupling a transcriptional regulator with an inducible promoter to respond to varying nutrient conditions, external toxicants, or communication signals. This interaction modulates the expression of a reporter gene, leading to a measurable signal change in a concentration-dependent manner. Commonly, regulator protein/promoter pairs for detecting environmental contaminants are based on natural resistance mechanisms or the metabolisms of toxic compounds. For instance, a *Bacillus subtilis* whole-cell biosensor was created using the CadC regulatory protein and *cadC* promoter for cadmium detection, responding to cadmium, lead, and antimony with nanomolar sensitivity. Another biosensor used the ZntR regulatory protein and its corresponding *zatAp* promoter from *E. coli* to monitor zinc, lead, and cadmium.

However, these biosensors struggled to detect arsenic, a highly toxic element. To address this, the arsenic detoxification *ars* operon, controlled by the regulatory protein ArsR, was employed. ArsR binding to the *arsR* promoter repressed reporter protein expression in the absence of arsenite. Upon arsenite introduction, the ArsR-promoter complex dissociated, allowing reporter protein expression. Previous designs placing reporter genes downstream of the *arsR* gene resulted in high background expression. To reduce this, a transcriptional insulator was introduced downstream of arsR and upstream of the reporter gene, blocking RNA polymerase read-through and significantly reducing background expression, resulting in a much lower detection limit.

The *ars* operon, commonly utilized for arsenic detoxification, may not be optimal for achieving the highest sensitivity and response as a designed cellular reporter for arsenic detection. This was addressed by decoupling the natural regulatory configuration, placing *arsR* expression under the control of either a *T7* or *lac* promoter while maintaining GFP expression under the *arsR* promoter. Similarly, the effect of promoter strength on ArsR expression revealed that a stronger constitutive ArsR production decreased arsenite-dependent EGFP output from the ars promoter, suggesting that uncoupled circuits may enhance expression levels and sensitivities for improved field-test assays.

For organic contaminants, various regulatory protein/promoter pairs have been employed. The XylR and Pu promoter pair from the xylene degradation pathway in Pseudomonas detects xylene, benzene, and toluene. The regulatory protein TbuT and the *tbuA1p* promoter from the toluene degradation pathway in *Ralstonia pickettii* control luciferase expression in response to volatile compounds. DmpR and the Po promoter in *Pseudomonas putida* monitor phenols, with a mutant DmpR increasing sensitivity by over 4-fold. An *E. coli* biosensor for L-arabinose detection was developed using the AraC regulatory protein and PBAD promoter pair, with a mutant AraC variant engineered for specificity toward D-arabinose.

Efforts to fine-tune specificity include engineering regulatory proteins for the recognition of targets with different chemical structures. A mevalonate responsive AraC variant was identified and used for monitoring mevalonate in the isoprenoid biosynthesis pathway. This variant selectively responded to mevalonate and was coupled with a PBAD-LacZ fusion to screen mutants of hydroxymethylglutaryl-CoA reductase (HMGR), demonstrating the capability to engineer regulatory proteins for sensing a wide range of novel targets.

Riboswitch and Reporter Gene Expression

Ribosomal switches are structured RNA domains that detect molecules and regulate gene expression. The interest in RNA-based detection and regulation has grown in recent years due to its ease of design and engineering. Riboswitches with natural and synthetic RNA aptamers have been developed to sense temperature, metal ions, nucleic acids, small molecules, and proteins. A whole-cell sensor based on an engineered riboswitch was developed to detect theophylline, a commonly used antiasthmatic drug. Theophylline concentration in blood serum was monitored using thymidylate synthase and an anti-theophylline aptamer. Artificial riboswitch has been used for in vivo monitoring of intracellular metabolites and engineering metabolic pathways. Whole-cell biosensors with engineered riboswitch have the potential to monitor novel targets, such as drugs and metabolites in clinical and environmental samples (Park et al., 2013).

An artificial riboswitch has been used for in vivo monitoring of intracellular metabolites and engineering metabolic pathways. The natural thiamine pyrophosphate (TPP) riboswitch found in the 5′UTR of the *E. coli thiM* gene was used to generate a TPP-activated riboswitch. The engineered TPP-activate riboswitch was fused to β-galactosidase and GFP, and the expression of these reporters was shown to induce in the presence of thiamine. A TPP riboswitch library was constructed using the TPP aptamer of the *B. anthracis tenA* gene, identifying several new TPP-activated riboswitches with enhanced sensitivity. Whole-cell biosensors with engineered riboswitch have the potential for monitoring novel targets, such as drugs and metabolites in clinical and environmental samples (Park et al., 2013).

Quorum Sensing

Quorum sensing (QS) is a widely used method for communication in microorganisms, utilizing diffusible small molecules called autoinducers. These autoinducers are produced, secreted, and recognized by specific bacteria, and can regulate various features such as virulence, biofilm formation, sporulation, genetic competence, and bioluminescence. Pathogens like *Pseudomonas aeruginosa* and *Burkholderia* *cepacia* use these signal molecules to regulate virulence determinants, which can cause lung diseases in cystic fibrosis patients.

A whole-cell biosensor was developed to detect AHLs in physiological samples, such as saliva, at concentrations down to 1 × 10^−8 M. AHL-mediated quorum sensing has been incorporated into this format for enhanced arsenic sensing. This method involves strong intercellular coupling over tens of micrometres, but the slow diffusion time of molecular communication leads to signal delays over the millimetre length scale. Prindle et al., (2012), constructed a gene circuitry to produce an oscillating amount of GFP in an *E. coli* reporter strain maintained inside microfluidic cavities (biopixels). The biopixel system output can avoid errors from detector/light source fluctuations, as the oscillation period is independent of the absolute fluorescence intensity (Park et al., 2013).

OTHER METHODS

Microbial sensors can be developed through various mechanisms, including conformational changes due to protein-protein interactions. For example, a high-signal-to-noise single-wavelength biosensor for maltose was created by fusing fluorescent proteins into a bacterial periplasmic binding protein (PBP). *E. coli* mutants with a genetically engineered glucose/galactose-binding protein (GBP) have also been used as biosensors for glucose.

Single-molecule detection is possible through biological nanopores as sensing platforms, which open in response to the binding of individual ligands. This method is routinely achieved through ligand-gated ion channel proteins, which require strong molecular amplification. The yeast two-hybrid assay using recombinant DNA technology can be used as a biosensor to identify interaction partners. This system detects interactions between estrogen receptors and their coactivators, showing that their specificity is dependent on the presence of estrogen. An efficient and reliable yeast two-hybrid detection system can also be constructed to evaluate the estrogenic activity of potential endocrine disruptors (Park et al., 2013).

Chimeric proteins are another elegant way for estrogen detection, typically constructed by fusing a target ligand-binding domain to an easily assayed reporter protein. This allows ligand-induced conformational changes in the target ligand-binding domain to be transmitted to the reporter and allosterically modulate its properties. Skretas et al., (2007) combined the ligand-binding domains of estrogen receptors with a highly sensitive thymidylate synthase reporter for identifying diverse estrogenic compounds.

WHOLE-CELL SENSOR BASED ON EXTRACELLULAR SYSTEM

Cell Surface Display Assembly

Cell surface display of peptides, proteins, and epitopes on living cells offers advantages for targeting molecules or substrates that are inaccessible to the intracellular environment. This method is particularly beneficial for enhancing kinetics, stabilization of enzymes and proteins, and facilitating purification compared to free proteins. Various cell surface components, such as outer membrane proteins, lipoproteins, S-layer proteins, cell-surface appendages, and autotransporters, have been utilized for display, with the ice nucleation protein (INP) being widely used for bacterial cell surface display.

Enzyme-based biosensors face limitations in cost and the labour-intensive purification process. Whole-cell biosensors expressing desired enzymes overcome these challenges, with *E. coli* cells expressing organophosphorus hydrolase (OPH) demonstrating enhanced stability and robustness compared to purified OPH. Surface display of OPH on engineered *E. coli* strains resulted in improved substrate degradation kinetics, highlighting the reduction of mass-transport limitations across the cell membrane. Similarly, xylose dehydrogenase (XDH) displayed on the cell surface enabled the detection of D-xylose, demonstrating a broad linear range and selective detection in real samples.

Autotransporter proteins, such as *E. coli* AIDA-I, have been used to display OPH and green fluorescent protein (GFP) on the cell surface for monitoring organophosphate compounds. Beyond enzymes, human antigens have been successfully displayed on yeast surfaces for detecting monoclonal antibodies. This approach proves valuable as yeast facilitates the production of soluble and functional mammalian proteins with appropriate post-translational modifications. Yeast surface display has been used for detecting monoclonal antibodies through immunofluorescence and enzyme-linked immunosorbent assay (ELISA), with potential applications in large-scale screening of positive antibody-producing hybridoma cell lines.

Overall, cell surface display strategies offer versatile and efficient tools for the detection of various molecules, ranging from environmental contaminants to biological markers, with potential applications in biosensing and biotechnology.

G-Protein Coupled Receptors for Detection

G-protein coupled receptors (GPCRs) have emerged as a noteworthy extracellular component for recognition in biosensing applications. GPCRs constitute the largest family of integral membrane receptors, playing a crucial role in diverse intracellular communications in response to external stimuli. The key advantage of exploring GPCRs lies in their extensive natural binding repertoire, encompassing small molecules, peptides, and glycoproteins. Due to their ability to respond to a broad array of stimulants, including hormones, neurotransmitters, taste, and chemicals, GPCRs are highly modular and customizable for sensing a wide range of targets.

Upon ligand binding to a GPCR, intracellular signalling is initiated through interaction with the GTP-binding protein (G protein), leading to the transmission of cellular responses. This inherent property makes GPCRs advantageous for whole-cell biosensing, as various cellular processes can be leveraged as the sensor readout. The versatility of GPCRs in recognizing diverse ligands and their ability to modulate cellular responses offer a promising avenue for the development of biosensors with broad applicability.

PHYSICAL METHODS

Microbe immobilization techniques primarily involve adsorption and entrapment, which are preferred when viable cells are required due to their minimal impact on the native structure and function of microorganisms. In physical adsorption, a microbial suspension is incubated with an electrode or an immobilization matrix like glass beads, leading to immobilization through adsorptive interactions (ionic or polar bonding) and hydrophobic interactions. However, adsorption alone often results in poor long-term stability due to microbial desorption.

Alternatively, entrapment immobilization can be achieved by retaining cells close to the transducer surface using methods such as dialysis membranes. Despite its effectiveness, entrapment immobilization introduces diffusion resistance from the entrapment material, leading to reduced sensitivity and detection efficiency.

Microbial biosensors typically function by the assimilation of organic compounds by microorganisms, leading to changes in respiration activity (metabolism) or the production of specific electrochemically active metabolites such as H2, CO2, or NH3, which are then secreted by the microorganism (Mulindi, 2023).

APPLICATIONS OF WHOLE-CELL BIOSENSORS

Use in Nanotechnology

Miniaturization in biosensors has numerous benefits, including improved signal-to-noise ratios, smaller sample volumes, lower assay costs, and increased binding efficiency towards the target molecule. This allows the bioreceptor to become an active transducer for the sensing system, enabling single-molecule detection. The double-layer capacitance decreases dramatically towards nanoscale dimensions due to its dependence on the electrode area, allowing ultra-fast electron-transfer kinetics and investigation of short-life intermediate species. The extremely low RsCdl time constant also reduces the time required for measurements in the nanosecond domain. Graphene and its oxidized form, graphene oxide, have opened new frontiers in biosensors and other research areas. Graphene, a pure form of carbon organized into single-atom-thick sheets, has exceptional chemical and physical properties. The integration of graphene, graphene oxide, carbon nanotubes, nanoparticles, and nanowires in electrode fabrication has led to biosensors with lower detection limits, enabling even single-molecule detection (Решетилов et al., 2010).

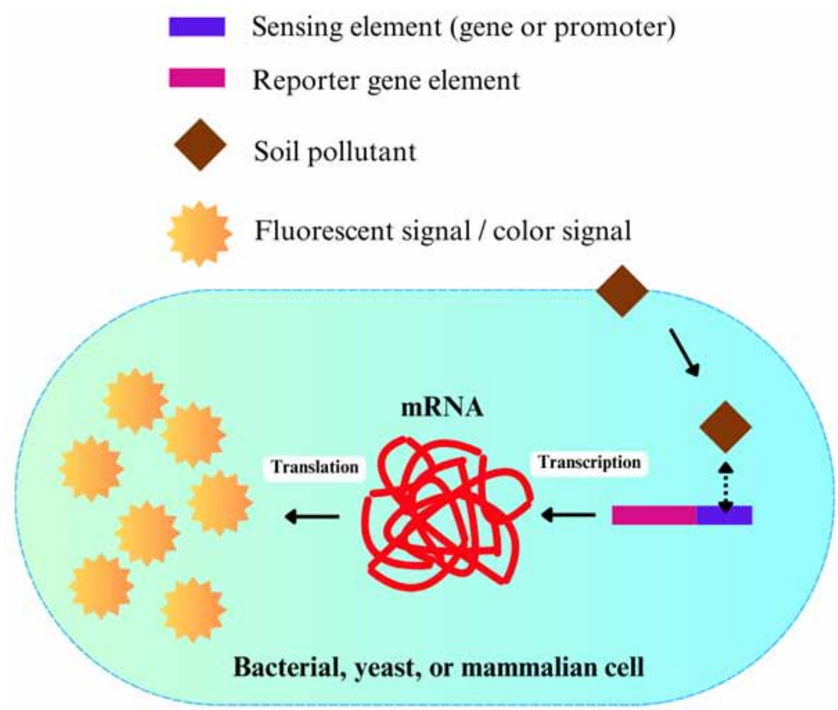
Carbohydrate Assessment

Carbohydrates are the most common analytes for enzyme and microbial sensors, with their determination being a widely used direction in biosensors due to their high bioavailability and practical significance in biotechnology, the food industry, and medicine (Решетилов et al., 2010). The most commonly reported "carbohydrate" sensors are glucose and lactose analyzers, but a large number of models have been developed for detecting other mono- and disaccharides and polymeric carbohydrates (Karube et al., 1979). Microbial carbohydrate analyzers include glucose and lactose analyzers, mediator sensors, hybrid sensors, and starch detection. Hybrid sensors are particularly suitable for di- and polysaccharide analysis, as one biocatalyst hydrolyzes glycosidic bond hydrolysis while the other determines generated monomers (Svitel et al., 1998). Examples include two hybrid carbohydrate sensors, sucrose determination based on invertase and *Zymomonas mobilis* cells (Park et al., 1991), lactose detection in dairy products based on glucose oxidase and *E. coli* cells, and determination of α-amylase activity using co-immobilized *B. subtilis* and glucoamylase (Svorc et al., 1990).

Alcohol and Organic Acid Detection

Biosensor determination of alcohols and organic acids is often used in conjunction with carbohydrate detection, with microbial cells possessing high selectivity often used alongside enzymes. Molecular yeasts

Figure 1. Basic principle behind the working of a whole-cell biosensor



from *Hansenula*, *Pichia*, and *Candida* genera are particularly promising for this purpose (Voronova et al., 2008; Korpan et al., 1993). Two microbial alcohol sensors based on recombinant *H. polymorpha* cells have been described, with the first using highly active alcohol oxidase immobilized on an oxygen electrode and the second using catalase-deficient cells and a peroxide electrode as a transducer (Gonchar et al., 1998). The original development involved creating an alcohol sensor based on *Agaricus bisporus* fungus tissue homogenate, which was fixed on a Clark-type electrode (Akyilmaz & Dinckaya, 2000). Microbial ethanol biosensors have been developed using ISFET and *Acetobacter aceti* cells (Kitagawa et al., 1987), and conductometric microbial sensors for ethanol based on alginate-immobilized yeast cells (Korpan et al., 1994). PQQ-dependent dehydrogenases of *Gluconobacter* represent a promising base for biosensor development, with a microbial sensor for ethanol detection based on *G. oxydans* cells and a glassy carbon electrode modified by ferricyanide (Tkac et al., 2003).

Xenobiotic Detection

The majority of xenobiotics have low MPC values, which indicates that biosensors for pollution measurement need to have high detection sensitivity. Biocatalytic sensors identify substances with low BOD and MPC values, while bioluminescent sensors provide highly selective detection at 10^-9-10^-7 M. Because these biosensors can identify harmful substances and pollutants with comparatively low MPC values, they are appropriate for use in environmental monitoring and other nature-conservation initiatives (Решетилов et al., 2010).

BOD Assessment

Biochemical Oxygen Demand (BOD) is a critical parameter used to assess the organic pollution level in the water. Traditional methods for BOD detection are time-consuming and require several days. Whole-cell biosensors offer a promising alternative, providing faster and more real-time monitoring of BOD levels. A whole-cell biosensor using genetically engineered *E. coli* responds to changes in dissolved oxygen levels, providing a quick and sensitive measurement of BOD in water samples (Решетилов et al., 2010). Several laboratory models and commercial BOD biosensor analyzers are known, providing BOD detection in the mean range of 5-300 mg/l for a few minutes. Pure bacterial and fungal cultures with broad substrate specificity are used in BOD sensors, with *Trichosporon cutaneum* being the most frequently used (Yang et al., 1996).

Surfactant Detection

Surface-active substances (SAS) are used in various fields, but they can increase the concentration of toxic substances, affecting living organisms. Biosensor systems are developed for detecting SAS, with microorganisms being especially useful due to their sensitivity to oxidation. Studies showed that *Pseudomonas rathonis* cells are highly sensitive to SAS (Решетилов et al., 2010). A microbial biosensor based on a column reactor containing activated sludge bacteria oxidizing linear alkylbenzene sulfonates was used for SAS analysis in river water, with a response time of 15 minutes (Nomura et al., 1994; Nomura et al., 1998).

PESTICIDES DETECTION

Whole-cell biosensors offer a sustainable and efficient solution for pesticide detection, enabling real-time monitoring of environmental samples. Engineered whole-cell biosensors have been developed to detect insecticides, including organophosphates and pyrethroids. These biosensors utilize cellular responses to insecticide-induced stress, enabling the selective detection of these chemicals in complex matrices. Direct detection of organophosphorus neurotoxins has been proposed using *E. coli*. This sensor can detect various organophosphorus pesticides and chemical warfare agents (Rainina et al., 1996). A similar sensor was described in 1998 (Mulchandani et al., 1998). The use of whole-cell biosensors in insecticide detection aids in monitoring agricultural runoff and potential impacts on aquatic ecosystems. Whole-cell biosensors employed for the detection of herbicides, such as atrazine and glyphosate, utilize genetically modified bacteria or yeast cells that respond specifically to the presence of herbicides, providing a rapid and sensitive detection method (Решетилов et al., 2010).

Sensing Hydrocarbons and Their Derivatives

The detection of aromatic compounds using microbial biosensors, emphasizing the varying toxicity levels of monoaromatics, naphthalene, and polynuclear aromatic hydrocarbons (PAH) and their chlorine derivatives can be achieved using biosensors. While monoaromatics and naphthalene are deemed relatively low toxic, the super-toxic nature of PAH demands highly sensitive analyzers, including bioluminescent sensors, chromatography, mass spectrometry, and immunoassay. Microbial biosensors have been developed for practical detection, such as an amperometric biosensor utilizing *Rhodococcus* cells for monoaromatics and an oxygen electrode with *P. putida* cells for benzene in industrial wastewater and groundwater analysis. A microbial biosensor for naphthalene detection, employing *Sphingomonas* sp. and *Pseudomonas fluorescens* strains, demonstrated a lower detection limit of 0.01 mg/l and 20 days of activity. Specific biosensors were also designed for 2,4-dinitrophenol and p-toluene sulfonate detection using *Rhodococcus erythropolis* HL PM-1 and immobilized *Comamonas testosteroni* BS1310 cells, respectively. The variety of microbial strains from genera *Pseudomonas*, *Sphinomonas*, *Rhodococcus*, and *Ralstonia* showcased the versatility of microbial biosensor models in environmental monitoring applications (Решетилов et al., 2010).

DETECTION OF METAL IONS AND INORGANIC ACIDS

Microbial biosensors have become a popular approach in biosensor analysis, primarily based on genetically modified microorganisms and optical detection. These biosensors are used for detecting heavy metals and inorganic acid ions, such as arsenic compounds. For example, a bioluminescent sensor based on recombinant *E. coli* strains was used for measuring arsenic toxicity (Cai & DuBow, 1997). Optical bacterial biosensors for zinc and copper detection in soil samples were developed using a consortium containing reporter bioluminescent *Rhizobium leguminosarum* biovar *trifolii* and *E. coli* strains (Chaudri et al., 2000). The lower detection limit for mercury detection was around 20 ng/g of soil (Rasmussen et al., 2000). Microbial sensors for cyanide detection were based on *Saccharomyces cerevisiae* cells and an oxygen electrode. These sensors were designed to detect decreases in glucose response to glucose in the presence of cyanide (Nakanishi et al., 1996). For nitrite detection, models were developed using the bacteria *Paracoccus denitrificans* and *Nitrobacter*. These sensors were designed for gaseous NO_2 analysis and were used as potential nitrite and nitrate analyzers (Takayama et al., 1996). Microbial biosensors for sulfate detection were developed using *Thiobacillus ferrooxidans* and oxygen electrodes, with potential applications in rainwater (Sasaki et al., 1997). The CyanoSensor, a bioluminescent sensor based on recombinant cyanobacteria *Synechococcus*, was used for detecting bioavailable phosphorus in water reservoirs (Schreiter et al., 2001). This was used as an indicator of the occurrence of a potential ‘algal bloom’ in the reservoir (Решетилов et al., 2010).

ASSESSMENT OF TOXICITY AND GENOTOXICITY

Sensors for genotoxicity and general toxicity are commonly used in biosensor assessment. The most common approach involves using SOS-promoters, which are induced at massive DNA damages, to create biosensor strains for nonspecific registration of genotoxic compounds and factors. General toxicity sensors assess nonspecific toxic impacts of different natures, with the principle of their action being the registration of attenuation of vital functions. Examples include a bioluminescent sensor designed for glucose and toxic compounds, a bioluminescent sensor based on recombinant strain *R. leguminosarum* biovar *trifolii* for general toxicity of the medium (Paton et al., 1997), and a bioluminescent sensor based on *E. coli* cells bearing the *lux*-genes of *V. fischeri* under the promoter of heat stress proteins (Rupani et al., 1996). Algae with chlorophyll fluorescence changing in response to the action of a toxic agent can also be used for general toxicity detection. Examples include an optical biosensor based on immobilized cells of *Scenedesmus subspicatus* alga, an optical biosensor based on *Chlorella vulgaris*, and electrochemical microbial toxicity sensors (Frense et al., 1998). In recent years, several commercial biosensor toxicity analyzers have been constructed (Решетилов et al., 2010).

CONCLUSION

This chapter emphasizes recent advancements in the field of whole-cell biosensors, focusing on approaches rooted in protein/cellular engineering and synthetic biology. Beyond enhancing sensor readouts for improved signals, ongoing efforts involve manipulating and creating recognition elements such as RNA, enzymes, and non-enzymatic proteins with heightened affinity and selectivity. Techniques currently employed to enhance product synthesis can readily be adapted for the design of whole-cell biosensors to optimize sensitivity, selectivity, and robustness.

To effectively utilize these whole-cell biosensors in rapid, point-of-care applications, there is a crucial need to develop improved materials that interface seamlessly with biological elements. This emphasizes the importance of advancing materials to enhance the integration and performance of these biosensors in practical applications.

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Chapter 20
Impact of Urbanization on Environment and Health Role of Different Environmental Sensors

Madhumita Hussain
Sophia Girls' College (Autonomous), Ajmer, India

ABSTRACT

The process of urbanization is characterized by the rapid growth and development of urban areas, and now has become a global concern with far-reaching implications for the environment and public health. This study explores the complex impact of urbanization on both the environment and human health, emphasizing the pivotal role played by various environmental sensors in monitoring and mitigating these effects. This chapter delves into the types and functionalities of environmental sensors employed to monitor urbanization's impact. Air quality sensors, water quality sensors, noise monitors, and solid waste sensors contribute valuable data to assess pollution levels, track environmental changes, and evaluate the overall well-being of urban ecosystems. The integration of real-time data from these sensors facilitates the formulation of effective policies and interventions to curb environmental degradation and enhance public health.

INTRODUCTION

With the rapid global urbanization, the vast expansion of metropolitan cities are prone to significant environmental challenges. As testified by the Ministry of Urban Development, the number of million-plus population cities has increased globally from 35 to 53, indicating a bull trend in urban growth as observed in the 2011 census (Ministry of Urban Development, 2011). Undoubtedly this expansion, while provoking economic progress, also announces several environmental risk factors. Ajmer, the 4th largest city in Rajasthan, accommodates 5,42,321 people (Census of India, 2011) is also facing similar challenges. Environmental risk factors in Ajmer include issues such as air and water pollution, deforestation, and the strain on natural resources. Additionally, increase in population and rapid urbanization lead to increased waste generation, poor waste management which are contributing to climate change and altering local

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ecosystems (Ayesha, John N., & Wadha Ahmed, 2022). Addressing these environmental risks through environmental sensors is crucial for ensuring sustainable urban development.

OBJECTIVES

- To present an overview of the urbanization process in Ajmer, highlighting population, infrastructure development, and land-use changes.
- To analyze air quality, identifying pollutants, and sources.
- To examine noise pollution levels, discussing sources and health implications.
- To evaluate the state of water supply and sanitation systems in Ajmer.
- To investigate solid waste management practices and their environmental impacts.
- Health Profile Analysis: Study the health profiles of Ajmer's residents by analyzing data on nine specific diseases.

LITERATURE REVIEW

A lot of Research work ranging from the late 1990s to the mid-2010s portrays the close relationship between the built environment and public health. Chaplin (1999), highlighted the critical issue of inadequate sanitation in India, directing towards the utter need for reforms in sanitation to address public health concerns in low-income groups. Butterworth (2000), and Jackson (2003), expanded on this by discussing how the built environment, encompassing human-made surroundings where people spend most of their time, not only reflects cultural and historical contexts but also significantly impacts health by fostering or hindering physical activity, thereby influencing the prevalence of chronic diseases.Studies by Galea et al. (2005), and Madhiwalla (2007), have elaborated on the adverse health impacts stemming from the growth of slums, urbanization, and the resultant overcrowding, poor housing, and unsanitary conditions, emphasizing the role of improved urban planning and infrastructure development in enhancing public health. Further research by Kyle, A., Woodruff, T., & Axelrad, D. (2006), Thompson, S. & Capon, A. (2012), and the Glasgow Centre of Population Health (2013), identified environmental factors such as noise pollution, housing quality, and lack of green spaces as direct influencers of physical and mental health, advocating for policies that promote healthier urban living conditions. According to Kumar et al. (2019), air quality monitoring networks in cities worldwide have enabled local governments to issue health advisories, implement traffic control measures, and enforce industrial emission standards more effectively. Moreover, the study by Zheng et al. (2020), emphasizes the role of IoT-based air quality sensors in creating dense, real-time pollution maps, which are instrumental in understanding urban pollution patterns and hotspot identification. The smart city infrastructures allow for continuous monitoring and rapid response to potential water quality issues. As mentioned by Smith and Liu (2018), modern technologies have been crucial in identifying pollution sources and preventing public health crises. A study by Green et al. (2021), found and mentioned that long-term exposure to high noise levels is linked to increased stress, sleep disturbances, and cardiovascular diseases. Mapping noise pollution is crucial for policymakers can implement zoning laws, traffic control actions, and urban planning strategies to mitigate its impact. According to Patel and Jain (2020), smart waste management systems, underpinned by sensor technology, have significantly improved recycling rates and reduced landfill usage in several urban areas. Patel, S. (2016), and subsequent studies have stressed the global nature of health issues related to the built environment, pointing to a strong connection between urban planning, lifestyle diseases, and the need for multi-sector partnerships to address urban health challenges effectively.

This chapter presents the arguments for the utmost need to reconsider and redesign urban spaces with a focus on health and sustainability. It highlights the importance of integrating health reflections into urban planning to mitigate the adverse effects of the built environment on public health.

RESEARCH GAP

After conducting an extensive review of the literature concerning the built environment, planning, and health impacts, a significant research gap has been identified. The widely held studies have only focused on one dimension of health either on physical or mental or social effects of the built environment. The current trends in urbanization, population growth, and increasing health issues, presents a clear need for a shift in development plans and policies. Thus, it is found crucial to explore the interaction between the natural and built environments from a well-being perspective.

STUDY AREA

India's fourth largest state Rajasthan covers an area of 3,42,239 km2 and has 50 districts which are grouped into 10 divisions.

Located centrally in Rajasthan, around 135 kilometres southwest of Jaipur, the state capital, Ajmer holds a significant historical position. Its coordinates lie between 25°38' and 26°58' North latitude and 73°52' and 75°22' East longitude. Nestled between the Taragarh and Madar Hills, Ajmer boasts a unique topography, surrounded by hills on three sides, which looks alluring, particularly during the monsoon season, the city comes alive with lush green hills, full lakes, and mesmerizing waterfalls. With a rich history of 1400 years, Ajmer has seen transformative changes that have shaped its urban layout.

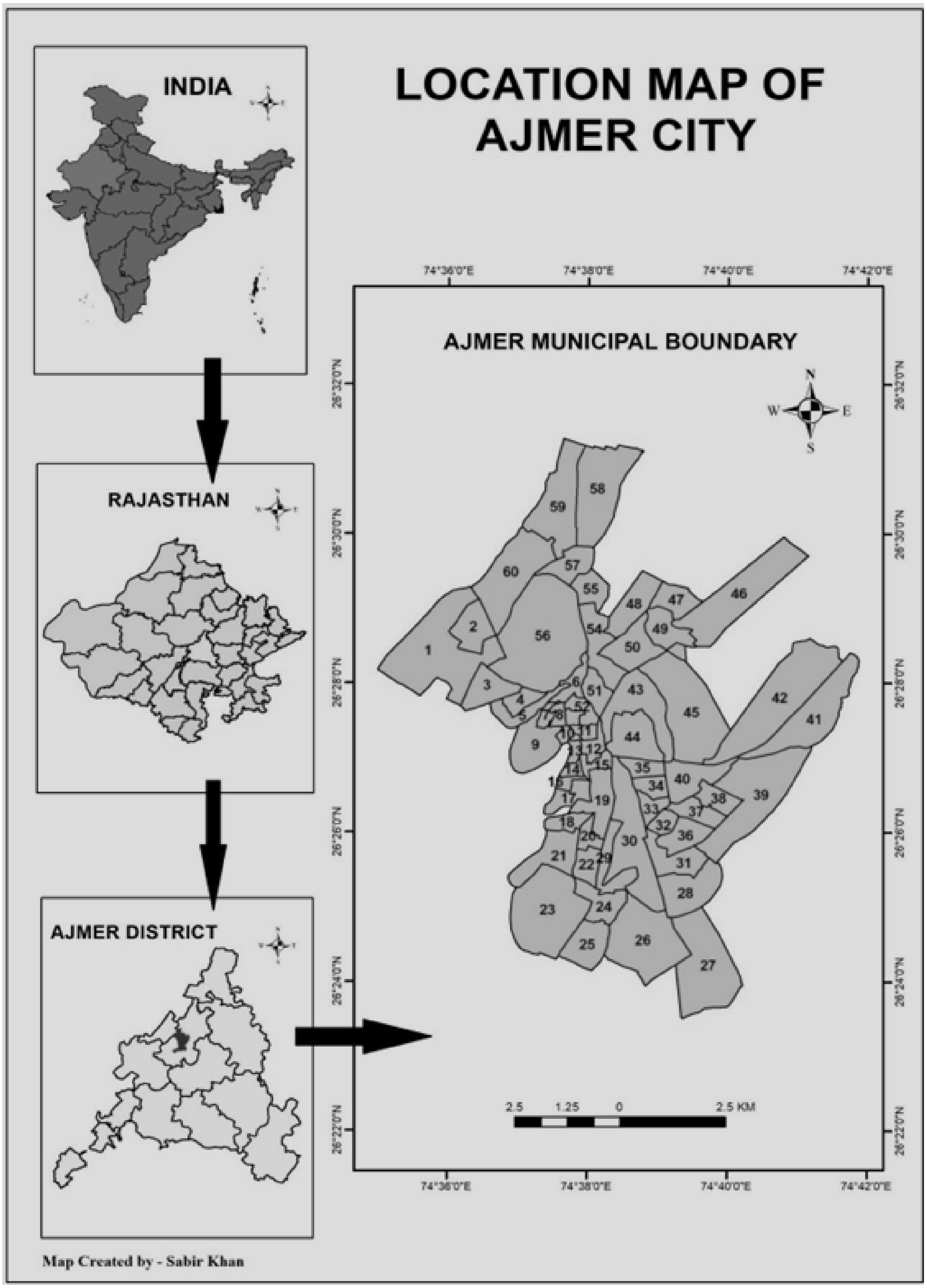
Today, approximately 56% of the world's population – 4.4 billion inhabitants – live in cities. This trend is expected to continue, with the urban population more than doubling its current size by 2050 (World Bank, Urban Development, 2023). A substantial increase in metropolitan cities has been noticed with a population of one million or more, from 35 to 53 and the overall count of towns and cities has surged from 5161 in 2001 to 7935 (Ministry of Urban Development, GOI, 2011).

Although cities are acknowledged as hubs for advancement and economic prosperity, same time they hand-to-hand struggle with various challenges such as increasing slums, sanitation issues, pollution, traffic congestion, and heavy traffic flow.

LAND USE AND LAND COVER

At the centre of the city neighbourhood, the streets are narrow mere 3 to 5 feet in width, creating an active centre for retail businesses. Here, the ground floors of the buildings are transformed into shops, while the upper floors become homes for the struggling residents. Houses of a modest income community, including skilled craftsmen like shoemakers, rope makers, and blacksmiths are found here. The

Figure 1. Ajmer city- location map



absence of proper drainage compounds the difficulties of everyday life. Despite the wear and tear on these structures, worn down by the passage of time, people stubbornly cling to them. They continue to inhabit these aged buildings, occasionally renovating them for use as guesthouses, especially for those who journey to the Dargah. Field surveys reveal a stark reality – numerous houses stand dilapidated, bearing the scars of their age. Although the government issues stern warnings against vertical expansion, citing dangers to both life and property, some residents persist in defying these warnings. They insist on extending their buildings skyward, ignoring the risks. Those who are aware of the harsh reality of urbanization, have made a genuine decision to seek refuge on the outskirts of the city.

Due to the increasing population of Ajmer, the demand for the facilities is continuously increasing which can only be met with the infrastructural development in the city. Presenting two data sets to see the present and projected Land Use and Land Cover of Ajmer city under various entities which clearly shows the dynamic change in infrastructural transformation of the city. Where one can easily analyse the physical transformation that would take place almost in the next decade, now this is the portal where conscience urban planning and implementation would be needed to develop a city situated in a valley, surrounded by Aravallis from all sides.

AIR QUALITY

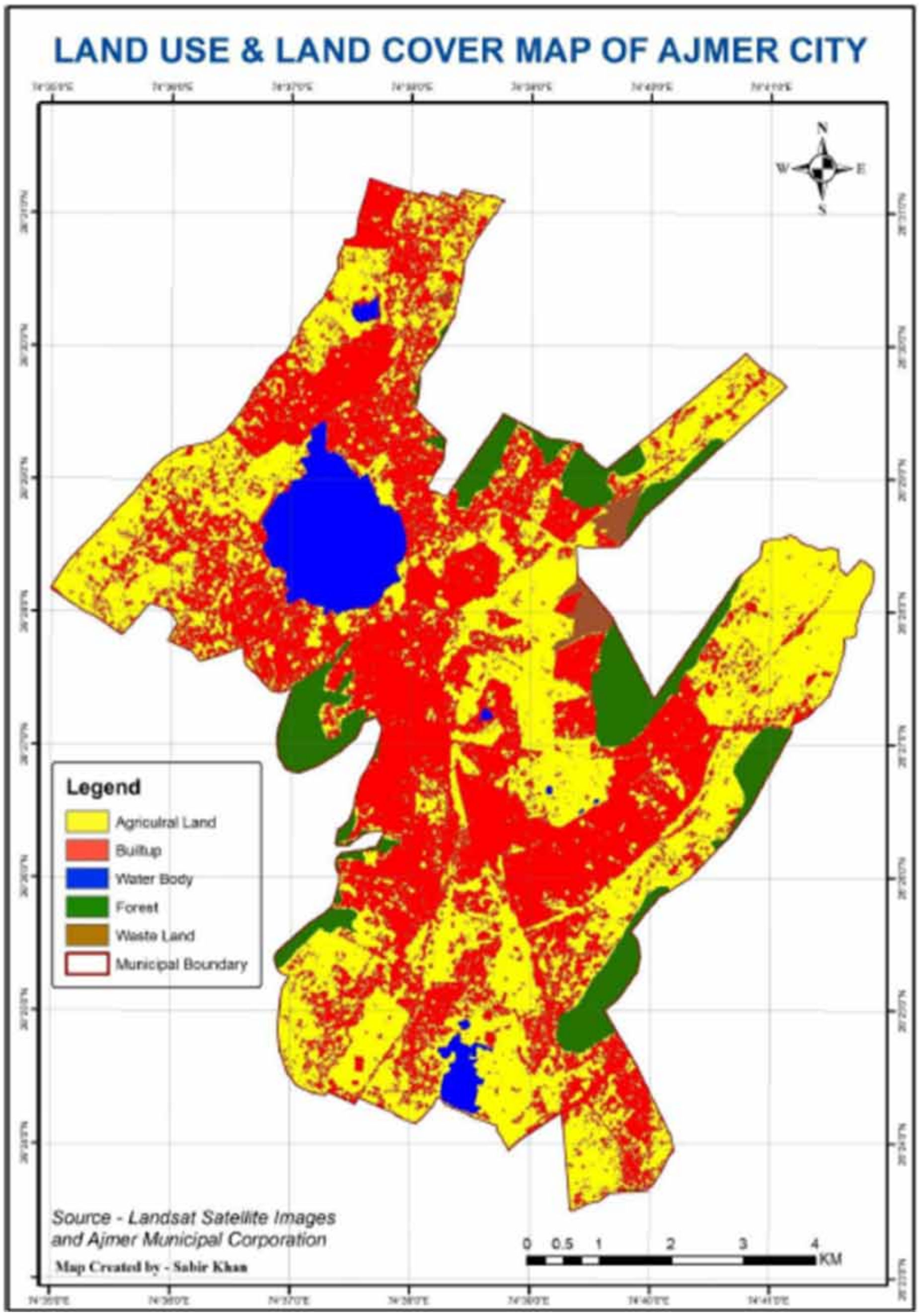
In the heart of Ajmer, two major industrial units, namely the Railway Carriage and Loco Workshop, emit significant amounts of CO, CO_2, sulphur oxides, nitrogen oxides, and dust, making a substantial contribution to air pollution. Small-scale industries in Parbatpura Industrial Area and H.M.T. Industrial areas are also impacting natural resources. Foundries and rolling mills in the Parbatpura industrial area,

Table 1. Present land use of Ajmer

S.No.	Land Use	Area in Acres	% of Developed Area	% of Urban Region
I	Residential	5922.07	69.09	7.82
Ii	Occupation	282.01	3.29	0.37
Iii	Industrial	1094.38	12.76	1.44
Iv	Governmental	95.92	1.12	0.13
V	Public and Semi-Public Services	1073.55	12.52	1.42
Vi	Entertainment	76.42	0.89	0.10
Vii	Transport Network	30.94	0.36	0.04
Viii	Nursery, Horticulture & Dairy & Poultry	47059.69		62.12
Ix	Govt. Reserved	353.75		0.47
X	Fallow Land	8501.86		11.22
Xi	Forest	9118.10		12.04
Xii	Hilly Area	1768.84		2.34
Xiii	Water Bodies	375.03		0.45
Total Urbanized Area		75752.56		100

Source: Ajmer Development Authority Report 2013

Figure 2. Present land use land cover map of Ajmer city



along with foundries in the H.M.T. Industrial area, release high levels of suspended particulate matter, affecting the surrounding regions.

Ajmer's well-established transportation network, connected to other parts of the state and country via roads and railways, is facing increased pressure due to its status as a religious, commercial, and educational hub. The city experiences a significant flow of vehicles, with 31% linked to Jaipur Road,

Table 2. Projected land use 2033

S.No.	Land Use	Area in Acres	% of Developed Area	% of Urban Area
I	Residential	11550	73.10	40.98
Ii	Occupation	990	6.26	3.51
Iii	Industrial	664	4.20	2.36
Iv	Governmental	128	0.82	0.45
V	Public and Semi-Public Services	2240	14.18	7.95
Vi	Entertainment	144	0.91	0.51
Vii	Transport Network	84	0.53	0.30
Viii	Nursery, Horticulture, Dairy and Poultry	436		1.55
Ix	Govt. Reserved	354		1.25
X	Forest and Hilly Area	10887		38.63
Xi	Water Bodies	708		2.51
	Total	28185		100

Source: Ajmer Development Authority Report 2033

Table 3. Residential areas

Sampling Stations	Main Sources of Pollution
Vaishali Nagar	Non- agricultural lands, use of coal as a fuel
Bihari Ganj	Industrial area, Construction work, brick manufacturing industries
Shashtri Nagar	Construction sites, unpaved roads

Sources of Pollution at:

42% to Nasirabad Road, 16% to Beawar Road, and 11% to Pushkar Road. Truck movements, a major source of air pollution, have been redirected through bypass roads. Two-wheelers and three-wheelers, serving as primary public transport, contribute to air pollution. Natural sources like dust from unpaved roads, construction sites, dry lands, and non-vegetated areas also contribute to high levels of suspended particulate matter, leading to an increased incidence of respiratory diseases.

Respirable Dust Sampler, Model No. AMP 451 has been used for picking up the samples from the height of 10 to 12 feet at morning 4am and evening 8 pm. Chemical analysis of SPM have been done by an expert to make an observation.

Table 4. Commercial areas

Sampling Stations	Main Sources of Pollution
Madar Gate	Road Traffic, Traffic Jams, highly crowded area
Khailand Market	Narrow lanes, lack of parking areas, heavy traffic, crowd
Kutchery Road	Highly crowded, High traffic flow

Table 5. Silent zones

Sampling Stations	Main Sources of Pollution
J.L.N. Hospital	Heavy road traffic, Closer to Bajrangarh region, hospital waste
M.D.S. University	Construction work, vehicular pollution
Janana Hospital	Agricultural lands, Road Traffic.

Table 6. Main traffic circles

Sampling Stations	Main Sources of Pollution
Gandhi Circle	Traffic jams, closer to railway station,
Bajrangarh Chaurah	Heavy Traffic flow, Vehicular pollution, closer to JLN Hospital
Nasirabad Road	Heavy traffic caused by trucks

Table 7. Industrial areas

Sampling Stations	Main Sources of Pollution
Parbatpura Area	Rolling Mills, foundries, blasting, truck traffic
Carriage Workshop	Carriage repairing, use of coal

Table 8. Pollutants and level of pollution in residential areas

Site	SPM (µg/m3)			SO_2 (µg/m3)			NOx (µg/m3)		
	Min.	Max.	Ave.	Min.	Max.	Ave.	Min.	Max.	Ave.
Vaishali Nagar	154.66	177.67	166.16	12.0	16.5	14.25	23.59	32.44	28.00
Bihariganj	162.23	188.75	175.49	10.5	15.5	13	25.19	35.85	30.52
Shashtri Nagar	154.16	168.05	161.10	7.0	9.5	8.25	19.89	32.10	25.95
Average	157.01	178.13	167.58	9.8	13.83	11.83	22.89	33.46	28.15

Table 9. Pollutants and level of pollution at commercial sites

Site	SPM (µg/m3)			SO_2 (µg/m3)			NOx (µg/m3)		
	Min.	Max.	Ave.	Min.	Max.	Ave.	Min.	Max.	Ave.
Madar Gate	355.29	385.33	370.31	8.00	11.50	9.75	55.70	71.61	63.65
Khailand Market	392.31	378.20	335.25	11.50	16.00	13.75	43.76	58.90	51.33
Kutchery Road	376.13	432.87	404.50	10.90	13.50	12.20	106.90	120.36	113.22
Average	374.57	398.8	370.02	10.13	13.66	27.56	68.78	83.62	76.06

The observations and calculations show that the city is has higher levels of SPM, SO2 and NOx than the National Ambient Air Quality Standards according to the Central Pollution Control Board, the Population of the city is at higher risk of air pollution which is causing various health problems like-

Table 10. Pollutants and level of pollution at main traffic circles

Site	SPM (μg/m3)			SO_2 (μg/m3)			NOx (μg/m3)		
	Min.	Max.	Ave.	Min.	Max.	Ave.	Min.	Max.	Ave.
Gandhi Bhawan	177.67	385.33	281.5	17	21.5	19.25	30.59	32.44	31.51
Bajrangarh Circle	168.05	388.00	278.02	16.2	19.5	17.85	19.89	32.10	25.95
Nasirabad Road	188.75	251.28	220.01	10.5	15.5	13	25.19	35.85	30.52
Average	178.15	341.53	259.84	14.5	18.83	16.7	25.22	33.46	29.32

Table 11. Pollutants and level of pollution at silent zones

Site	SPM (μg/m3)			SO_2 (μg/m3)			NOx (μg/m3)		
	Min.	Max.	Ave.	Min.	Max.	Ave.	Min.	Max.	Ave.
J.L.N. Hospital	289.80	377.95	333.87	7.50	9.00	8.25	42.76	53.78	48.27
M.D.S. University	71.0	78.37	74.69	4.80	7.10	5.95	22.11	26.89	24.50
Janana Hospital	73.91	80.81	77.36	6.20	9.00	7.60	17.69	27.05	22.20
Average	144.9	179.04	161.97	6.16	8.36	7.26	27.52	35.9	31.65

Table 12. Pollutants and level of pollution at industrial sites

Site	SPM (μg/m3)			SO_2 (μg/m3)			NOx (μg/m3)		
	Min.	Max.	Ave.	Min.	Max.	Ave.	Min.	Max.	Ave.
Parbatputa	279.21	267.59	423.40	39.29	53.50	46.38	30.96	40.83	40.39
Carriage Workshop	298.97	382.61	340.79	52.00	57.50	54.75	25.19	38.04	31.61
Average	289.09	325.1	382.09	45.64	55.5	50.56	28.07	39.43	36

Table 13. National ambient air quality standards for SPM according to CPCB

Status	(μg/m3) SPM Industrial Areas	(μg/m3) SPM Residential Areas
Low	0-180	0 - 70
Moderate	180 - 360	70 - 140
High	360 - 540	140 - 210
Critical	>540	>210

- The incidences of nasal infection, cold, asthma, and throat infection aggravate with increasing amounts of SO2 and SPM.
- Air pollutants can also affect the nervous system,
- Reduces learning ability
- Fluctuating blood pressure
- Chronic heart diseases etc.

NOISE VALUE

The terms sound and noise are often considered synonyms but it is not so. It is an underrated environmental problem World Health Organization (Report 2001) mentioned that "Noise must be recognized as a major threat to human wellbeing."

Noise can be produced internally within a building through neighborhood, music appliances, kitchen appliances etc. or externally by automobiles, industrial activities, construction sites etc.

Noise Is Classified As

a) Industrial Noise - It is the high-intensity sound caused by industrial machines, factories, mills, mechanical saws and drills.
b) Transport Noise – There has been an enormous increase in the number of automobiles on roads like trucks, buses, cars, and scooters in the last two decades. Noise pollution is hovering around the borderline in metropolitan cities due to increased vehicular counts.
c) Neighborhood Noise – This is the noise produced by household gadgets like TVs, VCRs, radios, televisions, telephones, loudspeakers etc. which has been increasing ever since the Industrial Revolution.

Health Impacts of Noise Pollution

- Contraction of blood vessels and muscles.
- Secretion of excessive adrenalin in the blood stream which is ultimately responsible for fluctuating blood pressure.
- Blaring sounds causes mental disorders.
- Heat attacks, Neurological problems, birth defects and miscarriages.
- Nervous breakdown.
- Reduces work efficiency.
- It also affects the digestive, respiratory, and cardiovascular systems of the body.
- It reduces the hearing capacity.
- Causes insomnia, impairment in night vision, and chronic damage to the inner ear.
- One can experience adverse behavioural and emotional changes.

Standards regarding noise pollution are laid under the Environmental Protection Act, of 1986 and the Model Rules of Factories Act, of 1948 for occupational health and safety issues.

WATER SUPPLY

Ajmer relies on surface water resources to fulfil the water needs of its residents. In 1884, the city began receiving piped water from the Anasagar reservoir when the population was around 50,000. To meet increased demand, Foysagar was constructed in 1892. However, due to population growth, Anasagar's area diminished, and household drainage was directed into the reservoir. Currently, Anasagar has become an ineffective water reservoir, with ten streams dumping household wastewater into it. Efforts have been

Table 14. Standard noise levels in different zones

Area Code	Category of Area	Limits in db	
		Day Time	Night Time
A	Industrial Area	75	70
B	Commercial Area	65	55
C	Residential Area	55	45
D	Silent Zone	50	40

Source: Environment Protection Act, 1986 amended in 2002.

Table 15. Ajmer city observed variation in noise levels (db) at different locations

Zones	Locations	Time (Hours)							
		8-10 am		10-12 am		12-2 pm		2-4 pm	
		Min.	Max.	Min.	Max	Min.	Max.	Min.	Max.
Commercial	Chudi Bazaar	58.2	75.8	62.3	83.1	61.4	80.2	72.8	96.4
	Madar Gate	57.3	83.5	62	80.3	63.7	84.7	62.9	110.2
Residential	Bank Colony	37.6	95.2	43.2	73.1	37	75.5	42	94.3
	Panchsheel Colony	51.5	84.9	61.3	82.2	64.8	79.2	64	98.3
Heavy Transport regions	Bajrangarh Chawraha	66.7	98.1	67.1	115.8	68.5	94.3	68.4	114.6
	Railway Station	69.3	108.2	69.1	116.2	62.8	103.7	67.5	107.2
	Bus Stand	67.2	96.5	65.7	113.8	63	92.9	63	98.1
Silent Zone	M.D.S. University	33.2	68.1	42.3	74.1	28.6	73.5	41.2	76.1
	Janana Hospital	50.4	86.2	62.7	88.6	48.6	79.9	48	76.6
	JLN hospital	39.9	79.2	52.3	83.1	37.5	78.2	47.2	84.6
	Railway Hospital	35.3	70.7	36.8	82.3	38	78.1	43.5	79

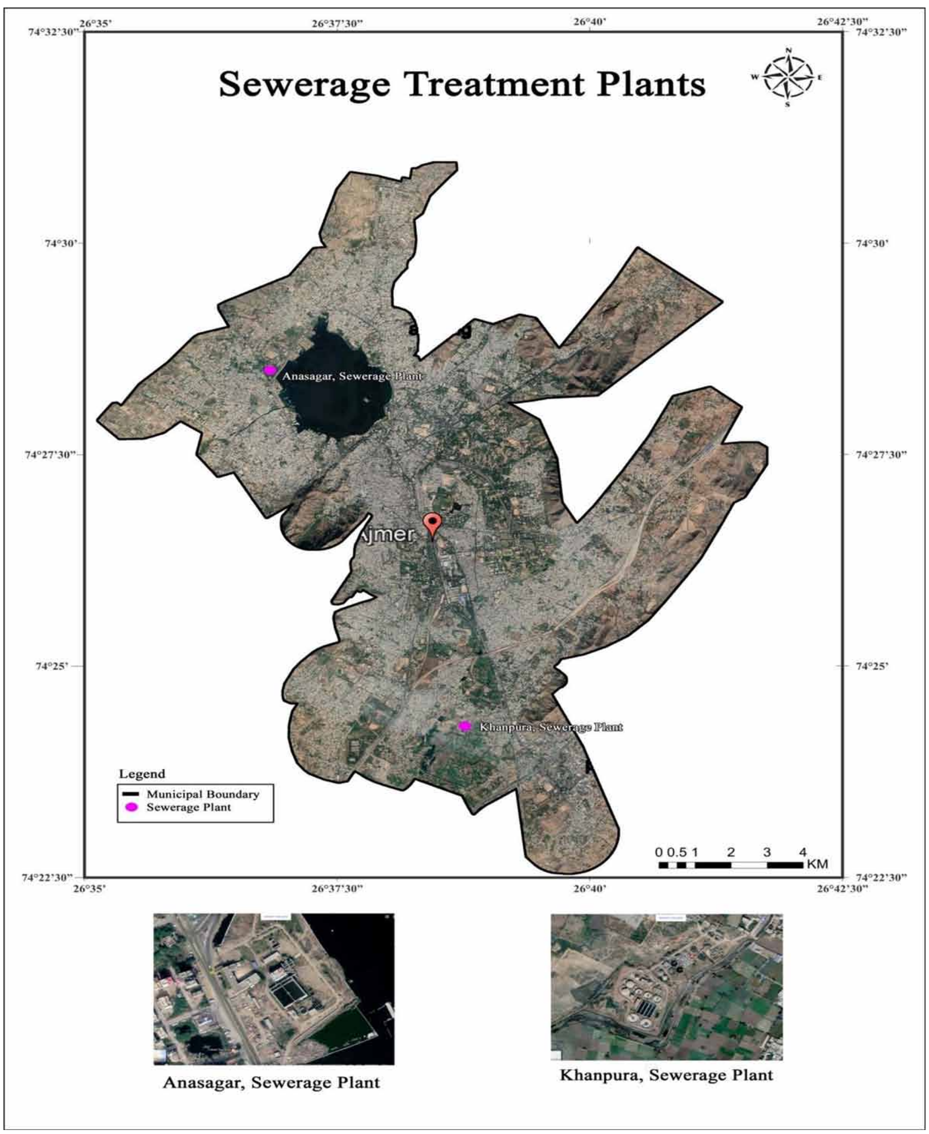
made to clean up this historical reservoir. The city currently receives approximately 68 MLD of water from the Bisalpur Phase project, 0.6 MLD from Foysagar, and 1 MLD from Bhewanta. Water quality is regularly monitored at the filter plant's laboratory, testing all fourteen parameters daily to ensure the city receives quality water.

SEWERAGE ISSUES

Ajmer faces challenges with an inadequate drainage system, sewerage treatment, flooding in low-lying areas during heavy rainfall, and an open drainage system. Drainage conditions, particularly in the old city and low-lying areas like Pal Bisla, Nagra, Bihariganj, and Prakash Road, are subpar. These areas experience waterlogging even with minimal rainfall. Sewerage is primarily discharged through nalas into Anasagar Lake and Pal Bisla tank from surrounding localities. About ten major/minor nalas carry around 13 MLD of wastewater into the lake. Settlements in the catchment, agricultural activities, and solid waste disposal have reduced the peripheral area of Anasagar. Water quality checks have revealed heavy metals such as iron, lead, zinc, and organo-chlorine pesticides like heptachlor and DDT. Continuous consumption of such water quality can directly or indirectly lead to adverse effects on human health, including neurological disorders, impacts on the brain, spinal cord, and nervous systems, changes in behaviour, dermatological issues, eye infections and irritation, renal disorders, gastrointestinal disorders, vomiting, diarrhoea, nausea, reproductive disorders, and respiratory disorders.

Solid waste management is emerging as global concern, particularly in developing nations, it is contributing to environmental issues such as air, soil, and water pollution, and release of greenhouse gases from landfills. The investigation reveals that the Ajmer Municipal Corporation (AMC) has not

Figure 3. Ajmer city- location of sewerage treatment plants
(Ajmer Development Authority)



effectively implemented Municipal Solid Waste Management (MSWM) and lacks a comprehensive plan for the coming years.

According to Municipal Officer Prateek Kumawat, responsible for addressing the city's sewerage issues, the current estimated population is 590,000, generating 400 grams of waste per person per day. The city produces approximately 220 to 240 tons of solid waste daily, with an additional 40,000/day from the floating population. The waste comprises residential, market, commercial, industrial, hotel, restaurant, park, garden, slum, biomedical, and slaughterhouse waste. Bulk waste generators include hotels, restaurants, hostels, marriage gardens, banquet halls, slaughterhouses, hospitals, and canteens, collectively generating 100kg/day of solid waste. Discussions with officials indicate that door-to-door waste collection is at 100% efficiency at the ward level, except for challenging sites like hilly areas and the Dargah region. The municipality employs Auto Tippers, Hand Carts, and E-Rickshaws as needed at the ward level, with 120 auto tippers (2 in each ward). The municipality collaborates with private entities for effective waste management, involving around 980 sanitation workers in drain and roadside cleaning, as well as maintaining public toilets.

Solid waste disposal occurs at the Makhupura bypass site, located 10 km from the main city on the western side of the Ajmer-Nasirabad highway. While the site currently has a capacity for over 20 years, the increasing population and urban growth pose concerns while waste management in the city may have improved with efficient waste collection and dumping, a new challenge arises. However, there are many studies and real time examples available telling that solid waste generated can be utilized and recycled effectively, yet this potential is not being adequately tapped, leading to health issues among the city's residents. The lack of awareness, and knowledge concerning the generation, collection, transportation, and disposal of solid waste results in several consequences:

- Air pollution caused by unpleasant odors.
- Emission of greenhouse gases.
- Solid waste dumping sites serve as breeding grounds for flies, mosquitoes, and germs.
- Increased acidity levels of soils due to garbage accumulation.
- Elevated risks of diseases and epidemics.
- Pollution of ground and surface water.

Various parameters of the built environment, including interior and exterior collectively impact the physical and psychological well-being of residents. These factors can act as both push and pull factors.

Table 16. Physical characteristics of MSW in Indian cities, 2011

Population Range (millions)	No. of Cities	Percent Composition of Municipal Solid Waste						
		Paper	Rubber, Leather and Synthetic	Glass	Metals	Total Matter	Inert	Total
0.1 – 0.5	12	2.92	0.77	0.57	0.32	44.59	43.57	100
0.5 – 1.0	15	2.94	0.74	0.34	0.33	40.05	48.37	100
1.0 – 2.0	9	4.71	0.71	0.46	0.49	38.95	44.57	100
2.0 – 5.0	3	3.19	0.47	0.48	0.58	56.68	49.07	100
>5.0	4	6.44	0.27	0.94	0.81	30.47	53.90	100

Source: Manual on Solid Waste Management, NEERI, 1996

Table 17. Chemical characteristics of MSW in Indian cities, 2011

Population Range (in Millions)	Moisture	Organic Matter	Chemical Characteristics			
			Nitrogen as Total Nitrogen	Phosphorous as P_2O_5	Potassium as K_2O	Calorific value in kcal/kg
0.1 – 0.5	25.81	37.09	0.71	0.62	0.84	1009.88
0.5 – 1.0	19.52	25.19	0.65	0.56	0.69	900.61
1.0 – 2.0	26.97	26.98	0.64	0.82	0.73	980.05
2.0 – 5.0	22.03	25.60	0.57	0.63	0.77	907.17
>5.0	37.72	38.07	0.56	0.52	0.52	800.71

Source: Manual on Solid Waste Management, NEERI, 1996

Substandard indoor and outdoor environmental quality is associated with health issues such as respiratory infections, tuberculosis, asthma, and various infectious diseases.

Diseases manifest when favourable conditions exist, influenced by physical, biological, and social factors. This analysis considers specific physical and social factors contributing to the current built environment, influencing the health of residents. Disparities in health profiles among inhabitants are evident, with overcrowded areas being particularly susceptible to diseases. These areas and their residents contribute to the spread of infectious diseases, impacting social well-being.

For this study, data on diseases directly or indirectly linked to the built environment, such as viral infections, intestinal infectious diseases, tuberculosis, respiratory disorders, eye infections, hypertension, and hormonal disorders, were collected from government dispensaries, urban public health centers, and the Chief Medical and Health Officer (CHMO).

Table 18. Ajmer city: Density of population UPHC / dispensary area wise

S.No.	UPHC	No. Of Wards included	Population Density	R1
1	GULAB BARI	6	10041	6
2	KASTURBA	5	32240	1
3	PAHAR GANJ	5	23088	3
4	POLICE LINE	9	6445	12
5	RAM GANJ	4	7687	9
6	AJAY NAGAR	5	13920	4
7	ANDERKOT	8	23396	2
8	DIGGI BAZAR	14	9690	7
9	GADDI MALIYAN	6	8219	8
10	PANCHSEEL	5	5221	13
11	RAM NAGAR	5	6464	11
12	SRINAGAR ROAD	6	12134	5
13	VAISHALI NAGAR	6	6863	10
14	J.P.NAGAR	2	3931	14
15	KOTRA	3	3646	15

Figure 4. Population density map

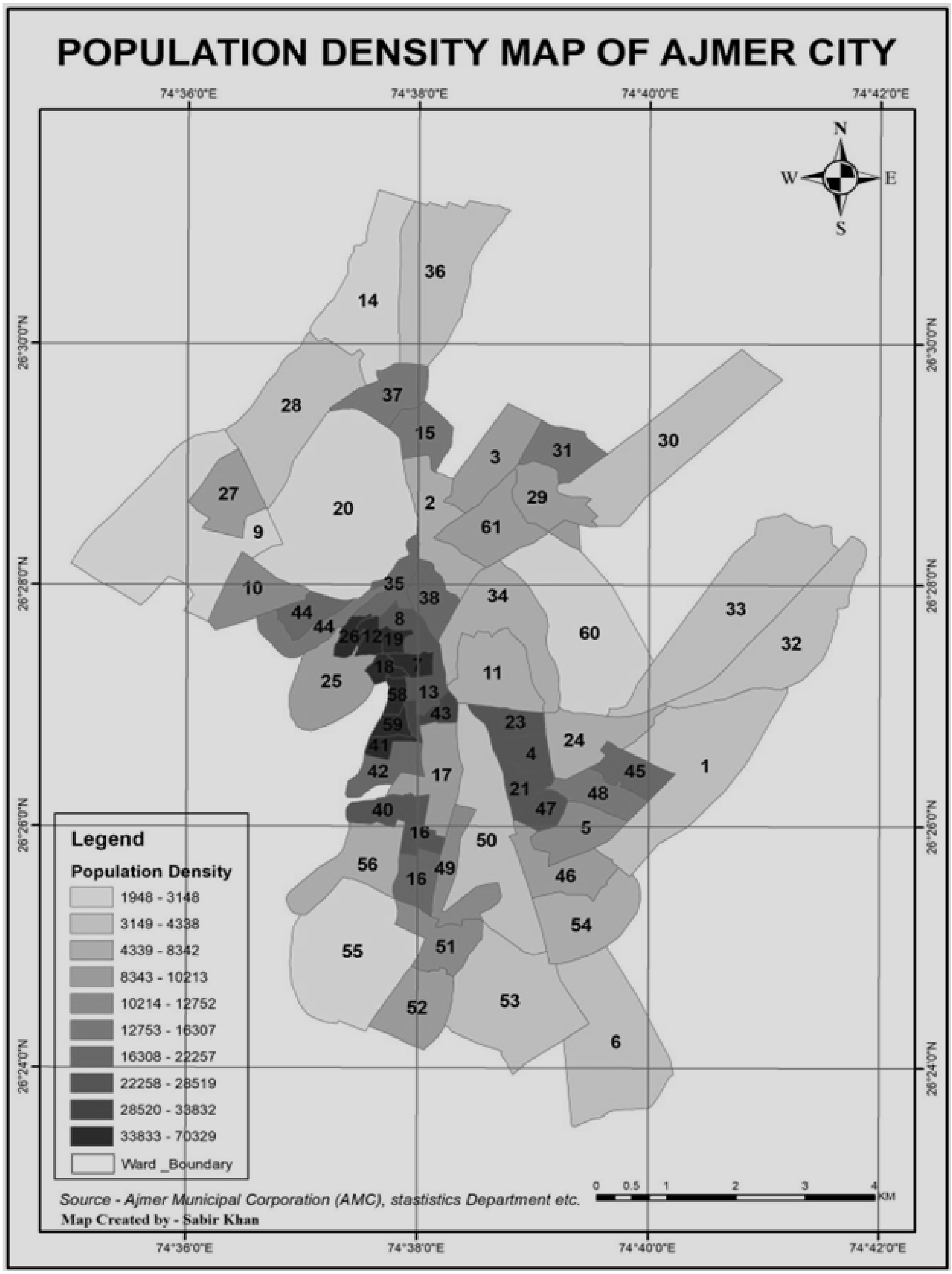


Table 19. Total registered cases of diseases in 5 years

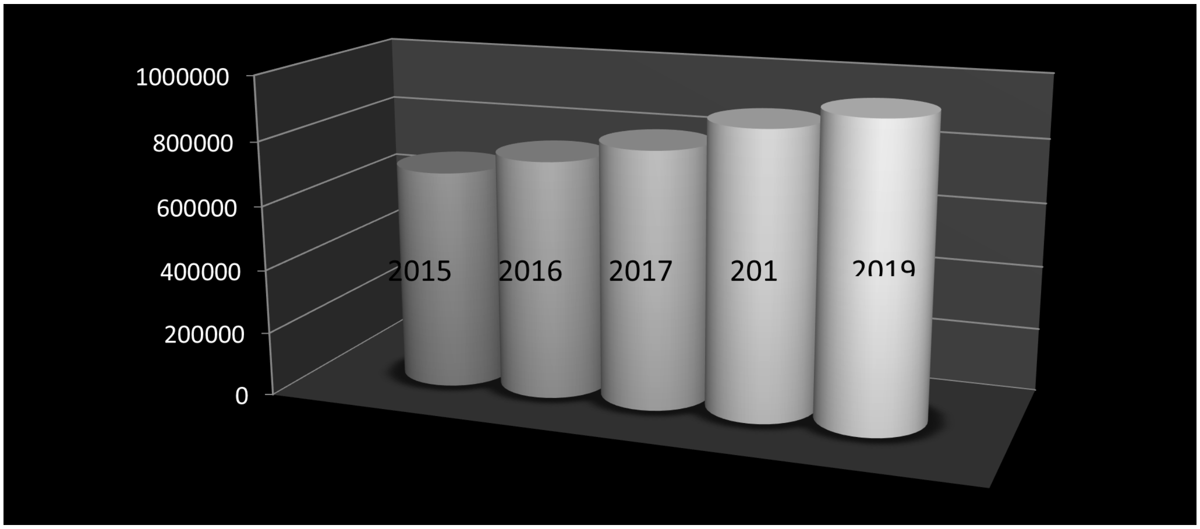
S No.	UPHC / Dispensary	Population	2015	2015 %	2016	2016 %	2017	2017 %	2018	2018 %	2019	2019 %	AVG.	AVG. %
1	Gulab Bari	51612	20102	38.95	28443	55.11	33700	65.29	42731	82.79	39344	76.23	32864	63.68
2	Kasturba	43250	69140	159.86	74324	171.85	79660	184.18	79888	184.71	79952	184.86	76592	177.09
3	Pahar Ganj	45253	65540	144.83	70595	156.00	72701	160.65	78191	172.79	80727	178.39	73551	162.53
4	PoliceLine	80322	71126	88.55	70872	88.23	81570	101.55	88135	109.73	96814	120.53	81703	101.72
5	Ram Ganj	35437	70212	198.13	68260	192.62	68703	193.87	79931	225.56	83835	236.57	74188	209.35
6	Ajaynagar	44686	40597	90.85	39078	87.45	35373	79.16	35465	79.36	34268	76.69	36528	81.74
7	Anderkot	71358	64777	90.78	76083	106.62	73231	102.62	84830	118.88	82329	115.37	76250	106.86
8	Diggi Bazar	27558	66101	239.86	78318	284.19	89282	323.98	89889	326.18	99133	359.72	84545	306.79
9	Gaddi Maliyan	44313	14370	32.43	17807	40.18	27285	61.57	26512	59.83	34535	77.93	24102	54.39
10	Panchsheel	47405	11415	24.08	20625	43.51	22319	47.08	30884	65.15	37359	78.81	24520	51.72
11	Ramnagar	36527	92816	254.10	95159	260.52	90796	248.57	94387	258.40	95578	261.66	93747	256.65
12	Srinagar Road	56794	35893	63.20	34528	60.80	34887	61.43	41360	72.82	45261	79.69	38386	67.59
13	Vaishali Nagar	54150	68789	127.03	73413	135.57	75480	139.39	78962	145.82	79382	146.60	75205	138.88
14	JP Nagar	19069	0	0.00	0	0.00	16948	88.88	16786	88.03	28632	150.15	20789	109.02
15	Kotra	26762	0	0.00	0	0.00	0	0.00	16948	63.33	16186	60.48	16567	61.90
	Total	684496	690878	100.93	747505	109.21	801935	117.16	884899	129.28	933335	136.35	55302	129.99

Source: AMC/UPHC/Dispensaries

The above figure represents the overall number of registered disease cases in the city at Government CMHO, dispensaries and UPHCs for five years which is shows the increasing tendency over the years.

This research forms a component of Social Geography, delving into the connection between aerial population density and nine distinct diseases. Correlation analysis serves as the methodology to explore relationships, whether between quantitative or categorical variables. Such studies prove valuable in discerning associations between variables, enabling predictions about future patterns. In the realm of social sciences, where understanding future trends is paramount, this correlational study assumes significance.

Figure 5. Total registered cases of diseases in 5 years
(CMHO, Ajmer)



The findings are poised to aid local governments in anticipating healthcare needs and facilitating effective and efficient provision of healthcare services.

Disease data have been collected from UPHCs and Dispensaries. Spearman's correlation has been applied to check the relationship *p = 1- ((6 Σd2) / (n(n2-1)))*. It is particularly useful for analyzing ordinal data, where variables can be ranked but not measured numerically, making it ideal for survey data analysis. Additionally, the Spearman correlation is robust against outliers and does not require the assumption of normally distributed data, offering a flexible tool for various real-world datasets. Its capability to handle tied ranks further enhances its applicability, making it a preferred choice for statistical analysis in scenarios where data may not meet the stringent requirements for other types of correlation measures.

Various aspects of the built environment, such as water and sanitation infrastructure, housing quality, population density, and food safety practices, play crucial roles. It has been deduced from the data available that this disease has a positive relationship between population density and Intestinal infectious diseases which is =+0.54.

The below data show that the recorded number of diseases is maximum at Anderkot, Kasturba, Diggi Bazaar, Paharganj due to high population density due to lack of fresh air and ventilation, dampness whereas Ramganj, and Ramnagar have open nallas, excessive dampness, foul smell, are the major causes of respiratory diseases. The correlation value is = + 0.5, with this it has been deduced that there is a positive correlation between density of the population and the occurrence of respiratory diseases.

Viruses can spread through air, contaminated water, direct body contact, and indirect transmission through mosquitoes, ticks etc. Crowd, unhygienic conditions, dampness, and lack of proper sunlight aggravate the occurrence of disease which is clear in the calculations as it shows a positive correlation of = +0.63 between population density and occurrence of viral diseases.

Tuberculosis is a stern bacterial disease caused by Mycobacterium Tuberculosis, mainly affects the lungs and causes pulmonary tuberculosis but it can also affect the lymphatic system, bones and joints,

Figure 6. Intestinal infectious diseases

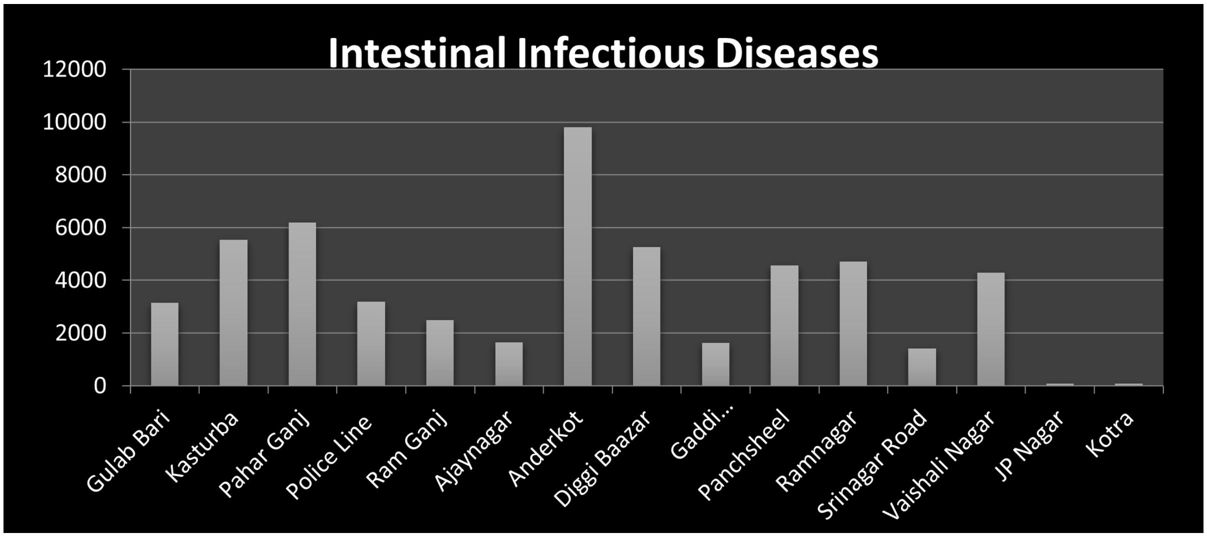
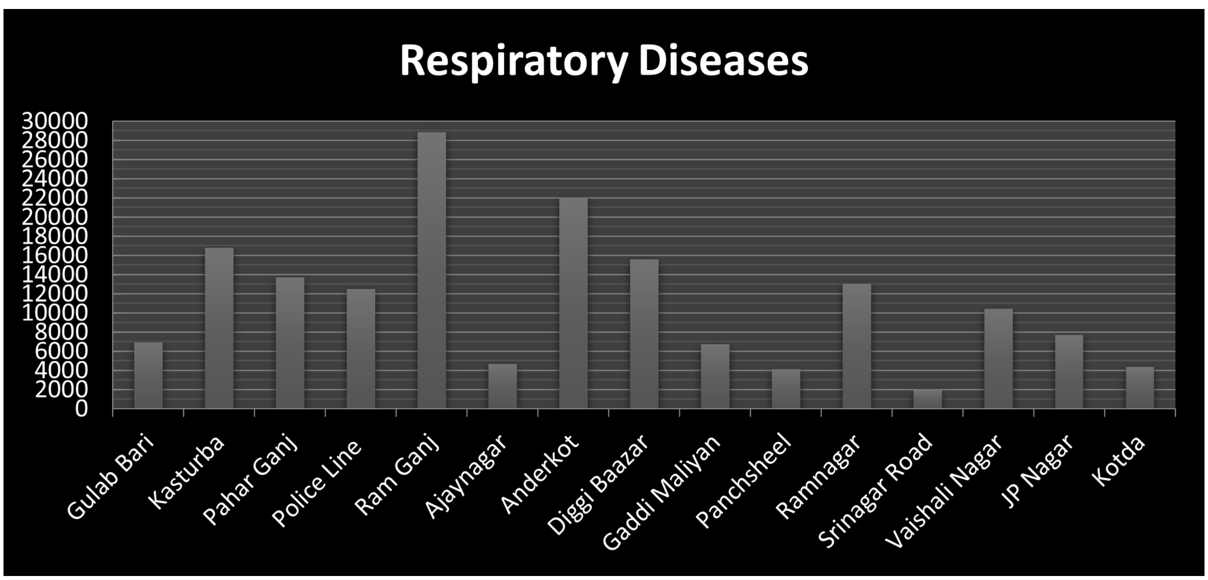


Figure 7. Respiratory diseases



intestine, meninges and other parts of our body. It is a social disease also known as a barometer of social welfare as the social indicators of this disease are size of family, quality of life, indoor and outdoor environmental conditions, crowding, level of nutrition, awareness and education etc. The disease shows a positive correlation = +0.63 the with density of the population. The recorded cases are maximum where population density is high. Major hotspots are Diggi Bazaar, Anderkot, Kasturba, Ramganj and Paharganj areas.

Eye infection indicates the primary health condition of the region. It has been noticed that eye infection is frequently reported in high-density areas where housing conditions are not good, lanes are

Figure 8. Recorded cases for viral diseases

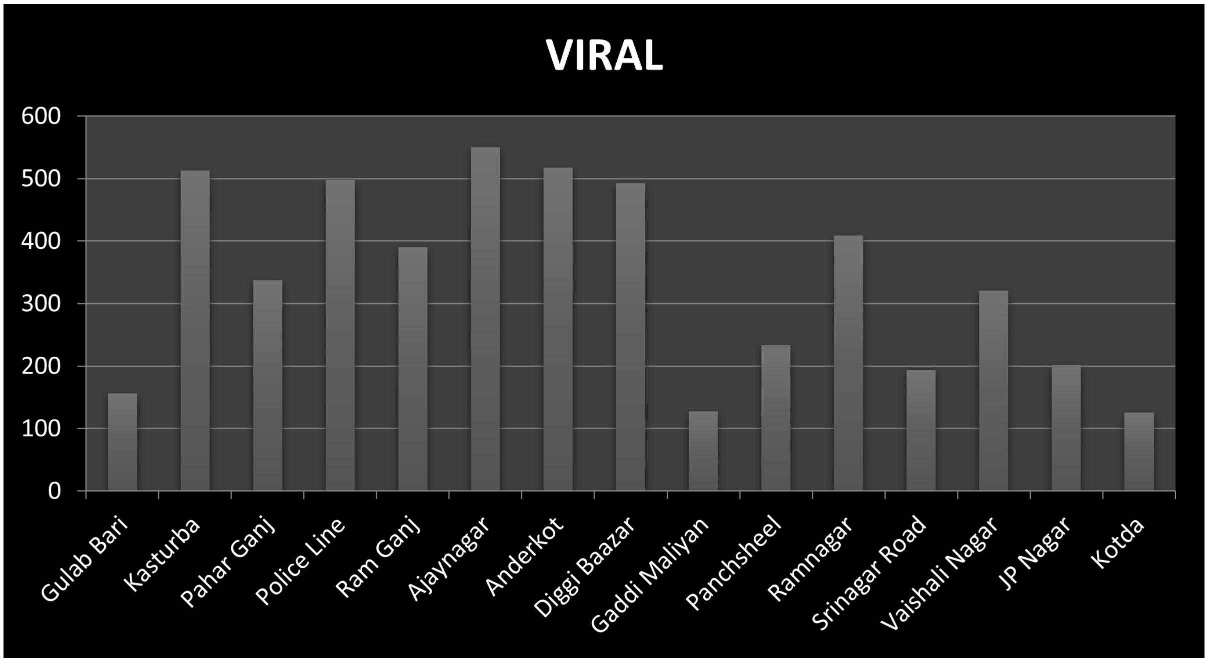
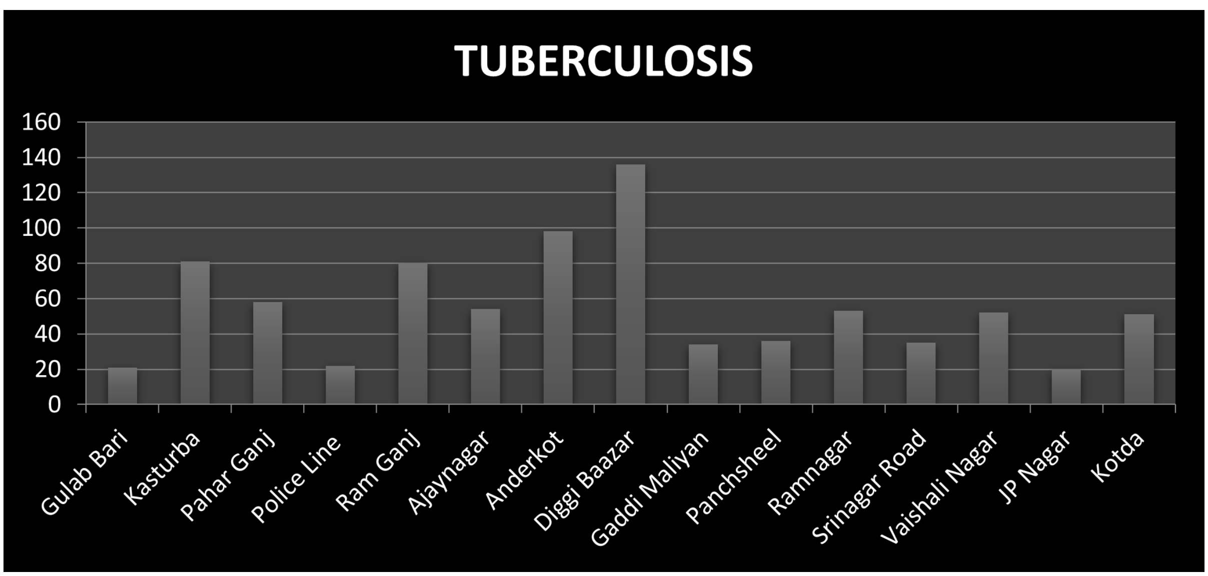


Figure 9. Recorded cases for tuberculosis cases



narrow, lack of sunlight and fresh air, poor sanitation facilities, and open drains and nallas are available which provide perfect breeding grounds to vectors. There is a positive relationship between population density and the occurrence of eye infections in the city and the correlational value is = +0.9, which shows a high correlation.

Figure 10. Eye infection cases

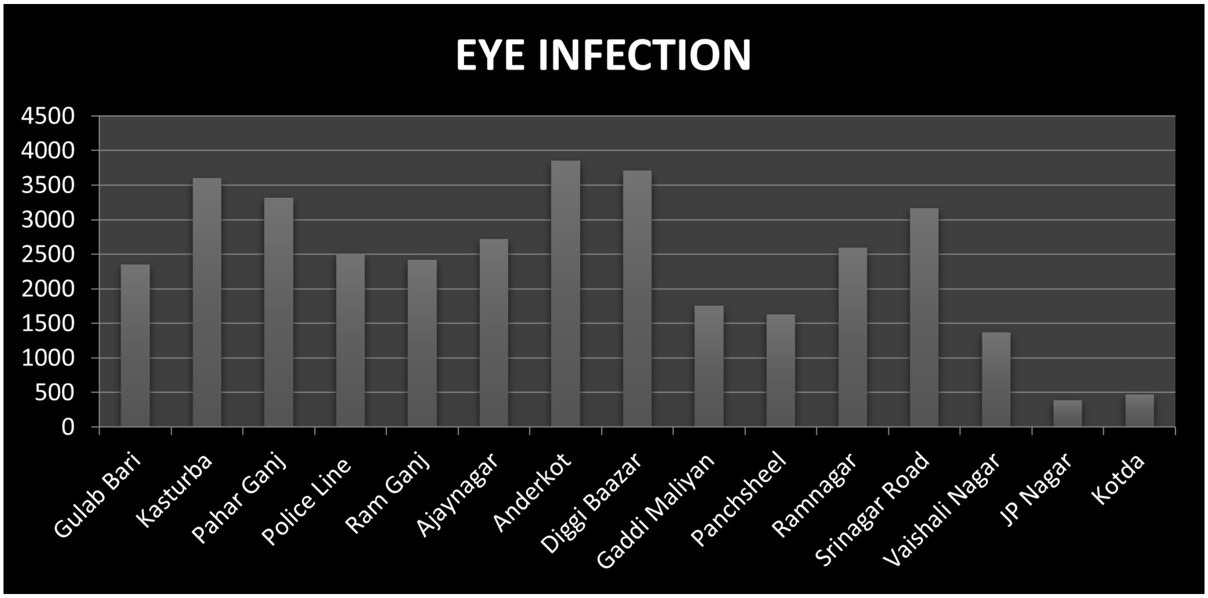
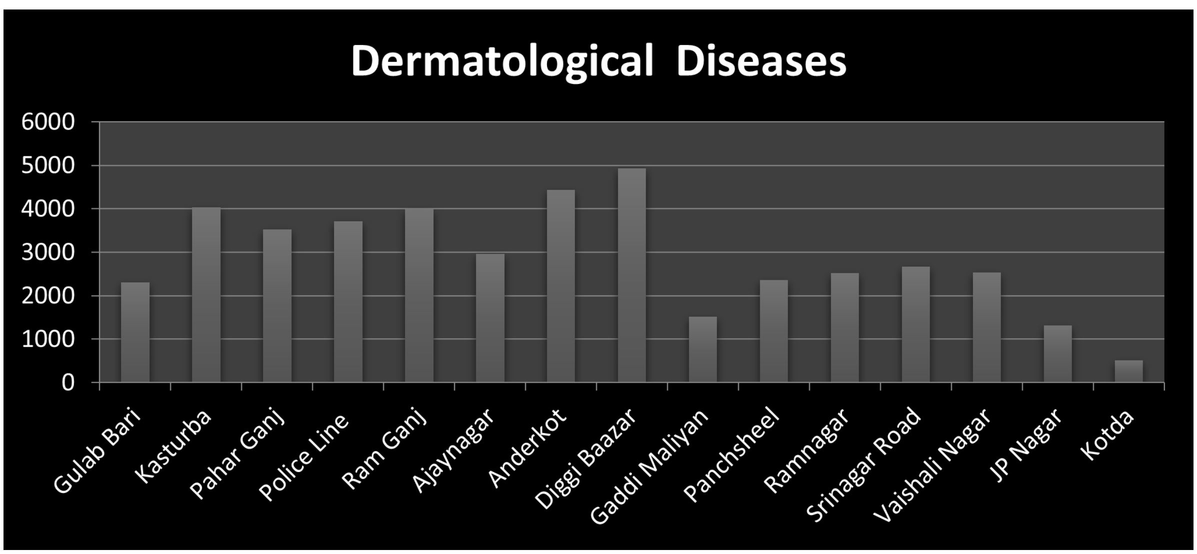
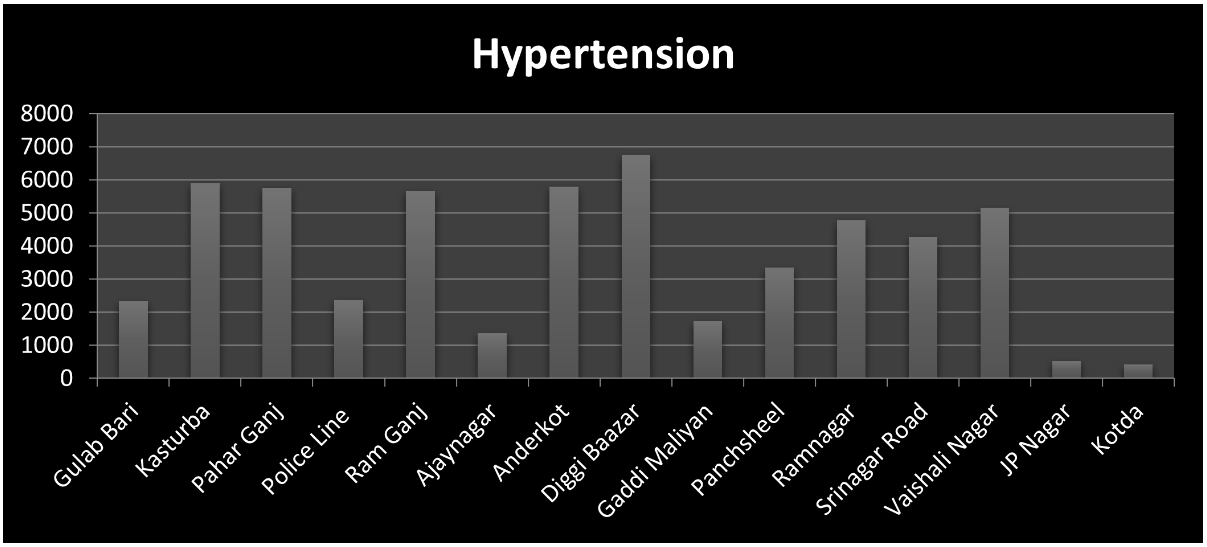


Figure 11. Recorded cases for dermatological diseases



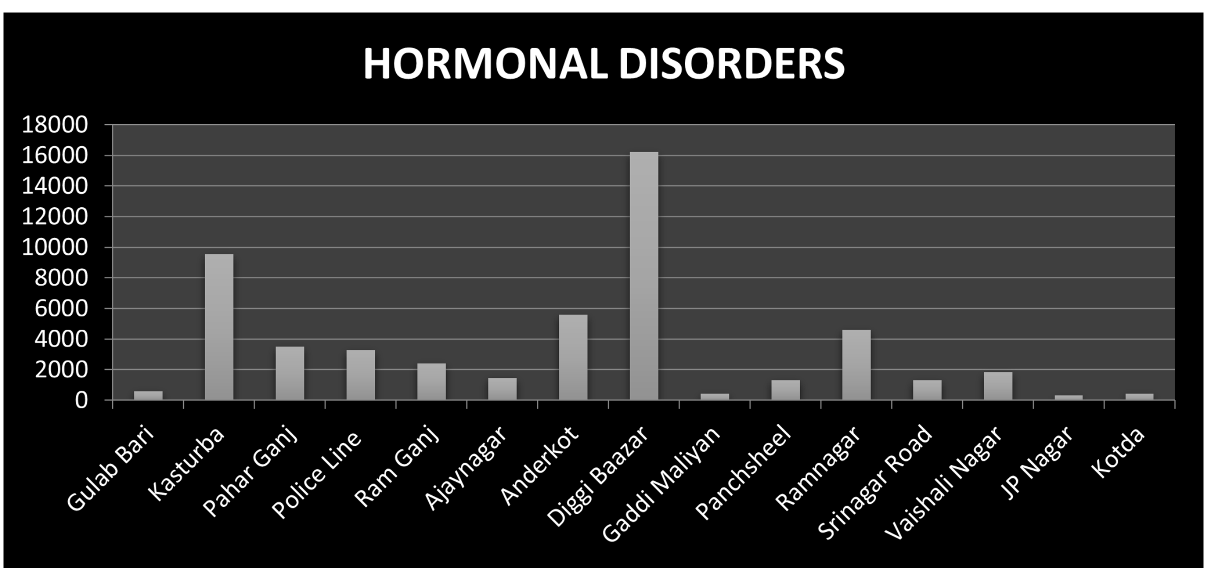
There is a high frequency of skin diseases in high-density population areas. It has been deduced that there is a high correlation of = +0.82 between density and skin disease. Skin works as a window for what is happening in the internal body, it shows stress, deficiency etc. These signs can help treat diseases at an early stage before they become a bigger problem. Some skin diseases are contagious when they spread due to direct or indirect physical contact with the infected person, chances of such diseases are maximum in areas with high humidity, lack of sunlight/fresh air, poor sanitation and unhygienic conditions etc.

Figure 12. Recorded cases for hypertension diseases



Hypertension is a major risk factor for mortality and morbidity. Studies show that the environment plays a major role in hypertension development. The unsystematic, unplanned built environment can aggravate the blood pressure which can result in multiple organ failure. This study shows a positive relationship with a value of = + 0.69 between crowd, road traffic noise and hypertension, The probable increased risk of hypertension when road traffic noise is above 80 db (24 h equivalent level) should be considered in city planning and when assessing the need for preventive measures.

Figure 13. Recorded cases for hormonal disorders



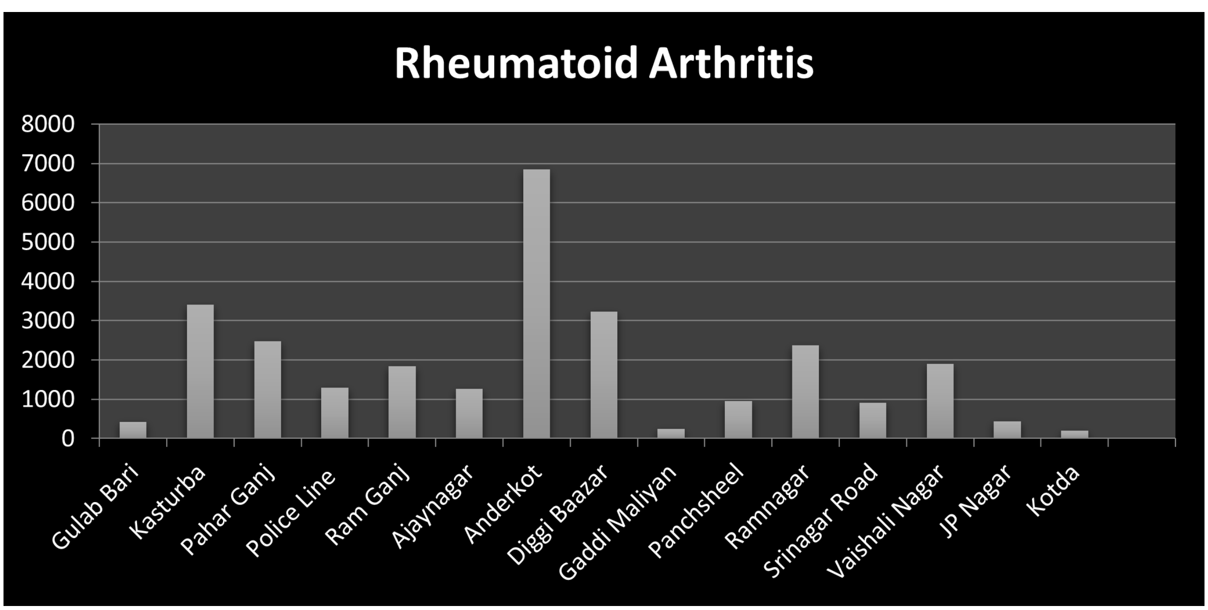
The hormonal glands create feedback loops by releasing hormones into the circulatory system, acting as chemical messengers. These hormones play a crucial role in regulating mood, growth, organ functions, metabolism, and reproduction. The presence of infectious diseases and stress significantly influences the levels of hormonal secretion in the body. The unplanned development of infrastructure and the deteriorating environment contribute to heightened stress levels and compromised immunity among residents. This study reveals that areas with increased infrastructure and population density exhibit a positive correlation with a higher incidence of hormonal disorders. The calculated correlation coefficient is = +0.77, indicating a strong association between density and the prevalence of hormonal disorders.

Research also has indicated that environmental factors may play a role in one's risk for rheumatoid arthritis. Some include exposure to smoke, air pollution, insecticides and pesticides, and occupational exposures to mineral oil and silica can cause arthritis. Ajmer city shows a positive correlation between the density of population and disease with = + 0.73.

CONCLUSION

A five-year study in Ajmer city, collected data from government dispensaries and health centres to understand how the population density relates to various diseases like intestinal issues, respiratory problems, viral infections, tuberculosis, eye infections, skin conditions, hypertension, hormonal imbalances, and arthritis. The findings show a clear connection between higher population density and more instances of these diseases. This supports the idea that the environment we create affects our health. Long-term illnesses not only bring physical challenges but also cause emotional distress and financial strain due to health-related costs. Mental health can suffer, impacting our overall well-being. While previous research focused on short-term effects, I aimed to explore how the built environment affects physical health, mental

Figure 14. Recorded cases for rheumatoid arthritis



health, and overall well-being over a more extended period. Our study used statistics and correlation analysis to link population density, household characteristics, and disease frequency. The results revealed that areas with high population density are more susceptible to diseases. These findings have practical implications. First, they emphasize the need for restoration in certain areas. Second, they highlight the financial challenges that can significantly impact residents' mental well-being. Third, promoting collaboration between the public and private sectors can lead to measures that improve physical and mental health outcomes, fostering social well-being in vulnerable communities.

"A hotspot analysis has been conducted based on available data, revealing a significant correlation between the intensity of disease occurrence and population density. The high alert zone encompasses Anderkot UPHC, Diggi Bazaar UPHC, Ramnagar UPHC, Kasturba Dispensary, and Ramganj Dispensary. These areas exhibit high population density but suffer from inadequate and inefficient health facilities. In the moderate zone, we find Police Line UPHC, Vaishali Nagar UPHC, Srinagar Road UPHC, Paharganj UPHC, and Aajaynagar UPHC. These areas are also susceptible to diseases, being near the high alert zone. Moreover, the population in this zone continues to rise. JP Nagar UPHC, Kotra UPHC, Panchsheel UPHC, Gaddi Maliyan UPHC, and Gulab Bari UPHC fall into the low-risk zone. These areas exhibit lower population density, less infrastructural development, and ample open spaces with proper air and light penetration. It's crucial to consider these findings for targeted healthcare interventions, especially in the high alert and moderate zones, to address the disparities in health facilities and curb the potential spread of diseases."

Thoughtful efficient efforts in some cities have been put towards the directions which can solve the issues in India, just to mention a few-

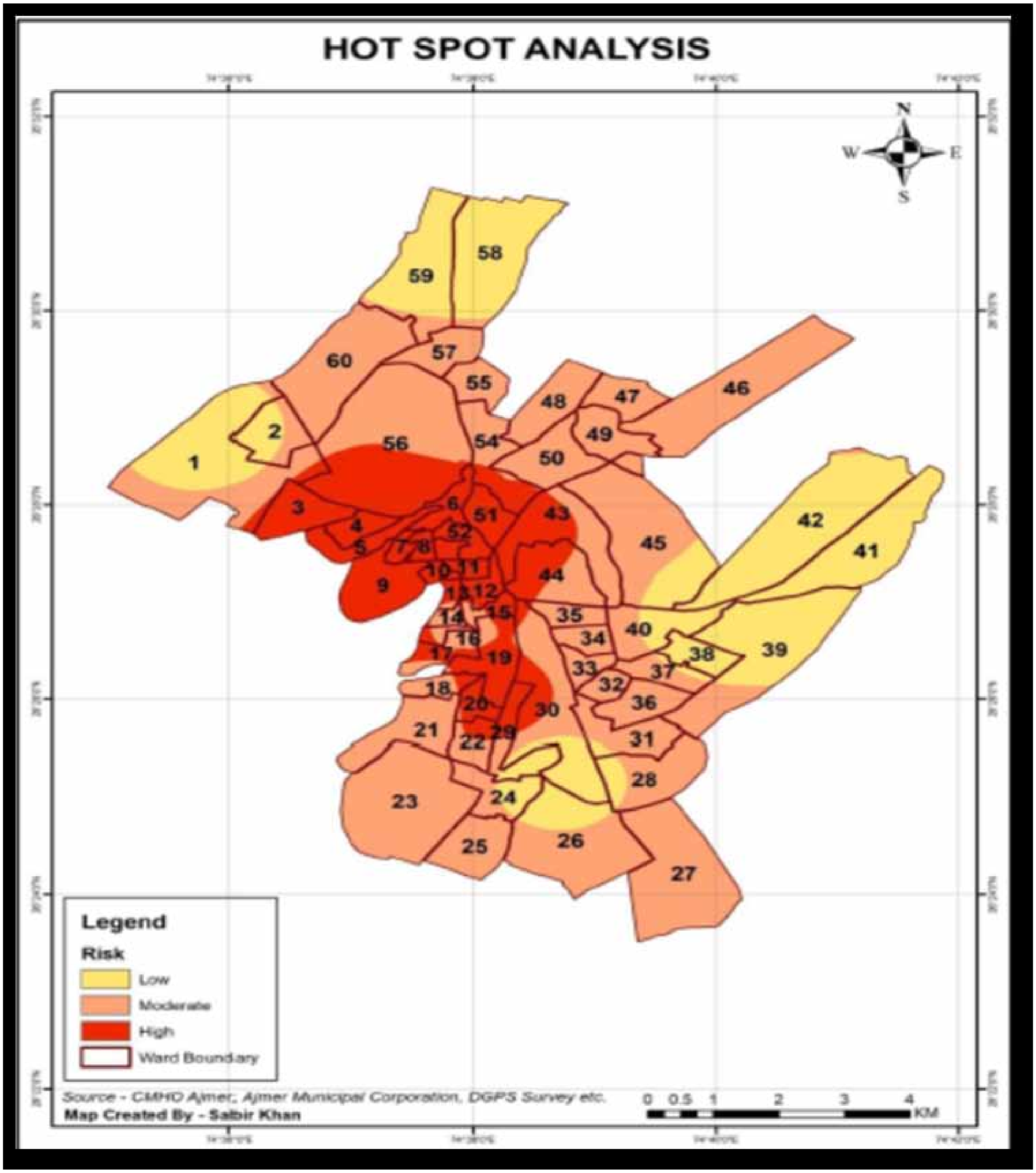
Indore, Madhya Pradesh: Swachh Survekshan and Waste Management

Inadequate waste management leading to unsanitary conditions and environmental pollution in Indore made people suffer at various fronts. Authorities and local people supported waste management reforms, including citizen awareness campaigns, waste segregation at source, and efficient waste collection and disposal practices. The city also actively participated in the Swachh Survekshan (Cleanliness Survey) initiated by the Government of India. The result is that Indore city was consistently ranked as one of the cleanest cities in India, showcasing the success of its waste management initiatives.

Ahmedabad, Gujarat: Sabarmati Riverfront Development

Pollution in the Sabarmati River affecting the urban environment was troubling the people and authority of the city. An outstanding stand was taken towards the solution, The Sabarmati Riverfront Development project aimed at transforming the riverfront into a vibrant and sustainable urban space. The project involved river cleaning, creating green spaces, and developing recreational areas along the river. Now, the Sabarmati Riverfront has become a prevalent public space, with improved air quality providing residents with recreational areas. The project is an effort to revitalize the urban environment and has been recognized for its innovative approach to urban planning.

Figure 15. Hotspot analysis



Delhi: Odd-Even Traffic Rule

Delhi is a red spot in the world map of world popular for its severe air pollution due to vehicular emissions, particularly during peak traffic hours. The Delhi government implemented the odd-even traffic rule, restricting the use of private cars based on their license plate numbers on alternate days aiming to reduce vehicular emissions.

The study of role of environmental sensors is beneficial in understanding and mitigating the impact of urbanization on both the environment and public health. To create resilient and healthier urban environments for current and future generations governments have to collaborate with policymakers, researchers, and urban planners. We are blessed to be born in the world with hi-tech technologies, such as the Internet of Things (IoT) Artificial Intelligence (AI), Geo-Informatics work in enhancing the capabilities of sense environmental sensors. These technologies enable more accurate and timely data collection, analysis, and interpretation, and help decision-makers to implement proactive measures for sustainable urban development. This area can be explored for further studies in Environmental Degradation and Human Health.

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Chapter 21
Environmental Sensors in Extreme Environments:
Scope and Validity

Aashish Verma
SAGE University, India

Sonam Verma
Rabindranath Tagore University, India

ABSTRACT

Many potentially harmful chemicals, released by industries and human activities, can contaminate water, soil, or air, and further impact the environment and public health. Real-time and in situ monitoring of various contaminants such as heavy metals, pesticides, pathogens, toxins, particulate matters, radioisotopes, volatile organic compounds, crude oil, and agricultural chemicals at low levels is mandatory in the fields of industrial plants, automotive technologies, medicine and health, water and air quality control, natural soil/land/sea, and so forth. Consequently, the monitoring of environmental pollutants became a priority. For this aim, sensors have captivated the attention of many scientists in modern times by virtue of their eco-friendliness, cost-effectiveness, miniaturization ability, and rapidness. Environmental samples, however, are very complex and unexpectedly relative to other ecosystems. Thus far, environmental sensors have been developed with greater sensitivity, simpler and more efficient detection, better environmental adaptation and etc. for pollutant detection.

INTRODUCTION

Marine monitoring is a comprehensive work that requires full understanding and the clear understanding of the significance helps in getting stronger data from oceans. Sustainable resources can be obtained when proper monitoring is done and it also involves strengthening the marine environment. Marine programs were initially developed for detection of contaminants covering wider aspects of the ecosystem.

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In the advent of new technology refined and efficient ways of monitoring was developed under EU marine strategy framework. The vision was to develop integrated ocean based observation system from sample collection helpful in assessment to produce scientific evidence for advice. Monitoring involves usage of new and traditional technologies that are used manually or with semi-autonomous modes. Collection of sample waters and fish is done for tracking movements where classification of microscopic and molecular techniques is used that helps in ensuring well founded ocean management and sustainable ocean industry-based operations.

CHALLENGES AND OPPORTUNITIES FOR OCEANIC SENSORS

Marine organisms are seen to be affected due to the anthropogenic sound emitted within underwater environment. The complexity as well as vastness of the oceans presents numerous challenges as well as opportunities due to the utilization of the sensors in extreme environments. Deployment of oceanic sensors has become extremely critical **(Dolson *et al.,* 2022).**

Challenges

Unfavourable condition of weather: the regions near the oceans are considered to be having an immense condition comprising high pressure, abrasive salt water, and the changes in temperature **(Feng *et al.,* 2022)**. These have the potential to pose a significant issue during the positioning and maintenance of the sensors. Thus, it requires more long-lasting technologies which can easily hold out against the exposure of such an environment.

Issues in data transmission and connectivity: In the aquatic environment, transmission of data from the sensors in real-time can be difficult. In addition to that, the physical obstacles such as depth of water and distance can be challenging for both data transmission and connectivity **(Wangand Menenti, 2021)**. Thus, it is required to develop better communicating mediums which can be capable of data transmission for long distance through various mediums.

Biofouling and fouling: algae, barnacles or similar marine organisms can possibly colonise on the sensor surfaces which further leads to biofouling as well as sensor degradation. The prevention of this biofouling can create barriers during the time of ocean monitoring as well as it also calls for more innovative solutions which can be helpful to maintain the accuracy and reliability of the sensor data **(Kim *et al.,* 2021)**.

Opportunities

Better understanding of marine ecosystems: the environmental sensors have the potential to provide valuable insights about the dynamic aquatic ecosystems. These insights may include water temperature, nutrient level which is present in the ecosystem and salinity. The continuous monitoring can provide parameters, making it easier for the scientists to gather knowledge about various aquatic processes as well as their impact on marine life **(Fisher *et al.,* 2022)**.

Quick detection of environmental changes: the sensors are able to detect the environmental changes in an early manner which includes acidification of ocean, sea level rise, various events related to pollution. The early detection helps in generating prompts to mitigate the issues and protect the marine ecosystem.

DEFINITION AND CLASSIFICATION OF EXTREME ENVIRONMENTS

An extreme environment mainly defines the characteristics of habitats by the conditions of a harsh environment which goes beyond the optimal range of human development. Such as pH2 or 11, −20°C or 113°C, saturation of salt concentration, high radiation, and 200 bars of pressure are considered to be challenging conditions, causing extreme environments **(Whitt *et al.,* 2020)**.

Extreme Temperature

There are two specific kinds of extreme environments that can be found such as cold and hot.

- Extremely cold environment: this occurs when the temperature goes below 5°C. This condition can be found in deep ocean, Polar Regions as well as high mountains.
- Extremely hot environment: this occurs when the temperature goes above 45°C. The condition can be caused by geothermal activities, volcanic areas and deep sea vents.

Extreme pH

Extreme environments can also be divided into two types, alkaline and acidic based on the level of PH.

- If the pH level rises above 9, it is considered to be an extreme alkaline environment.
- On the contrary, if the pH level drops below 5, it is considered to be a natural condition under an extreme acidic environment.

Extreme Ionic Strength

The environment with an ionic concentration higher than 3.5% is known as hypersaline environments.

Extreme Pressure

If the environment is below the extreme hydrostatic or litho pressure, such an ecosystem on the deep surface of the ocean is known as an extreme pressure environment **(Mahrad *et al.,* 2020)**.

High Radiation Environments

These kinds of environments are basically those areas which are being exposed to high radiation. The high top of mountains, deserts are possibly to high radiation such as gamma rays and ultra violet rays.

Xeric Environments

The arid habitats which have limited sources of aquatic activities are known as xeric environments. Hot deserts or cold poles are considered as one.

CHARACTERISTICS AND UNIQUE CHALLENGES OF OCEANIC ENVIRONMENTS

Mysterious Deep Sea and Hydrothermal Vents

The deep sea is known to be mysterious because of the darkness as well as the extreme conditions. To some extent, life adapts to survive without the sunlight in a different worldly environment created by hydrothermal vents. Mysterious creatures such as yeti crabs, tube worms can be found in those inhospitable regions creating a better diversity in aquatic ecosystems.

The Importance of Plankton in Marine Food Webs

The planktons lie at the base of the marine food chain, where they act as the fuel to the productivity of oceans. The microscopic creatures also play a huge role as they capture solar energy and convert the same for the high tropic levels. The absence of plankton can create complexity in the interaction that can further cause issues in sustaining marine life, causing an imbalance in the interdependence of the ecosystem **(Medina-Lopez *et al.,* 2021)**.

Human-Induced Challenges Facing Marine Ecosystems

Activities such as overfishing, pollution and habitat destruction always have huge consequences on the aquatic ecosystem. The action of overfishing and pollution from various sources also creates threats to the entire ecosystem as well as the well-being of organisms. Elements such as industrial wastes, plastic and contaminations ruptures the lifecycle of marine life **(Jiao *et al.,* 2021)**. The pollution related to plastic waste endangers marine species through ingestion as well as entanglement.

THE IMPACT OF CLIMATE CHANGE ON MARINE ENVIRONMENTS

Issues such as temperature rise on sea surface, acidification of ocean, and the rise of sea level is becoming a major concern for the habitats ultimately affecting the overall maritime. The temperature rise of the ocean has affected the coral reefs, leaving them as bleached.

The issues related to ocean acidification are being caused by absorption of carbon dioxide in an excessive manner from the atmosphere. This further creates a threat for the shell-forming organisms such as molluscs as well as corals. As the acid level rises in the ocean, the consequences can be seen through the disrupted food chains and disrupted ecosystem **(Tyagi *et al.,* 2020)**.

POLLUTION AND ITS DETRIMENTAL EFFECTS ON OCEAN HEALTH

The debris of plastic elements create issues for marine life as they often consume plastic, thinking of it as food which further leads to internal injuries, blockage and many other hazardous conditions. In addition to that, marine life also gets affected by the plastic wastages due to the hindrances while swimming or reproducing.

Oil spills, agricultural runoffs and other chemical pollutants have a huge impact on the overall health of the ocean. The issues related to oil spill on the ocean surface creates a disastrous impact on the marine lifecycle which further leads to death and demolition of all the habitats resulting through ecological consequences **(Li *et al.,* 2020).**

OVERVIEW OF KEY PARAMETERS AND VARIABLES TO MONITOR IN OCEANS

The ocean and its surface temperature play an important role in energy exchange, creating momentum as well as moisture in the atmosphere. The temperature of the surface is considered to be the determinant of how the air and sea interact based on the climate variability. Furthermore, it is responsible for incidents such as storms, hurricanes and other natural calamities **(Ullo and Sinha, 2020)**. Moreover, the surface temperature is also helpful in determining climate change and gathering knowledge about the forecasting related to weather. To take the proper measurements of the surface water and Upper Ocean, the IR measurement tools as well as micro waves are being used. In this process, the microwave is highly absorbed by the clouds giving a better picture of the ocean surface, while on the other hand, the IR measurements are used through the water vapour to understand and measure the water vapour.

SENSOR TECHNOLOGIES FOR ENVIRONMENTAL MONITORING

Robust Enclosures and Materials

The enclosure of the sensors requires a design that can withstand extreme conditions. These conditions can comprise temperature, pressures, difficult atmospheric conditions which leads to harsh conditions. Thus, stainless steel, titanium, ceramics like materials are being used for the processes to ensure the durability and longevity. The sensors can be protected from dust, moisture and contaminations through sealed and hermetically sealed enclosures **(Wen *et al.,* 2020)**.

Temperature Sensors

Instruments such as thermocouples, thermistors and resistance temperature detectors (RTDs) can be used for the extreme high temperature in volcanic regions or subzero temperature in Polar Regions **(Mamun *et al.,* 2020)**.

The sensors help in providing accurate measurements which are reliable to understanding the thermal dynamics and changes in climate.

Optical Sensors

These types of sensors are utilised for light-based technologies to measure pH, turbidity, and chlorophyll fluorescence in marine ecosystems **(Tmusic *et al.,* 2020)**.

Real time measurements, monitoring water quality and health of the ecosystem can be measured through the help of Fluorescence, absorbance, and scattering-based optical sensors.

Acoustic Sensors

Acoustic sensors play a huge role in mapping and monitoring ocean depths, underwater habitats and ice-covered regions.

The sensors such as sonar, acoustic Doppler sensors help in getting high resolution images and capabilities to conduct research based on topography, and marine life under extreme conditions.

MULTI-AUV-AIDED DATA COLLECTION FOR MISSION CRITICAL IoUT

The V-AUV and H-AUV are two different types of AUVs. For the purpose to collect oceanic data from IoUT objects on the seabed, H-AUVs move horizontally. They then transmit that data to V-AUVs, which move vertically to transmit the data that the H-AUVs have collected to a surface station. This clever tactic can lower the frequency of H-AUV diving and floating mobility while maintaining continuous data collection and consuming less energy **(Lou *et al.,* 2023)**.

Cabled Underwater Observatory Systems

The European Multidisciplinary Seafloor and Water Column Observatory (EMSO), the Monterey Accelerated Research System (MARS) in the United States, Ocean Networks Canada (OCN), and Dense-Ocean floor Network System for Earthquakes and Tsunamis (DONET) in Japan, and several other cabled underwater observatory systems have been installed **(Winther *et al.,* 2020)**.

Deployment Strategies and Platforms

Moorings: Moorings entail securing sensors with weights or anchors to the ocean floor. A cable connects the sensors to a buoy at the surface, enabling real-time data transmission or periodic data retrieval. Mooring is so appropriate for maintaining specific locations for nutrient concentration that helps in understanding several processes in the analysis.

Autonomous Underwater Vehicles (AUVs): An autonomous underwater vehicle is robotic machinery that is important for monitoring and navigating underwater operations without any operator or required input. This is also helpful in understanding the usefulness of sensors, instruments and thrusters that help navigate underwater and maintain the collected data **(Shu and Huang, 2022).**

Drifters: In the case of underwater operation, drifters refer to an instrument that has been used in monitoring and tracking the movements of ocean currents. These are also important in maintaining the movement of the ocean surface and collecting data about salinity, temperature and other oceanographic phenomenon.

Satellites: Satellites are important in marine biology and play a significant role in scientific operations by providing crucial data about marine life and oceanography. The equipped sensors from separates can monitor the altimeters and radiometers that allow the scientists to understand and navigate the information about ocean colour, temperature of the surface, and rise of sea level.

DIFFERENT ISSUES AND SOLUTIONS IN MAINTAINING AND IMPROVING UNDERWATER SENSORS IN HARSH OCEANIC CONDITIONS

Issues

Biofouling: Biofouling refers to the accumulation of marine organisms in total peace through merging all the sensors in the seawater. Several organisms such as mussels, algae and barnacles are used to accumulate and colonize the sensors underwater which leads to decreased efficiency, continuous deterioration and increased maintenance costs of the sensors and equipment deployed in the ocean.

Corrosion: Corrosion is one of the known properties of several metallic materials that deteriorate due to electrochemical and chemical reactions with the environment. In the ocean, saltwater has a proper corrosive property that can harm several parts of the sensors and their working ability in long-term installation.

Mechanical Damage: Mechanical damage mainly occurs during extreme weather conditions such as underwater waves currents and ocean debris. The high energy of these environmental properties is harmful to the insert and makes them vulnerable.

Data Transmission: In extreme weather conditions low connectivity and inefficiency of data transmitting channels the physical process of data transmission Has been harmed the major barrier in this situation are water depth efficiency of the sensor's distance from the data transmitting centre.

Solutions

Anti-fouling Coatings: Anti-fouling coatings are important for stopping the biofouling of marine life on the sensor surface. These are important to maintain the walking ability of these surfaces. Proper coating can be impactful for resisting biofouling or eco-friendly biocides.

Remote Monitoring and Maintenance: Put in place systems for remote monitoring that let researchers keep an eye on the health and performance of sensors in real time. Utilize satellite communication and telemetry systems to troubleshoot problems remotely and carry out necessary maintenance.

Modular Design: Understanding the designing process that can be effective in underwater conditions is necessary for the researcher. The proper establishment of different answers is necessary to upgrade and replace the modular components of the sensors in the fieldwork.

Sensors that save energy: Saving energy underwater is necessary that create and transmit data with low energy and power-efficient processes. These are important for the sensors that include better battery life and maintain the frequency of maintenance costs and visits.

EMERGING TRENDS AND FUTURE DIRECTIONS IN ENVIRONMENTAL SENSOR TECHNOLOGY FOR OCEANIC MONITORING

Underwater Robots

IoUT systems are used by a variety of underwater robots, as Figure 5 illustrates. While the Russian-developed "Peace 1" and "Peace 2" underwater robots are the only manned submersibles in the world capable of cooperative underwater exploration, the US Navy's "bluefin" AUV has the capability of self-sufficient underwater navigation and object detection.

Underwater Acoustic Positioning Sensors

Underwater acoustic positioning sensors (UAPS) are devices that have been navigated by the use of sound waves and find out several positions of targeted objects underwater. These sensors are also important in finding out different applications that include underwater robotics marine biology research and navigating several submarine paths.

USBL: Ultra short baseline is a type of underwater acoustic positioning system that is important in determining the position of several objects that are mainly related to surface reference points and the surface objects. Angles are measured by the transceiver, which has numerous transducers. Three or more transducers are usually positioned ten centimetres or less apart on the transceiver head.

SBL: Typically, an SBL system consists of three or more transducers placed 20 to 50 meters apart. The accuracy of the measurement can be increased by increasing the distance. But these sensors' biggest flaw is that it's hard to calibrate them. Typically, the three transducers in an SBL system are positioned 20–50 meters apart. By increasing the distances, the accuracy of the measurements can be improved. But the basic problem with these sensors is that they are hard to calibrate **(Hein *et al.,* 2020)**.

LBL: A collection of acoustic transponders with known relative positions positioned on the ocean floor make up LBL. Using them, robots within the acoustic signal's range can be localized using a minimum of three acoustic beacons with baseline lengths ranging from 100 m to 20 km. The system becomes costly to set up and maintain because an underwater acoustic network needs to be deployed and collected on a regular basis. The LBL sensor is not impacted by the depth of the water and can achieve high measurement precision.

APPLICATION OF NEW TECHNOLOGIES

Aquatic Animal Tracking

Tracking aquatic animals can be very beneficial to efforts to protect marine species. In general, humans should avoid contact with endangered or extinct animals. The food chain and ocean ecology may suffer if marine species go extinct. It used to be necessary for marine specialists to capture animals in order to retrieve data from attached tags. Nevertheless, this obstacle may be surmounted by the IoUT. Acoustic tags are used in IoUT systems because they perform better than radio waves. These tags are attached to ocean buoys, which use satellite communication to transmit the received data.

Water Quality Monitoring

Water is a crucial component whose qualities determine whether plants and other living things including people and animals survive. Ocean ecosystems and other water resources, however, are threatened by pollution and shortages **(Glaviano *et al.,* 2022)**. Currently, one of the biggest problems facing the world's water resources is the absence of adequate protections.

SCOPE AND VALIDITY

a. ***Parameter monitoring:*** The ocean-based sensors are important in several situations and understanding the importance of marine biology and scientific research. However, these sensors are important in measuring several physiological, chemical and biological parameters that include pH, temperature, salinity, dissolved oxygen, BOD, turbidity, COD, chlorophyll level, nutrient concentration and others(**Agarwala, 2020**).
b. ***Spatial Coverage:*** The special coverage of different underwater acoustic positioning systems is important and also depends on different factors such as operational frequency, operating depth, transducer array design, terrain and obstacles and others that help understand the ecosystem and monitor the data collection procedure through different water depths such as surface water to deep-sea habitat.
c. ***Temporal Resolution:*** Sensors provide high temporal resolution for analyzing seasonal variations, long-term trends, and short-term processes in oceanic parameters by continuously collecting data over extended periods of time.

Validity

a. ***Accuracy:*** Ocean-based sensors are made to measure environmental parameters accurately. They are frequently validated by comparison with independent measurements or calibrated against reference standards.
b. ***Precision:*** Sensors have a high degree of measurement precision, making it possible to identify minute fluctuations in oceanic conditions over long periods of time.
c. ***Quality Control:*** To guarantee the precision, dependability, and consistency of sensor data, quality control procedures are put in place. These procedures include sensor calibration, maintenance procedures, data quality evaluations, and metadata documentation.

SUMMARY

This chapter presented an overview of the environmental sensor based monitoring in extreme environments. Different challenges and definition of extreme environments shows that Extreme temperature, Extreme pH, Extreme ionic strength and Extreme pressure has made marine monitoring more essential. It also stated that robust enclosures and materials, temperature sensors, optical sensors and acoustic sensors are the sensors used for ocean monitoring. Scope as well as validity has been stated which shows that sensor calibration is necessary. In the end it has been learnt that future insights of sensor based technologies shows that more effective tracking for marine animals in order to save ocean environment is necessary.

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Chapter 22
Examining the Effects of Forest Fires:
A Framework for Integrating System Dynamics and Remote Sensing Approaches

Müjgan Bilge Eriş
Yeditepe University, Turkey

Duygun Fatih Demirel
https://orcid.org/0000-0001-8284-428X
İstanbul Kültür University, Turkey

Eylül Damla Gönül Sezer
https://orcid.org/0000-0002-9237-0468
Yeditepe University, Turkey

ABSTRACT

Forest fires have been a major concern for many countries over an extended period of time due to natural and human induced factors. In recent years, detection of forest fires has progressively shifted toward advanced technologies where the remote sensing approaches are fully operational. To enhance fire management strategies, it is crucial to gain a comprehensive understanding of the fire dynamics and its consequences on the environment, operational sources, and economic sectors. Therefore, this chapter develops an integrated framework to predict and analyze the effects of forest fires by using system dynamics approach and remote sensing technology, ultimately leading to the establishment of a conceptual model and conclusive insights.

INTRODUCTION

Forest fires are one of the most damaging types of disasters to understand and handle compared to other disasters. These incidents can burn hectares of land in a matter of minutes and cause significant

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environmental, social, and economic damage. The complexity of managing forest fires occurs as a consequence of both natural and human-induced factors (Dhall et al.,2020; Nolan et al.,2021). Therefore, dealing with forest fires becomes a complicated and often hazardous process that requires the collaboration of numerous organizations and teams (Dorrer et al., 2021). The most crucial factors in combating forest fires have been identified as early fire detection, accurate fire classification, and fast responses from firefighting teams (Akay and Şahin, 2018; Khan and Khan, 2022). Fire detection can be generally evaluated in two categories. Firstly, there is traditional public reporting, which involves fire alerts from anonymous individuals and on-site examination. Secondly, there are operational detection systems such as lookout towers and remote sensing tools that rely on technological advancements (Dogra et al.,2018). Although public reporting systems are valuable in specific situations, they may encounter issues like delayed and inaccurate reporting, limited coverage of the region, or false alarms. For instance, in flat areas, a tower-based fire detection system can directly identify hotspots without any barriers. However, in articulated terrains, where the ignition point might be hidden by hills, the system can only indirectly detect the fire, often picking up smoke columns or plumes. Thus, operational detection systems have become more reliable and secure compared to public reporting. In that sense, remote sensing has become a key player in forest fire management.

The increasing reliance on remote sensing technologies signifies a notable shift towards more advanced and effective methodologies (Cosgun et al.,2023). With the help of remote sensing, certain characteristics of forest fires such as location, extent, temperature, burn severity, smoke, and aerosols can be easily detected. However, the detection and monitoring of forest fires is a comprehensive process that goes beyond understanding fire behavior and utilizing remote sensing technologies; it also entails the application of data analysis and the development of predictive models for effective forest fire tracking. Hence, modeling is another critical component after collecting and processing the data. Due to the nature of forest fires, it is important to consider numerous causal relations involved in the prevention and suppression. In addition, forest fire management problems mostly occur because long-term natural processes don't align with short-term planning (Loncar et al, 2006; Collins et al.,2012). When considering the nature of forest fires, it would be prudent to take advantage of the system dynamic model and its long-term predictive capabilities. Utilizing the system dynamics methodology provides an alternative to current approaches that rely on linear future predictions for a specific system (Saveland, 1998; Collins et al., 2012; Thompson et al.,2019). Therefore, this chapter aims to show a framework consisting of spatial information obtained from drones and a system dynamics conceptual model for effective forest fire management. It will represent the complex mechanisms that lead to forest fires, as well as the impacts of these fires on ecosystems, operational teams, and economic sectors. In addition, firefighting teams would benefit from the framework by being able to understand the dynamic behaviors of fire management, evaluate the suppression and preventive actions, and set up multiple strategies for minimizing the economic and ecological damage under different disaster impact scenarios.

The rest of the paper is designed as follows: In the following section, an exhaustive review of related studies will be undertaken, distinctively examining both forest fire and remote sensing approaches. Additionally, the literature will be explored for works that interconnect system dynamics with forest fire management and investigate the integration of drone technology. In the methodology section, a comprehensive overview of the system dynamics approach is presented. Subsequently, the suggested conceptual model and the stock-flow model are outlined. Next, the framework for the integration of drone technology and the system dynamics model is explained. Finally, the study concludes with a discussion and explores solutions and potential future implications.

REMOTE SENSING TECHNOLOGIES

Remote sensing has been addressed in various ways; basically, it can be defined as the science of telling something without contacting or touching it (Fischer et al.,1976). Traditionally, the term remote sensing involves the identification and observation of physical objects within an area by analyzing radiation remotely, often through satellites or aircraft equipped with sensors. Images of physical objects such as buildings, vegetation, and soil can be obtained through sensors by scanning them electronically or by using electromagnetic radiation. Image resolution of physical objects denotes the potential detail obtained from the imagery, i.e. feature of the image representation. There are three types of resolution in remote sensing: spatial, spectral, and temporal. While spatial resolution refers to the level of spatial detail such as the size of the smallest area that can be individually recorded as an entity on an image, the temporal resolution represents time between images of the same geographical area. Lastly, spectral resolution presents the ability of the sensor to distinguish finer wavelengths of the electromagnetic spectrum, the high spectral resolution corresponds to a narrow bandwidth (Frisken et al.,2013; Elachi and Zyl, 2021). Regarding spatial, spectral, and temporal resolution, there exists a broad spectrum. However, there is a fundamental tradeoff exists among spatial, spectral, and temporal resolutions. Generally, as spatial resolution increases, spectral and temporal resolutions decrease, and conversely, higher temporal resolution corresponds to lower spatial and spectral resolutions.

The characteristics of platforms equipped with remote sensors significantly contribute to the efficient observation of the object space. Data can be acquired from different platforms such as satellites, airborne, unmanned aerial systems, mobile/static ground, and crowd sensing. To obtain reliable data, it is important to accurately observe the area traveled by the platform. There are several ways to enhance the observational potential of a platform. The most prominent solution is to install multiple sensors on the same platform, looking in different directions, such as forward and backward-facing cameras and/or Lidar (light detection and ranging) sensors on mobile platforms (Petrie, 2009). In addition, although the main sensors which can be classified as active and passive are mainly available on all platforms, the object range is mostly dependent on system complexity. It should be also noted that crowdsended platforms consisting of imagery or video data are becoming increasingly accessible (Toth and Jóźków, 2016). After the relevant data is acquired from one of these platforms, related information is extracted from the sensor analysis. Finally, analyzed remote sensing data can be integrated with other relevant data about the application area (Campbell and Wynne, 2011).

FOREST FIRES

Forest fires are natural events that affect communities and the environment worldwide, leading to property and human losses. This causes changes in the composition of vegetation and destroys soil properties in the coming years. In various regions of the world, an increasing number of forest fires, are associated with climate (Hillayová et al.,2023; Zong et al.,2020) and human-induced changes (Nagy et al.,2018; Vilar et al.,2016). However, there is no single factor that alone causes uncontrollable fires; instead, they arise from the combination of at least four elements such as ignitions, continuous fuel sources, droughts, and appropriate weather conditions (Pausas & Keeley, 2009; Boegelsack et al., 2018). When these elements are exceeded, the fire's scale is significantly influenced by the duration of adverse fire weather conditions and the abundance of continuous fuel sources across the landscape.

Forest fires often start due to natural causes, and one of these causes is lightning. In the event of a lightning strike, the high temperature can lead to the ignition of surrounding materials. This situation can result in fires in other natural areas. However, the primary drivers of forest fires are mostly human-induced factors (Mann et al.,2016; Masoudvaziri et al.,2021). Human activities can lead to ignitions, either inadvertently through accidents such as cigarettes, equipment malfunction, electrical power, or intentionally. Furthermore, forest fires also indirectly occur by modifying fuel availability and increasing sensitivity to ignition. For instance, previous research has demonstrated a strong link between the expansion of agricultural areas and deforestation rates, highlighting a shift from natural fire patterns to human-influenced fire patterns in many regions in recent years (Aragon et al.,2010; Andela and Van Der Werf, 2014). Openings created by people in vegetated areas, due to road and building construction, tree-cutting activities, etc., increase the presence of fine dry fuels, contributing to both human-caused and natural ignitions. In addition to clearing the land for construction and development of agricultural land, removing crop residues, controlling pests, and urban growth are also examples of human activities that increase the amount of forest fires.

Climate is commonly considered a determining factor in the size of fires, and historically, drought has been a significant factor (Madadgar et al.,2020; Ruffault et al.,2018). The effects of fires on forests are exacerbated by drought (Brando et al.,2014), leading to long-term changes in forest structure and biomass. While short-term rainfall during dry seasons can suppress fire activity, in drier ecosystems, precipitation in wet years may contribute to fuel accumulation, increasing susceptibility to burning in subsequent years. (Andela et al.,2017). Although drought presents a clear climate signal and is likely a key factor behind major fire incidents, there is also a growing concern about the role of anthropogenic climate change. It extends the duration of the fire season and raises the frequency of dry years. Increasing temperatures elevate heat stress in trees by enhancing evaporation and lowering average humidity. Consequently, extended periods of drought and significantly prolonged forest fire seasons emerge, creating optimal conditions for ignition and, thus, increasing the number of critical fire weather days. It is also reported that human-induced warming probably increased the summer forest fires by drying out the fuels, and this trend will persist. In addition, due to ongoing warming and a probable gradual decline in fall rainfall, significant fires will likely become more frequent in the fall (Williams et al.,2019).

Apart from climate, weather is another key driver of forest fire activity. Abnormal weather events increase the likelihood and spread of uncontrollable forest fires. Unless facing extreme weather conditions, a few ignitions are unlikely to evolve into a forest fire. However, there is a critical threshold of ignition beyond which the likelihood of a sudden forest fire surge increases. (Bradstock, 2010). The main weather variables that affect fire behavior are determined as air temperature, relative humidity, wind direction, and wind speed (Cawson et al.,2017). The consumption of fuels with a high surface area/volume ratio is significantly influenced by air temperature and relative humidity, in contrast to fuels with a low surface area/volume ratio. (Ottmar,2014). Additionally, precipitation decreases fuel consumption, while wind accelerates fuel consumption, for all types of fuels.

Slope, aspect, and elevation can be considered as topographic features that influence forest fires. For instance, slope is a critical factor affecting fire spread. Steeper slopes in elevated areas facilitate faster propagation compared to forests with gentler slopes, which are less prone to fire. Besides, elevation factor plays an important role in influencing various parameters like wind speed, temperature, precipitation, and vegetation cover, all of which impact the spread and intensity of forest fires. This spatial variation is significant in determining patterns of vegetation cover and soil properties (Hong et al.,2019). Finally, the slope aspect determines the micro-climatic conditions of the terrain, affecting variables such as solar radiation absorption, surface temperature, moisture levels, wind patterns, and vegetation distribution (Abdo et al.,2022).

As aforementioned, fuel load is another essential factor, and highly depends on plant growth and decomposition. Fuel loads are addressed as combustible sources and affect the fire intensity and spread positively. The amount of fuel accumulation heavily relies on the intervals between consecutive burns and the precipitation received during this time. With shorter intervals between fires, less fuel can accumulate particularly woody fuel. This accumulated material will be comprised primarily of herbaceous plant material and leaf litter. Conversely, as the time between fires lengthens, the component of larger twigs and branches will increase. The impact of fuel load is altered by how quickly various plant species in the area grow and their physical structure. In essence, fuel development depends on the prevailing vegetation in terms of different plant species, the population structure of each type of plant, and the amount of rainfall.

Fuel patterns are also highly affected by human activities. For instance, agriculture and urban development contribute to the fragmentation of ecosystems and disrupt the continuity of fuel across landscapes. In densely populated regions, significant fires frequently subside upon reaching agricultural areas. There has been a worldwide decline in fire activity in recent years, as documented by studies partially linked to the expansion of agriculture, particularly in tropical areas (Ward et al.,2018). On the other hand, from savannas to mountains, changes in agricultural practices disrupt traditional fire management methods, leading to unforeseen fire challenges. Societies employ various strategies like fire bans and fuel management to address wildfire threats, but some approaches inadvertently exacerbate the problem. This is because they overlook the dynamic relationship between fire and vegetation—altering one affects the other. Therefore, effective land management policies must acknowledge wildfires as a persistent aspect of flammable landscapes, requiring adaptable approaches rather than seeking a permanent solution. Nevertheless, numerous factors are amplifying fuel continuity and fostering increased fire activity in numerous regions globally. Forestry plantations are another potential cause of the increase in fuel quantity and continuity. They are sometimes established in non-forest natural ecosystems, significantly elevating fuel loads in these systems (Pausas and Keeley, 2009).

Incidence of fire activity tends to decrease due to factors such as rapid detection, proximity to firefighting resources, and fuel fragmentation which can be related to high population density. Nevertheless, even with the reduced impact of high population density in decreasing fire incidents, there is an observed trend indicating that the presence of high population and housing density still elevates the probability of human-caused ignition. Due to fuel accumulation resulting from abandoned agriculture and even intentional field clearing in certain regions, the likelihood of anthropogenic ignition increases (Song and Katsikis, 2023). Furthermore, fuel load and its moisture content, wind speed and direction, relative humidity, and air temperature are regarded as the most important factors affecting fire ignition (Rossa, 2018).

REMOTE SENSING TECHNOLOGIES AND FOREST FIRE MANAGEMENT

The remote sensing field has been vastly expanded in recent years due to the advancements in technologies. Its application areas encompass various fields, including agriculture, tourism, military, energy, coastal, transport, and shipping (Mahrad, et al.,2020). Furthermore, utilizing different remote sensing approaches for collecting environmental data has become prevalent. With the help of this environmental data, it becomes possible to identify areas prone to environmental disasters such as forest fires, ultimately leading to a reduction in fire occurrences and mitigating damage (Gülçin&Deniz,2020). Since remote sensing technologies enable analyzing the forests and other environmental areas on spatial scales, it supports effective forest fire management which includes five main components: analyzing the potential fire hazards and risks, determining hot spots for risk reduction and prevention, firefighting readiness, monitoring the ongoing fires, and post-fire evaluation (Filho et al.,2021).

In forest fire management, obtaining timely and accurate information about the environmental conditions is crucial for a rapid response. Characteristics of the environment, such as the structure of tree canopies and species information, as well as the status of the fire, the rate of fire spread, burn severity assessment, and fuel estimation, can be accurately and rapidly obtained from remote sensing data (Chuvieco et al., 2020; Gale et al.,2021). In literature, two conventional methods for collecting information from the environment are generally addressed: field measurements (traditional methods) and aerial photo interpretation. However, acquiring information through traditional methods is often time-consuming and costly, especially for large areas. Remote sensing technologies, particularly satellite remote sensing techniques, have the advantage of overcoming the limitations of traditional methods by swiftly acquiring information at local, regional, and even global scales (Pu et al.,2021).

Satellite images are utilized for mapping, categorizing, and evaluating the interested environmental areas. This enables the abstraction and evaluation of land cover information, such as waters, bare lands, trees, and buildings. The data obtained from these remotely sensed pictures can be used to predict the risk of forest fires. Additionally, satellite images of the selected region before and after forest fires can be categorized into different classes, and the effects of these fires on burned areas can be investigated (Mohammed and Khamees, 2021). However, data collected from satellite platforms from manned aircraft can be sensitive to cloudy atmospheric conditions. In such situations, electromagnetic wave attenuation can occur, which results in information loss and data degradation (Xiang et al.,2020). Furthermore, Lidar technology is an effective tool to provide enhanced spatial coverage. To acquire Lidar data, aerial surveys are conducted over potential forests, however, it can be prohibitively expensive (Riano et al., 2003; Wang et al.,2020). On the other hand, traditional photogrammetry methods may not provide the necessary point cloud density to determine the number of trees per hectare in the forest. In recent years, Geographic Information System (GIS) technology has become popular for environmental management purposes. It is a technology developed to capture, store, verify, and visualize data about locations on the Earth's surface. GIS technology can be combined with other approaches such as optimization models, machine learning techniques, and/or remote sensing data to gain a more comprehensive understanding of forest fire management (Mangiameli et al.,2021; Abedi-Gheshlaghi et al.,2020). On the other hand, an alternative solution can be presented as motion photogrammetry. This method uses unmanned aerial vehicles (UAV) which can generate high-density point clouds suitable for estimating the number of trees (Srivastava, et al.2022). UAVs which are also referred to as drones can be defined as unmanned aerial machines capable of autonomous operation or remote control, minimizing the necessity for constant user intervention (Dougherty et. al,2015). They have found applications in diverse fields such as humanitarian supply chains, healthcare, agriculture, environmental monitoring, and disaster response (Kim et al.,2017; Ahirwar et al.,2019; Adsanver et al.,2021). Various types of drones are available in the market today, catering to both commercial and civilian purposes. They can be categorized according to their ranges, sizes, prices, payloads, model complexity, number of blades, and other factors (Momeni et al.,2023). Specifically, drone sizes can vary from a small class known as "smart dust," measuring a minimum of 1 mm in length and weighing 0.005 grams, to massive fixed-wing drones with a wingspan of up to 61 meters and weighing 15,000 kg. Generally, two common types of drones are fixed-wing and rotary-wing drones which have their own set of advantages and disadvantages. Fixed-wing drones offer advantages such as higher cruising speed and altitude, increased flight efficiency, and longer endurance and range. Besides, they only require energy for forward movement, not for sustaining themselves in the air, making them highly energy efficient. Conversely, rotary-wing drones are more flexible, as they can vertically take off and land regardless of the environmental conditions. Additionally, hybrid drones that integrate the benefits of both types are becoming increasingly prevalent in modern applications (Kinaneva et al.,2019).

Recently, drones have been employed for forest fire detection, image processing, monitoring, and route planning since they offer several advantages as an alternative to traditional methods (Chen et al.,2017; Guimarães et al.,2020). They can fly over challenging terrains inaccessible to firefighter teams, allowing them to access remote or rugged areas. Since, drones can be equipped with multispectral cameras and sensors to measure parameters like pressure, temperature, relative humidity, gases, and radiation; they can efficiently gather data faster than human crews (Themistocleous, 2017). They are also capable of creating accurate maps of the fire's extent and preventing the fire from spreading further (Loncar et al.,2006; Yandouzi et al.,2022). Additionally, the utilization of drones enables quicker analysis compared to satellites and cost-effectiveness relative to other technologies in use (Jiao and Fei, 2023; Yuan et al.,2017; Israr et al.,2022). Despite the pros mentioned earlier, drones can be unsuitable for large-area acquisition because of their limited flight duration, and they do not enable the simultaneous coverage of the entire area of interest, as is possible with satellite platforms (Matese et al.,2015). Nevertheless, they have several benefits making them valuable for environmental purposes.

A drone application supporting forest fire management is undoubtedly the most advanced and practical activity among all disaster-related efforts (Restas, 2016). Drones can serve multiple purposes in forest fire management, including pre-fire hot spot detection, providing real-time information during intervention for effective fire management, and post-suppression monitoring after extinguishing. Detecting hotspots from the air before civilians report them is beneficial for fire managers in limiting damages caused by fires. In addition, if the firefighting team is on-site, they may be too close to effectively manage the fire and its surroundings. Managing the fire along with its surroundings is crucial since extinguishing forest fires takes time, and the fire continues to spread during this period. In that sense, the use of drones during interventions can be highly effective because obtaining a general overview of a forest for the coordination of intervention measures. Without aerial surveys, coordination relies on information among individuals in different locations. However, subjective assessments by firefighters in various positions may not align. Aerial examination helps eliminate subjectivity, aiding in prioritizing different areas effectively.

The efficiency of drones in detecting fires is influenced by the time taken for aerial-based hot spot detection, which, in turn, is dependent on the flight parameters of drones. Enhancing the efficiency of aerial hot spot detection requires an examination of these flight parameters. To minimize the average detection time, it becomes necessary to increase flight speed. However, the challenge lies in the objective limitations to raising flight speed. Analyses of camera focus and altitude yield slightly varied results. Elevating the onboard camera allows for monitoring a broader area (grid). If the frame of the monitored area remains constant, and the monitored grid is larger than before, the flight path might change, resulting in a shorter duration.

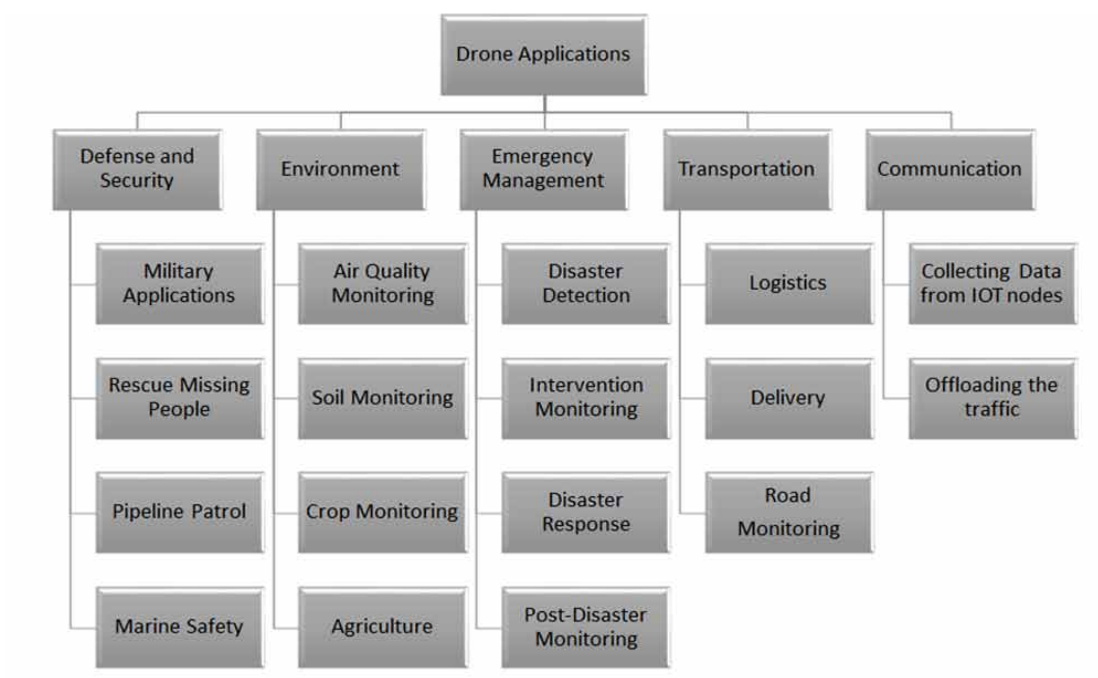
The main reason for not always using drones is the high cost of antennas. Undoubtedly, aerial surveillance with drones allows for the rapid identification of hotspots, providing timely reports to firefighting teams. However, economically, this method may be most effective in specific situations, such as areas with exceptionally high Fire Weather Index (FWI) and challenging geographical features (Restas,2015). Simply, the higher the fire risk indicated by FWI, the more areas need to be monitored because the likelihood of hot spot detection is higher, which leads to higher costs. Consequently, if using drones for this task is cheaper than the traditional method with manned aircraft, choosing drones becomes a more cost-effective solution.

There are several attempts to increase the efficiency of drones. For instance, NASA's research and funding have contributed to laying the foundations for different remotely operated and autonomous aircraft to have a much more significant role in our lives. This includes small drones delivering packages and even the possibility of taking out the deliveries one day, whereas larger, jet-sized drones inspect cellphone towers and other infrastructures. On the other hand, companies and researchers have been working on various types of drone integration for delivery. Hybrid distribution systems, utilizing both a large vehicle (such as a truck) and a small vehicle (such as a drone), have been developed (Li et al.,2023; Amaral et al.,2022). In addition, drones can be also utilized for health purposes such as rescuing individuals experiencing sudden heart attacks or combating the virus during a pandemic (Tang & Veelenturf, 2019; Chamola et al., 2020), or monitoring and rescuing missing people (Mayer et al.,2019; Pensieri et al.,2020). Figure 1 below, summarizes the implementation areas of drones recently.

SYSTEM DYNAMICS AND REMOTE SENSING TECHNOLOGIES

System Dynamics (SD) simulation modeling, which was initially introduced by Forrester offers solutions to the modeling complexities. By incorporating feedback loops and time variables into the model,

Figure 1. Application of drones in various areas



it provides a comprehensive approach to analyzing the structure and behavior of complex systems. In the literature, several studies integrate the predictive and dynamic nature of SD models with the spatial analysis capabilities of remote sensing technologies, mostly GIS analysis. Considering the competence of GIS, which has limited capabilities in temporal modeling, and the strength of SD in representing temporal processes despite its limited spatial modeling abilities, a reasonable alternative is to couple SD with GIS to model spatial dynamic systems. Ahmad and Simonovic (2001) proposed a spatial system dynamics model (SSD) to model dynamic processes in both time and space. The SSD approach enables a two-way flow of information between SD and GIS, facilitating feedback in both temporal and spatial dimensions. Initially, GIS provides spatial data to the SD model, which, through dynamic modeling, identifies changes in spatial features over time and feeds them back to GIS. These spatial changes subsequently influence decisions and policies over time, enabling integrated modeling of processes in both temporal and spatial domains while capturing feedback loops. For instance, Pakere et al.,(2022) provided a SD model with a GIS platform to evaluate space and time indicators of renewable energy resources based on their resource, economic, and technological features. Moradi et al., (2020) used GIS and SD to generate an SSD to evaluate the impact of storm surges. Additionally, Xu and Coors (2012) expanded SSD by integrating a 3D visualization model to GIS and SD to study urban residential development. In this research, the SD model contributed to the study by assessing the developmental tendency of the main factors.

On the other hand, there are a limited number of studies that focus on the combination of SD and the utilization of drones. One of the existing studies in the literature proposed a method for the swarming UAV (drones) combat system based on the SD model. Throughout the model, the task completion degree and the survival rate of drones have been considered as two crucial factors for determining the duration in which ground enemy targets are eliminated. Additionally, the experiments revealed that the integration of drones, along with improved information transmission, coordination, and enhanced reconnaissance capabilities, positively affects combat efficiency (Jia et. al.,2019).

SYSTEM DYNAMICS AND FOREST FIRE MANAGEMENT

Fire can be defined as a dependent spatial process, and it is unlikely to exhibit a simple linear relationship between forest fire drivers and activities. Due to their nature, they are characterized by high dynamics, time constraints, and uncertainty (Thompson and Calkin, 2011). Even small changes in fire drivers can lead to sudden shifts in fire regimes, making predictions challenging. To better understand the dynamics of forest fire management and design appropriate policies, the system dynamics simulation technique has become one of the most preferable tools. It addresses challenges by examining non-linear relations and feedback loops (Thompson et al.,2019).

In literature, the theme ‘fire paradox’ has been frequently discussed by existing studies (Calkin et al.,2015; Ingalsbee,2017). Fundamentally, the ‘paradox’ arises from the thought that managing forest fires failed because past forest fires were quickly controlled on a small scale, causing too much fuel and plant growth. In other words, the aggressive suppression of uncontrollable fires in fire-prone forests leads to the accumulation of dangerous fuels. This accumulation results in uncontrollable fires burning at higher intensities, resisting control, and eventually leading to an increased demand for suppression efforts. This situation can also be observed from the system dynamics approach where the positive feedback loops result in negative consequences. For instance, Collins et al.,(2013) employed a system dynamics model for fire management in Portugal. They compared management policies, focusing on budgets allocated to firefighting and prevention, and discovered that emphasizing firefighting yielded immediate benefits but could lead to an increase in fire activities in the long term.

The System Dynamics approach allows the designing of scenarios and policies to ensure improvements in the behavior of the system. According to Plooy and Botha's (2021) study, the scenario analysis revealed that the strongest levers of fires are high tree density, strong winds which increase the rate of fire spread, and a substantial amount of fuel in the biomass. In addition, the simulation showed that the individual responsible for igniting the fire played an insignificant role in the ultimate damage caused by the forest fire. Instead, monoculture species, windy dry weather, and the presence of a substantial amount of fuel were the critical factors contributing to the devastating Australian forest fires.

Some of the studies evaluated and compared the implementation of the policies in the long run based on the systems dynamics approach. Pandey et al., (2023) found that developing forest fire prevention policies has great potential to mitigate the forest fire risks consisting of human human-based ignitions, the containment of fire propagation, and strategic management to change fire dynamics. Thompson et al.,(2019) applied a system dynamics model that integrates human and natural fire-prone systems to assess changes through seven forest fire response scenarios. The study indicated that pursuing aggressive burning rate targets while implementing policy changes gradually over time can potentially restore forest conditions to their original state without undesirable levels of burn severity and departure rates. Farkhondehmaal and Ghafarzadegan (2022) performed simulation-based policy analysis, and in contrast to studies seeking the most effective policy to control forest fires, their research demonstrated that the long-term solution is not a single action but a combination of multiple actions considering both the human and natural aspects of the system simultaneously.

Besides that, the interaction between firefighter teams and technology has become vital due to institutional policies and the pressure to extinguish fires promptly. As aforementioned, the effects of technology on fire suppression led to the adoption of new technological decisions. The information gathered from drone technology such as geographic location, land-based information, and physical features of active fires have a vital role in intervening in a fire and minimizing the damage, however, this information as parameters is not always sufficient. They must be integrated into the model to comprehend the dynamics of a system in terms of burned area, resource availability, efficiency, economic sectors...etc. Therefore, ensuring a system-focused research approach is vital for understanding these complex dynamics. This book chapter aims to contribute to the literature by utilizing drone technology and system dynamics approach to achieve these objectives.

THE MAIN FOCUS OF THE CHAPTER

The study is driven by the following key research questions:

RQ1: How can the characteristics of data collected by drones be effectively integrated into a system dynamics model to enhance understanding of forest fire dynamics?
RQ2: What is the relationship between information gathered by drones, and the dynamics of forest fire management as represented in the system dynamics model?
RQ3: What are the consequences of forest fires on tourism, energy, and transportation infrastructure sectors, as investigated by the system dynamics model?

RQ4: What strategies can be implemented in the short and long term to mitigate the impacts of forest fires?

The aims of this chapter are:

Aim 1: Identify the relationship between ecological, operational, and economic factors and fire management systems.
Aim 2: Develop a comprehensive framework by integrating drone-derived data into a system dynamics model to enhance the understanding of forest fire dynamics.
Aim 3: Explore how drone-collected information can be utilized to estimate fire suppression and assess the impact of improved efficiency of firefighters on the overall dynamics of the forest fire system.
Aim 4: Determine short-term and long-term strategies to support firefighting operations.

METHODOLOGY

The objective of this study is to indicate the factors influencing forest fires and assess their impacts on ecological systems, operational teams, and economic sectors such as tourism, energy, and transportation infrastructure with a specific emphasis on integrating drone-derived data into the analysis. In addition, the chapter seeks to explore strategies for mitigating the effects of forest fires and formulating proactive policies to prevent their recurrence in the future. The chosen methodological approach is System Dynamics (SD) for a comprehensive examination of the variables, particularly incorporating inputs from drone observations, and for designing effective policies for sustainable forest fire management.

Simulation methods play a crucial role in understanding complex systems, and among them, SD stands out as a methodology that leverages the concept of time continuity, defining relationships between events as non-linear rather than linear. Its mathematical foundation is built upon differential equations. According to the results of the literature review, SD is frequently employed for developing strategies and policies. By utilizing the SD method, relationships between events or variables are depicted through interactions. These interactions which can be direct, indirect, or mutual are employed to unveil complex relationships that cannot be captured through data analysis. Consequently, decision-makers can analyze the current system more accurately and, at the same time, simulate the situation through various scenarios.

PROBLEM DEFINITION

Forest fires pose a significant threat to natural ecosystems, necessitating the development of effective forest fire management strategies to improve firefighting processes and safeguard communities. In recent years, researchers have embraced principles of systems thinking to cope better with the complex dynamics of managing forest fires (Thompson et al.,2016; Thompson et al.,2018; Steelman and Nowell,2019). Due to natural fuels (vegetation), weather conditions, and lightning ignitions, and those caused by humans, forest fires have been increasing day by day (Mhawej et al.,2017).

The use of UAVs, commonly referred to as drones, in the context of disaster response, presents a hopeful avenue for research. There is an interest in exploring how drones, can provide not only intervention through water bombing but also faster and more effective situational awareness in the context of forest fires. Their mobility, aerial perspective, and rapid data collection and transmission capabilities position them as a central tool in fire assessment and intervention (Somers and Manchester,2019; Nigam and Agarwal 2014). In this context, integrating drone-derived data into an SD model emerges as a promising approach for enhancing our understanding of forest fire dynamics and improving intervention strategies. However, a comprehensive investigation is required to explore the relationships between key drone-collected parameters and critical aspects of fire behavior, including average burned area, fire severity and speed of spread, and fire duration. Addressing this knowledge gap will contribute to the development of more efficient and data-driven approaches for forest fire prevention, intervention, and management.

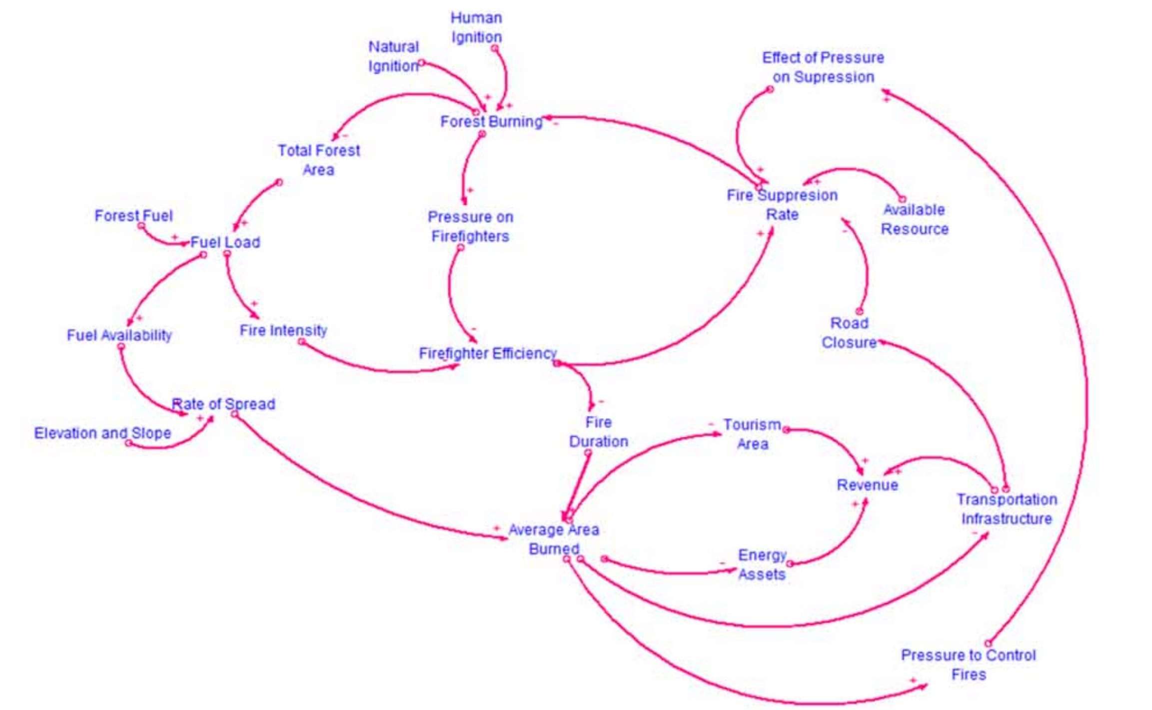
CONCEPTUAL MODEL

Conceptualization is the stage where the map of the dynamic problem begins to be drawn using boxes and connections. Mostly, it is done by using causal loop diagrams (Johnson and Pen, 2022). The conceptual representation of the system must be realistically constructed, and within this representation, all relationships and their directions should be defined. During this phase, the conceptual model of the system needs to be outlined, incorporating the key variables identified while defining the problem. The arrows explicit the relationships between variables, where the origin of the arrow represents the influencing variable, and the end represents the influenced variable.

The directions of the relationships can be defined at the end of the arrows either positive or negative (Bala et al.,2017; Yearworth,2014). A positive link is used to depict that an increase (decrease) in one variable leads to an increase (decrease) in another variable, i.e., positive sign. Conversely, a negative link is a connection where an increase (decrease) in one variable leads to a decrease (increase) in another variable i.e. negative sign. In this conceptual model, a loop is created by revisiting the variable chosen as the starting point through a relationship path. To decide whether a loop is reinforcing (positive) or balancing (negative), several positive and negative signs are counted. Thus, the loop is considered positive when there is an even number of negative signs in the loop, and conversely, it is labeled as negative when the total number of signs is odd. Reinforcing loops typically undermine the stability of the system, whereas negative loops contribute to maintaining equilibrium in the system. Positive feedback loops drive or strengthen changes, deviating the system from a state of equilibrium and rendering it more prone to instability. On the other hand, negative feedback loops tend to mitigate or buffer changes, aiming to maintain stability within the system and enhance its resilience (Sterman, 2000).

The primary variables within the model suggested in this study are “total forest area”, “fuel load”, “fire intensity”, “average area burned”, firefighter efficiency”, “fire suppression rate”, “tourism area”, “energy assets”, and “transportation infrastructure” and “revenue”. Here, “revenue” represents the economic gain from tourism, energy, and transportation infrastructure sector. The connections between these fundamental variables and their respective directional relationships are illustrated in the following Figure 2.

Figure 2. Proposed conceptual model for fire management



STOCK-FLOW DIAGRAMMING

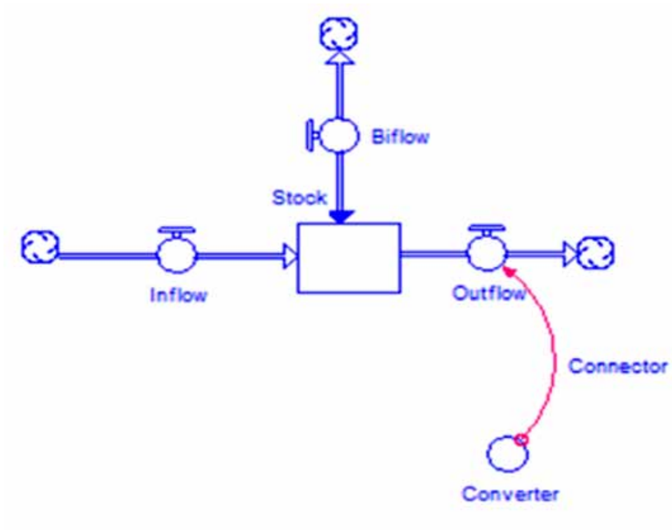
In this stage, a conceptual model is turned into a simulation model by using a stock and flow diagram. This approach allows for the creation of a comprehensive top-level representation of the system. The essential components in the stock flow diagram are represented in Figure 3 below.

Stock represents the quantity to be accumulated, and its value changes over time, representing the desired variable to be tracked. Flow variables can be categorized as inflows or outflows. The arrow points towards the stock, i.e. inflow leads to an increase in the stock value. Conversely, if the arrow from the stock points in the opposite direction, i.e. outflow results in a decrease in the stock value. It is also possible to indicate both increment and decrement by using a single flow which is called a bidirectional flow. In addition, converters which are shown by small circles are used to define the logic that modifies the flow. Finally, connectors which are represented by straight arrows used to connect model variables.

When developing Stock-Flow diagrams, the initial step involves classifying variables as stocks, flows, and converters. Following that, it becomes imperative to construct the stock-flow diagram. Within this framework, the model is developed by incorporating all essential indicators. Mathematical equations are subsequently formulated, utilizing stocks, flows, and converters. The interrelationships between these indicators can be expressed through the mathematical equation provided below (Sterman, 2000).

Stock (t)=Stock () +) ds

Figure 3. Blocks of SD



In this equation, while indicates the start time, t- 0 represents the time interval. To calculate the current value of the stock variable the initial value of that stock variable is added to the cumulative net change in the corresponding flows over the specified period. Completing the entire stock and flow diagram will provide a clearer picture of the data needed to run the model. Subsequently, the process of gathering and analyzing the required data in detail will commence. Once the necessary data is integrated as input into the simulation model, the simulation model will be executed, and the behaviors of variables over time for the base scenario will be obtained through graphs and tables.

The simulation model is analyzed by considering three sub-systems. (1) Ecological Factors and Forest Fire (2) Operational Factors and Forest Fire (3) Economic Sectors and Forest Fire.

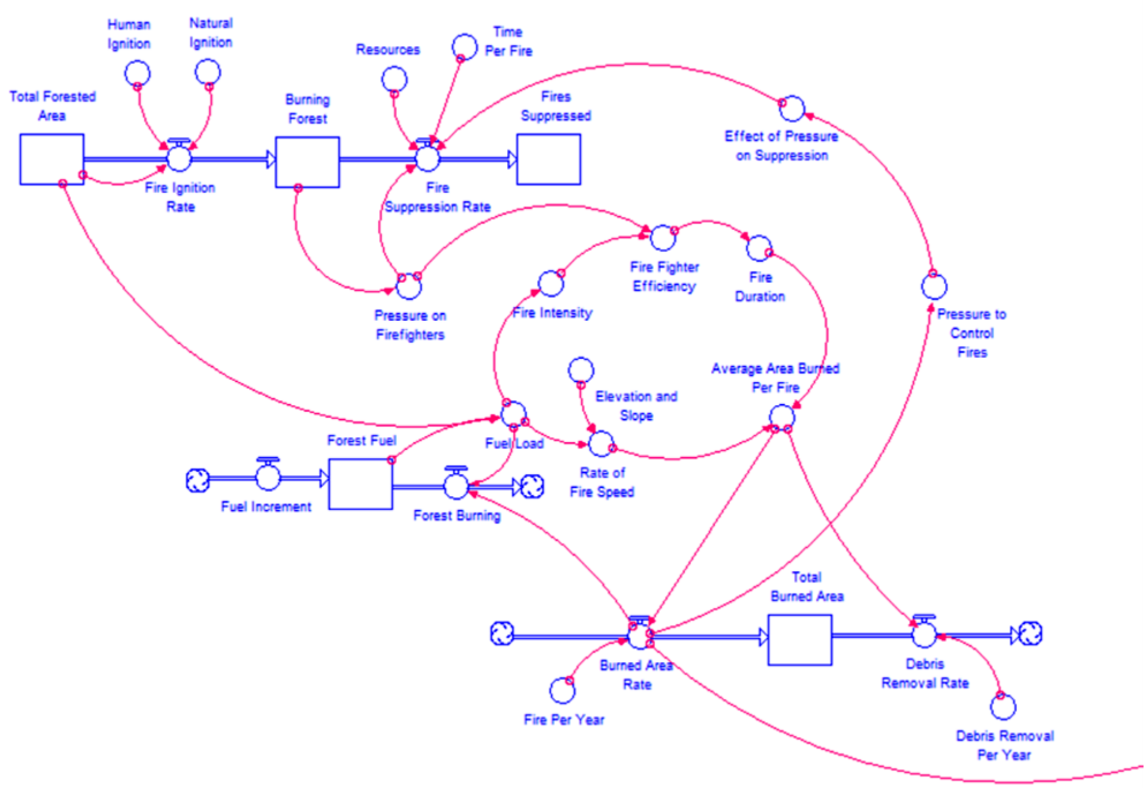
ECOLOGICAL FACTORS AND FOREST FIRE

The ignition of forest fires is often attributed to the simultaneous occurrence of ecological factors reaching a critical threshold. Human activities, such as campfires or discarded cigarette butts, can act as sources of ignition, while natural factors like lightning strikes can also initiate fires. As the fire spreads, it tends to consume the most combustible plant species, resulting in a reduction of forested areas. Consequently, the landscape transforms, with open areas devoid of any vegetation expanding. In such areas, where all plant species are eliminated, the landscape becomes barren. In addition, the amount of fuel in forest areas is one of the significant contributors to forest fires since it determines the intensity of the fire. In other words, the accumulation of fuel load will increase the fire intensity, leading to the burning of even larger areas. Furthermore, topographical features in a forest environment impact the rate of fire spread. For instance, steep slopes and high elevations can increase the rapid spread of forest fires. Similarly, different soil types affect the speed of forest fires. Specific soil types may be more prone to combustion, leading to faster forest fire spread. On the other hand, the fire management system involves determining which resources will be obtained (such as air tankers, and transport aircraft), where they will be deployed, the types of facilities to be established at bases, and the specific personnel requirements for the operation. As the amount of resources available to extinguish or prevent a fire increases, the fire suppression rate increases. Final critical relationships are observed between the fuel loads and the suppression efforts. Fire suppression results from accumulated fuel. This unintended consequence which is also known as the fire paradox causes larger and more intense fires.

OPERATIONAL FACTORS AND FOREST FIRE

The intensity of the fire will inevitably reduce the efficiency of firefighters. This, in turn, will lead to an extended duration of the fire and an increase in the average burned area. As the burned area expands, it becomes more challenging to bring the fires under control, resulting in a decrease in the firefighting suppression rate. Moreover, the pressure on firefighters will increase in such situations. The larger the area affected by the fire, the more difficult it becomes to contain and extinguish the fires. This cascading effect could lead to a higher number of forested areas being engulfed in flames. Consequently, the heightened pressure on firefighters will persist.

Figure 4. Ecological and operational factors of SD model



ECONOMIC FACTORS AND FOREST FIRE

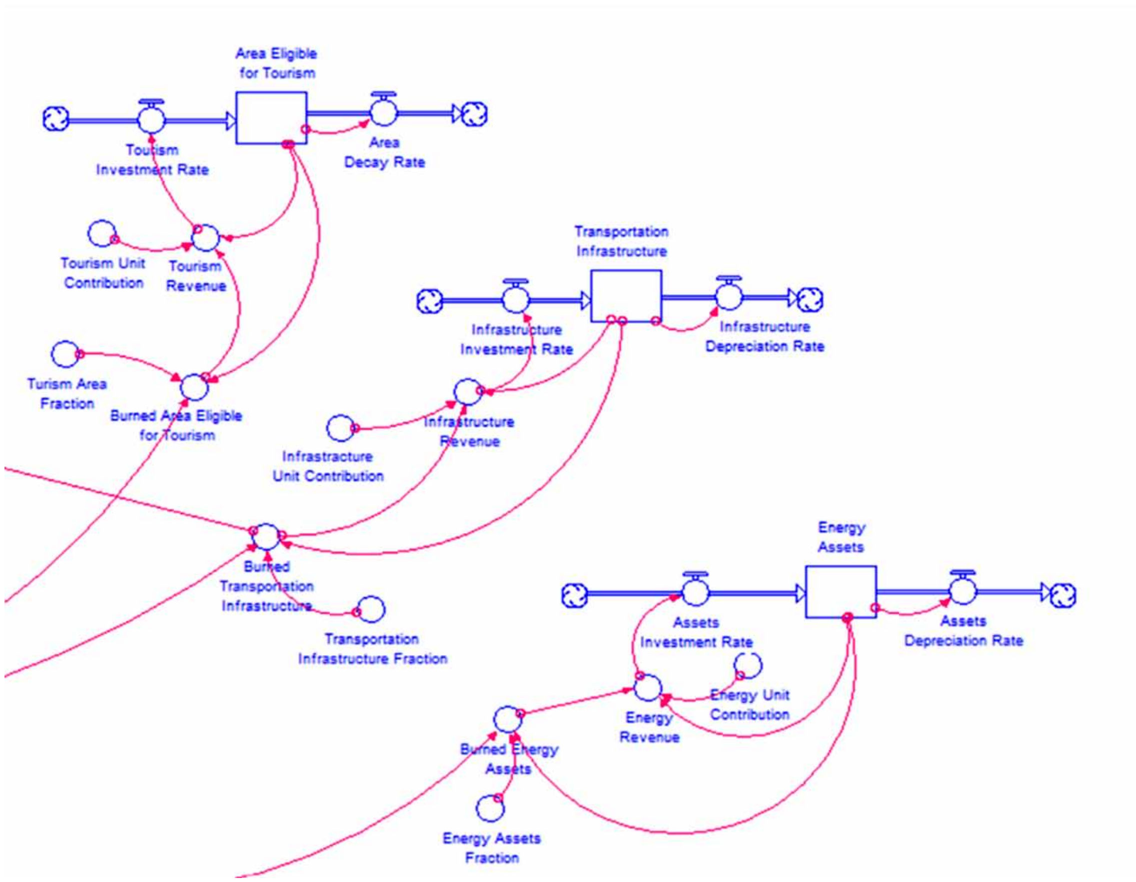
Recent forest fires have posed serious threats to various areas and brought economic difficulties. Although a significant amount of literature has examined the potential harmful and immediate effects of forest fires, few studies examine their impact on economic indicators (Sfetsos et al.,2021). These fires have the potential to harm energy assets and inflict significant damage on electricity transmission lines and energy production facilities. Due to fires, energy production may be interrupted, transmission lines may be disabled, and energy facilities may need long-term maintenance and repair. Additionally, fires can limit the availability of energy resources and negatively impact energy supply, resulting in economic losses. Controlling fires and strengthening energy infrastructure can play an important role in reducing such negative impacts.

Moreover, forest fires can affect transportation infrastructures and cause road closures. As a result, the fire suppression rate will decrease since firefighting teams cannot reach to fire area easily. Another negative consequence of damage to infrastructure can be road visibility. Similarly, it will also decrease the fire suppression rates. In addition, road assets are sensitive to operational damages related to economic losses. In many countries, network users are required to pay tolls for the use of highways. When a highway is disrupted due to a natural disaster and toll booths cannot continue their operations, the revenue generated from tolls decreases. On the other hand, forest fires can have negative effects on tourism revenues. Fires can destroy the natural beauties and ecosystems in tourist areas, reducing the interest of tourists in the region. This situation may reduce the number of reservations and visitors to tourist facilities, thus leading to a decrease in tourism revenues. Additionally, infrastructure may be damaged due to fires, and impacts such as road closures may hinder tourist activities, resulting in loss of income. A decrease in tourism revenues could significantly harm the regional economy and negatively impact local businesses.

DRONES AND SYSTEM DYNAMICS FRAMEWORK

This chapter introduces a system structured around two primary components, illustrated in Fig. 6: (a) Employing drone analysis and visualization to clarify the spatial patterns of forest areas. (b) SD analysis for evaluating forest fire management. The analysis of drones consists of the following three stages. Firstly, drones can detect fire hotspot points with thermal cameras and sensors replace them. In that case, hotspots composed of different materials, such as wood, thatch, or sepiolite; hotspots with different sizes, ranging between 0.15m and 1.5m; hotspots with different stages of dynamics starting from ignition to close-to-be-extinguished can be inspected with cameras (Viseras and Garcia, 2019). Secondly, relative data is acquired concerning data acquisition factors. Drone speed, altitude, integration time, battery needs, flight time, and environmental conditions impact the data acquisition. Although the longer the flight time of the drones, the better the applicability of the system in real missions, battery time restricts the flight time which can reduce the efficiency of firefighting teams and resources. It is known that high-performance commercial drones currently provide approximately 30 minutes of uninterrupted flight. On the other hand, flying at higher altitudes increases the camera's distance from the ground surface, potentially causing more false alarms. In contrast, rotary-wing drones offer greater flexibility for close monitoring. Therefore, instead of relying solely on fixed-wing drones, which operate at altitudes ranging from 350 meters to 5500 meters for comprehensive coverage, incorporating rotary-wing drones may be more suitable for precise monitoring needs.

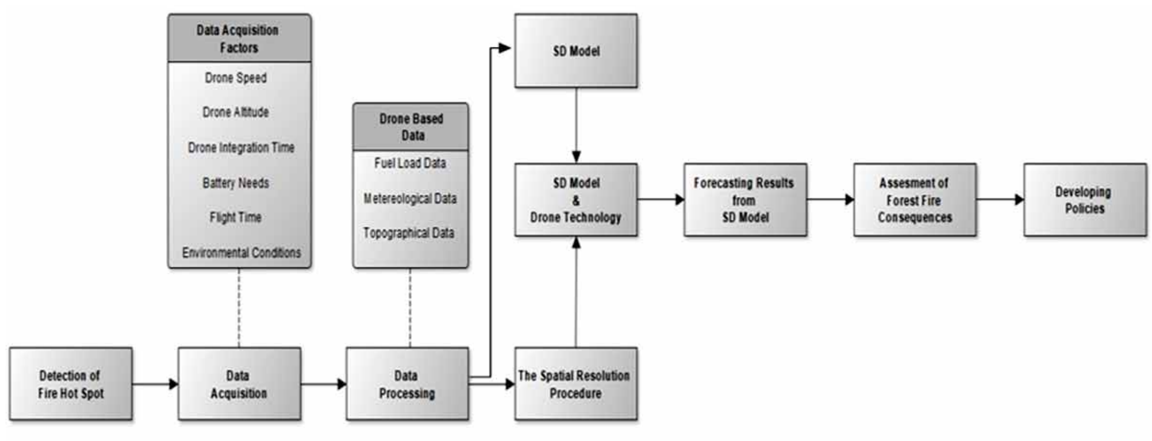
Figure 5. Economic factors of the SD model



In the next step of drone analysis, meteorological, topographic, and fuel load information data is gathered. These data encompass a range of essential parameters, including temperature, humidity, wind speed, and direction, which provide insights into prevailing weather conditions influencing fire behavior. In addition, while fuel load content measurements help assess the flammability of vegetation, topographic features such as aspect, elevation, and land cover type are also crucial. Aspect determines the direction a slope faces, influencing sun exposure and moisture levels, which in turn affect fire behavior. Elevation influences temperature and vegetation types, impacting fire intensity and spread. Land cover type, including vegetation density and composition, affects fuel availability and fire behavior.

Thirdly, drone-based data is processed, and high spatial-resolution images are developed. This data can be transmitted to the fire and rescue department for early warning. However, communications pose a challenge for drones in vast and remote areas, particularly in firefighting missions where constant information exchange between various parties is crucial. It can be anticipated that drones need a communication range of 5 km to function effectively in such scenarios. In this way, fire crews can be informed of a possible fire early and response times can be shortened. Thus, it can help them to understand the extent and direction of the fire and reduce the pressure on firefighters while increasing their efficiency. When the efficiency of firefighters increases, fire duration can be decreased which results in less area burned.

Figure 6. Proposed framework for forest fire management



In the second part of the conceptual model, drone-based data can be integrated into the SD model to estimate the possible consequences in terms of economy, ecology, and also operations. In other words, by combining the real-time data with the SD model, the simulation model will explore the interactions between ecological, operational, and economic systems in forest fire management and assess different policies.

SOLUTION AND RECOMMENDATION

Strategies for combating forest fires primarily focus on preventing the occurrence of fires. However, even the most comprehensive and successful prevention programs cannot completely avoid forest fires in the region. Despite the best prevention efforts, there are many accidents and intentional ignitions that will continue to lead to widespread fires. Hence, it is necessary to set up a detection and reporting network that can identify, report, and monitor forest fires within and in proximity to forest reserve areas. To combat effectively with a fire, taking advantage of remote sensing technologies is crucial. To enhance the ability to respond to more fires, the time allocated to each fire incident should be minimized. Considering advancements in drone technology, spending less time on each fire can lead to the suppression of more fires. This would result in less average area burned per fire and economic losses.

Although it is not possible to completely avoid forest fires, several fire management policies can be applied via a system dynamics model to analyze its effects in the long term. The policies can be determined as implementing education programs to influence human behavior, applying different fuel management strategies to reduce combustible vegetation such as planning prescribed burning methods, ensuring effective firefighting such as increasing and/or reallocating the resources, and finally, removing mature trees by clear-cutting. While providing education programs can reduce the number of human-caused fires which would result in a lower fire ignition rate, implementing different fuel management strategies can decrease the accumulation of flammable materials such as dry grass, underbrush, and fallen tree branches and minimize the rapid-fire spread. For instance, the prescribed burning policy can be planned as a preventive measure against fires to reduce the fuel load. This approach is employed as a land management technique that aims to improve environmental protection and decrease fire risks in forested areas.

Furthermore, resources to suppress fires are limited and have to be allocated based on management strategies. Identifying high-risk areas and strategically deploying resources and equipment while implementing preventive measures can effectively reduce the incidence of fires. Therefore, increasing the resources and capacity to extinguish fires or allocating additional resources to firefighting aims to reduce the damage caused by fires. The firefighting capacity can be increased by purchasing additional aircraft or hiring more people to fire-fighting crews which would increase the effectiveness of operational teams. On the other hand, in the operational model where the performance of firefighting teams is crucial, spending progressively less time on each fire can result in inadequate clearing, giving rise to re-ignitions that further strain the firefighting capacity. These trade-offs should be managed by policy-makers. Nevertheless, if the initial allocation of the resources for prevention is sufficient, the fuel amount can remain more stable. Additionally, increasing the firefighting expenditures can weaken preventive fuel management. This situation would lead to an accumulation of excessive fuel and pave the way for more intense fire seasons in the future.

Finally, the areas with a high or very high risk of easily igniting and potentially leading to large forest fires should receive special attention. Drones should be deployed more frequently in these extensive forested areas, and communication between the drones and firefighting teams should be carefully maintained. As an alternative, a clearcutting (clearcut logging) policy can also be applied where the mature and strong vegetation trees in an area are removed, and the area is replaced with younger trees. However, this policy can be dangerous in the long term since plantation trees can be highly vulnerable to fire. Besides that, precaution is required in non-forested areas with a higher risk of ignition. Particularly, when these areas are close to potentially hazardous zones that need protection, many fires starting in agricultural or shrub areas can rapidly spread to forest stands or wooded regions, so caution should be exercised.

FUTURE RESEARCH DIRECTIONS

In this book chapter, the modeling framework has focused on analyses related to the ecological state of the forest, as well as the economic sectors such as tourism, energy, and infrastructure. However, the costs associated with fire prevention and suppression, which can be equally important driving forces in forest and fire management, have not been considered here. Specifically, while the use of drones may reduce intervention times in forest fires and lead to more efficient work by rescue teams, the costs of using drones, including transportation, monitoring, and charging costs, should be calculated, and evaluated. Taking these variables into account may require reconsideration of the resilience of the formulated policies. For instance, higher resistance near communities to increased burn rates and the costs involved can be included in the policy analysis framework to help determine the return on investment.

Another dynamic factor that could be included in the model is how climate change may intensify fire severity and impede regeneration. The compound effects of this, especially considering how sustained burning could further solidify an undesirable shift in conditions, will strongly emphasize the importance of minimizing high-severity fires. In addition to climate change factors, land management activities such as timber harvest, hazardous fuel load reduction, or educating the population about forest fires can be investigated in further research. Fire prevention, which is fully integrated into land-use planning, is necessary to counteract the effects of land-use change on fire hazard and risk.

CONCLUSION

Forest fires have been a persistent challenge in various regions worldwide, posing significant ecological, operational, and economic consequences in sectors such as tourism, infrastructure, and energy. This study aims to understand the root causes of the system and proposes the development of policies to mitigate potential negative impacts. A conceptual model is developed by bringing together the relationships of various factors to cover all relevant factors in the system. The main parties are determined as the environmental factors that will start forest fires; the operational factors consisting of firefighting teams who will carry out the necessary operations to extinguish the fire; and economic factors such as tourism areas, energy assets, or transportation infrastructures. The application of SD methodology in the planning of forest fire management can be concluded to provide an alternative to existing management approaches primarily based on linear projections of a specific system's future. Such an alternative should not be overlooked. Additionally, most of the regions have low population density and are less accessible for firefighters as they are situated farther away from roads. Therefore, in fire planning and monitoring efforts, it is essential to simultaneously assess and analyze the fire risk in these areas. In that sense, drones play an important role in simultaneous data collaboration with firefighters. With the help of these data, the SD model can estimate the ecological, operational, and economic outcomes.

The proposed framework shows that utilizing drones for early detection of potential fire-prone areas or the origin of ongoing fires, coupled with simultaneous alerts to firefighting crews, can increase the suppression of fires. This approach could lead to a decrease in the average area burned per fire incident. Additionally, the feedback mechanisms represented in the conceptual model enable researchers to capture the dominant factors in the forest fire problem, aiding in a more comprehensive understanding of the issue.

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About the Contributors

Khursheed Ahmad Wani is Assistant Professor in the Department of Environmental Science, Government Degree College Thidim Kreeri, J&K. Dr. Wani served at ITM University Gwalior as Assistant Professor in the Department of Environmental Science from 2011 to 2017. He has completed his M. Sc. and Ph. D. in Environmental Science from Jiwaji University, Gwalior, Madhya Pradesh. He has also qualified Jammu and Kashmir State Level Eligibility Test (JKSET). His areas of interest include Environmental management, Environmental Impact Assessment and Occupational Health. He has published research papers in various national and international journals and is the author of three books on Environmental Science. He is a member of several national and international organizations and is in the editorial board of various journals. He has organized different programmes on Environmental Awareness and has completed research project sponsored by Madhya Pradesh Council of Science and Technology, Bhopal, India. Dr. Wani has organized various national and international conferences/ seminars/ workshops as well.

***

Kumud is working as Assistant Professor in the Department of computer Science. Kumud has more than 5 years of research and teaching experience. She has worked in the area of Computer Sensors. She has published research papers in peer reviewed Journals and book chapters in various books of International repute.

Naseema Banu A is a science graduate who completed her Bachelor's (2021) and Master's (2023) in Applied Microbiology from Ethiraj College for Women, Chennai, Tamil Nadu, India. She was the Editorial Secretary for the department's annual journal (2020-21). She has worked as a Student Editor for the Conference Proceedings on Integrative Approach for Conservation of Life Systems (2022-23) with ISBN 978-93-91332-50-1. She has presented a poster in the conference and attended many others as well. She is presently working as an Associate Content Editor at Clarivate Analytics Pvt. Ltd.

Pritam Kumar Barman received his M.Sc. degree in Forestry with a specialization in Forest Biology and Tree Improvement in 2022 from Sam Higginbottom University of Agriculture, Technology and Sciences, Prayagraj, India. He is presently pursuing a Ph.D. degree at the Sam Higginbottom University of Agriculture, Technology and Sciences, Prayagraj, India. He presented his research at several international conferences. He has taken part in numerous trainings and workshops nationally as well as internationally. He also attended the IIRS Academia Meet-2022. His research interests include forest genetics, tree phenology, environmental studies, remote sensing, and GIS.

Pankaj Bhambri is affiliated with the Department of Information Technology at Guru Nanak Dev Engineering College in Ludhiana. Additionally, he fulfills the role of the Institute's Coordinator for the Skill Enhancement Cell and acts as the Convener for his Departmental Board of Studies. He possesses nearly two decades of teaching experience. Dr. Bhambri acquired a Master of Technology degree in Computer Science and Engineering and a Bachelor of Engineering degree in Information Technology with Honours from I.K.G. Punjab Technical University in Jalandhar, India, and Dr. B.R. Ambedkar University in Agra, India, respectively. Dr. Bhambri obtained a Doctorate in Computer Science and Engineering from I.K.G. Punjab Technical University, located in Jalandhar, India. Over an extended period, he fulfilled many responsibilities including those of an Assistant Registrar (Academics), Member (Academic Council/BoS/DAB/RAC), Hostel Warden, APIO, and NSS Coordinator within his institution. His research work has been published in esteemed worldwide and national journals, as well as conference proceedings. Dr. Bhambri has made significant contributions to the academic field through his role as both an editor and author of various textbooks. Additionally, he has demonstrated his innovative thinking by filing several patents. Dr. Bhambri has received numerous prestigious awards from esteemed organizations in recognition of his exceptional achievements in both social and academic/research domains. These accolades include the ISTE Best Teacher Award in 2022 and 2023, the I2OR National Award in 2020, the Green ThinkerZ Top 100 International Distinguished Educators award in 2020, the I2OR Outstanding Educator Award in 2019, the SAA Distinguished Alumni Award in 2012, the CIPS Rashtriya Rattan Award in 2008, the LCHC Best Teacher Award in 2007, and several other commendations from various government and non-profit entities. He has provided guidance and oversight for numerous research projects and dissertations at the undergraduate, postgraduate, and Ph.D. levels. He successfully organized a diverse range of educational programmes, securing financial backing from esteemed institutions such as the All India Council for Technical Education (AICTE), the Technical Education Quality Improvement Programme (TEQIP), among others. Dr. Bhambri's areas of interest encompass machine learning, bioinformatics, wireless sensor networks, and network security. Dr. Bhambri possesses a wide array of professional responsibilities, encompassing the duties of an educator, editor, author, reviewer, expert speaker, motivator, and technical committee member for esteemed national and worldwide organizations

Ankur Bhardwaj is working as Assistant professor in the Department of Biotechnology, Shri Vaishnav Institute of Sciences, Shri Vaishnav Vidyapeeth Vishwavidyalaya, Indore. He received B.Sc.[HONS] (2009) in Biotechnology from Allahabad Agricultural Institute-Deemed University, Allahabad, Uttar Pradesh; M.Sc. (2011) in Biotechnology from SRM University, Kattankulathur, Chennai, Tamil Nadu and Ph.D. (2021) in Molecular Biology and Microbiology from Mangalayatan University, Aligarh, Uttar Pradesh. He started his career as Teaching Assistant in Department of Biotechnology and Life Sciences, Mangalayatan University, Aligarh in 2014 and served there for more than 5 years. He has more than 10 years of teaching and research experience. He prominently has worked in the field of plant Biotechnology, Molecular Biology, Immuno-informatics and Microbiology. He has published 10 research papers in peer reviewed Journals, 02 book chapters. During 2017 to 2019 he received 03 young scientist award and best thesis award in 2021.He has successfully guided more than 10 academic students in their final year project. Dr. Bhardwaj is a member of the Scholars Academic and Scientific Society and has organized different educational trips for his B. Tech and M.Sc. Students.

Duygun Fatih Demirel is an Assistant Professor at the Department of Industrial Engineering at Istanbul Kültür University, Turkey. He received BSc degree in Systems Engineering from Yeditepe University, Turkey, and PhD degree in Systems Engineering from Yeditepe University, Turkey. His research interests include systems dynamics, disaster management, socioeconomic modeling, fuzzy set theory and its applications, Bayesian forecasting, facility location/network design problem, system dynamics, and wastewater treatment systems design.

Müjgan Bilge Eriş is a research assistant and PhD student at the Department of Industrial Engineering at Yeditepe University, Turkey. She received BSc degree in Industrial and System Engineering from Yeditepe University, Turkey and MSc degree in Supply Chain Management from Vienna University of Economics and Business, Austria. Her research interests include system thinking, system dynamics, and multi-criteria decision-making.

Rajni Gautam received Ph.D., M.Sc. and B. Sc. Degrees in Electronics from University of Delhi, India, in 2014, 2009, and 2007 respectively. She has 16 publications in International Journals of repute, 15 publications in International conferences, 6 book chapters, 4 books and one patent. Her total citations are 389 with h-index of 10. Her research interests include device modeling and simulation for advanced metal oxide–semiconductor field-effect transistors (MOSFET) structures such as surrounding gate MOSFET with study of Reliability issues and biosensing applications and Synthesis and Characterization of doped metal oxide nanoparticles. She has more than 8 years of teaching experience and currently supervising two PhD scholar.

Dygun Fatih Demirel is an Assistant Professor at the Department of Industrial Engineering at Istanbul Kültür University, Turkey. He received BSc degree in Systems Engineering from Yeditepe University, Turkey, and PhD degree in Systems Engineering from Yeditepe University, Turkey. His research interests include systems dynamics, disaster management, socioeconomic modeling, fuzzy set theory and its applications, Bayesian forecasting, facility location/network design problem, system dynamics, and wastewater treatment systems design.

Sarah Grace P is a science graduate who received B.Sc (2021) and M.Sc (2023) in Applied Microbiology from Ethiraj College for Women, Chennai. She is working as an Associate Language Editor for American Chemical Society (ACS) publications at TNQ Tech.

Surendra Prakash Gupta is working as Assistant professor in the Department of Biotechnology, SVIS, Shri Vaishnav Vidhyapeeth Viswavidhayalaya, Indore. He received B.Sc. Hons. in Chemistry (2002) from Dayalbagh Educational Institute, Agra; M.Sc. (2006) & M.Tech (2008) in Biotechnology from C.C.S University, Meerut and Uttarakhand Technical University respectively; and Ph.D (2015) in Biological Science from Dayalbagh Educational Institute, Deemed University, Agra - Uttar Pradesh. He started his career as Assistant Professor in Department of Biotechnology, NIET, NIMS University, Jaipur - India in 2015 and served there for more than 2.5 years. He is now working as Assistant Professor at Department of Biotechnology, SVIS, Shri Vaishnav Vidhyapeeth Viswavidhayalaya, Indore and actively involved in teaching and research activities. He has 15 years of academic experience under various capacities in University. He has worked in the area of Drug-DNA interactions, Bioenergy, and Computational Biology. He has qualified GATE in 2006 in Life Science. He has published 05 research papers in peer reviewed Journals, 02 book chapters, 04 conference papers and more than 30 conference abstracts. He has supervised B.Tech and M.Sc Biotechnology students successfully. He is also a member of several reputed professional bodies like, IAENG, Education and Development Research and ASR etc. and Lifetime Member of IARA, and ISTD, Indore Chapter.

Alphonsa Haokip is currently the Headmistress of Christ King High School, Chingjaroi Khullen, Manipur. She has completed her doctorate entitled, "Attitude, Problem Solving Ability, and Achievement in Mathematics Learning among the Secondary School Students of Thadou Kuki Tribe in Manipur". Her areas of interest are Mathematics Learning of Secondary School Students, their problem-solving ability, their academic achievement, mathematics teachers and their concerns, paradigm shift in higher education, and gender issues.

Minakshi Harod is working as upper middle teacher in madhya Pradesh Govt as a Chemistry teacher, district Chemistry master trainer Harod has more than 7 years of research and teaching experience. She has worked in the area of natural sciences, chemical sciences etc. She has published research papers in peer reviewed Journals and book chapters in various books of International repute.

Madhumita Hussain is Associate Professor of Geography Sophia Girls' College (Autonomous), Ajmer. She holds a Ph.D. in Built Environment and Health and have a comprehensive understanding of Urban, Health, Physical, and Quantitative geography. Her focus is on the intersection of the built environment and health. Additionally, Her expertise in this field is supported by extensive research and numerous academic publications, which are well-written and engaging.

Kousar Jan is Principal at Government Degree College, Thindim Kreeri - Kashmir and actively involved in teaching and research activities. She has more than 30 years of research and teaching experience. He has worked in the area of Environmental Biosensors, and limnology. She has published research papers in peer reviewed Journals and book chapters in various books of International repute.

Dea V Jose is working as Associate professor in the Department of Computer Science, CHRIST University, Bangalore. She received PhD (2016) in Computer Science from CHRIST University, Karnataka. She started her career as Assistant Professor in Department of Computer Science CHRIST University India in 2006 and serves there till date. She is actively involved in teaching and research activities and is interested in the areas of sensor networks, IoT, and AI. She has published more than 40 research papers in peer reviewed Journals, conferences and books. She has successfully guided PhD students. She has worked as Principal Investigator in research projects and is a member of several national and international reviewer board of various journals.

Kmal Kishore is working as Associate Professor in department of Chemistry & Biochemistry, Eternal University Baru Sahib, Himachal Pradesh (India). He has fourteen years of teaching and one year of pharmaceutical industry (Alkem Laboratories Ltd.) experience. He received his Ph.D. degrees in Chemistry entitled, 'Physico-chemical, thermal and acoustical behaviour of terbium soaps' from B.U. Bhopal (M.P.) under the supervision of Prof. S.K. Upadhyaya (Ex. CSIR pool officer and recipient of Dr. Radhakrishnan Award). Dr. Kamal Kishore is author & co-author of over 28 technical publications, one book with title- CSIR-UGC NET (Chemical Sciences) and edited books for UG courses with Satya

Prakashan, New Delhi. He is editorial board member & reviewer of many reputed national and international Journals. He has successfully supervised Ph.D. and M.Sc. students for their thesis.

Javid Manzoor is working as Assistant professor in the Department of Environmental Science, Shri JJT University, Jhunjhunu, India. He has obtained his Master's degree and doctorate from Jiwaji University, Gwalior, Madhya Pradesh. He has five years of teaching experience. He is an awardee of University Research Scholarship. He is a permanent member of people for animal. His areas of interest include Environmental pollution, Environmental monitoring and assessment. He has published research papers and book chapters in various national and international journals with impact factor. He has been working as editorial board member and reviewer of various national and international journals.

Adul Qayoom Mir is currently working as Associate Professor in Environmental Sciences in the Higher Education Department Govt. of Jammu and Kashmir for the last 16 year. Prior to that Dr. Mir has worked as Assistant Professor at Azad Institute of Engineering Lucknow, UP. After pursuing M.Sc. Environmental Sciences from Dr. R.M.L.A. University Faizabad in 2004, Dr. Mir completed his Ph.D. Programme in the Department Of Environmental Sciences from Central University Lucknow in 2008 with specialization in Air Pollution and Medicinal Plants. Dr. Mir has also cleared the UGC NET in 2004. With a teaching experience of some 17 years and research experiences of more than 20 years Dr. Mir has published his work in reputed national and international Journals besides presenting his work in different conferences and seminars. He has guided 4 M.Phil and 2 Ph.D. Students.

Satyendra Nath, currently working as Associate Professor & Head, Department of Environmental Sciences & NRM, College of Forestry, SHUATS, Prayagraj, Uttar Pradesh, India. He obtained Ph.D degree from Motilal Nehru National Institute of Technology Allahabad. He has been more than 16 years experiences in Consultancy, Research and Teaching in the field of Agriculture, Environmental sciences and Engineering. Dr. Nath published more than70 publications in International/National Journals/Conferences.

R anjeevi is an accomplished academician and researcher serving as the Associate Professor in Environmental Science and the Head & Principal (i/c) of the Nims Institute of Allied Medical Science and Technology (NIET) at NIMS University, located in Rajasthan, Jaipur. His extensive qualifications include M.Sc., M.Phil., Ph.D., and a Post-Doctoral Fellowship (CSIR-RA), along with a PG Diploma in Industrial Waste & Wastewater Treatment, all focused on Environmental Science and Engineering. With over 14 years of experience, Dr. R. Sanjeevi's expertise encompasses a wide array of fields within environmental science, including water analysis, wastewater treatment, waste-to-energy conversion, renewable energy resources, air pollution monitoring and control, solid waste management, bioprocess technology, environmental biotechnology, and remote sensing & GIS. His contributions to academia and research have been widely recognized, evidenced by his impressive Google Citation Index and numerous awards and recognitions. Notable among these are his awards for best paper presentations at national seminars and conferences, his role as chairperson in various academic forums, and his contributions as a resource person and subject specialist in research conventions and seminars. His dedication to advancing environmental science and engineering, coupled with his commitment to sustainable development, make him a significant figure in both academia and the field of environmental research. His multifaceted expertise and numerous accolades underscore his significant contributions to the domain of environmental science and his commitment to excellence in research and education.

V Muthu Ruben is a distinguished Associate Professor at the School of Law, Christ University, situated in Bengaluru, Karnataka, India. Driven by an extensive scholarly foundation and a steadfast dedication to legal education, Dr. Ruben makes substantial contributions to both the academic community and the domain of law. His proficiency transcends numerous spheres within the realm of law, and he significantly influences the educational journeys of students enrolled at Christ University. Motivated by an ardent interest in legal research, he actively participates in scholarly endeavors, thereby making significant contributions to the ongoing legal dialogue. In addition to his scholarly responsibilities, Dr. V. Muthu Ruben is renowned for his commitment to cultivating an atmosphere that encourages intellectual engagement. His mentorship and counsel motivate pupils to explore into the complexities of the law, fostering the development of critical thinking skills and a profound comprehension of legal principles. In his role as an Associate Professor, Dr. Ruben provides the School of Law with an abundance of expertise, experience, and a forward-thinking perspective, thereby enhancing the institution's dedication to providing superior legal education.

Pashantkumar B. Sathvara is currently employed at Nims Institute of Allied Medical Science and Technology, Nims University Rajasthan, Jaipur. He holds a diverse academic background, including a pursuing Ph.D. in Environmental Science (Thesis Submitted), M.Sc. in Environmental Science and Technology, P.G. Diploma in Geo-informatics System, and a B.Sc. in Safety and Fire Technology. His research contributions are primarily focused on environmental science, with a particular emphasis on carbon sequestration mapping, vegetation change detection, and the application of remote sensing and GIS techniques. He has published 3 publications in peer recognized international and national journals, 2 book chapter and 9 book chapter under reviewed and accepted He has also undergone extensive training programs, including projects at Space Application Center (ISRO) and safety and fire courses, further augmenting his skills and knowledge. His computer skills include proficiency in advanced software such as ArcGIS, QGIS, ENVI, and Google Earth Pro, as well as familiarity with various operating systems and office tools.

Rnjit Singha is a Doctorate Research Fellow at Christ (Deemed to be University) and holds the prestigious American Psychological Association (APA) membership. With a strong background in Research and Development, he has significantly contributed to various fields such as Mindfulness, Addiction Psychology, Women Empowerment, UN Sustainable Development Goals, and Data Science. With over 15 years of experience in Administration, Teaching, and Research, both in Industry and Higher Education Institutions (HEI), Mr Ranjit has established himself as a seasoned professional. Mr Ranjit is dedicatedly involved in research and teaching endeavours, primarily focusing on mindfulness and compassion-based interventions. His work in these areas aims to promote well-being and foster positive change in individuals and communities.

Surjit Singha is an academician with a broad spectrum of interests, including UN Sustainable Development Goals, Organizational Climate, Workforce Diversity, Organizational Culture, HRM, Marketing, Finance, IB, Global Business, Business, AI, Women Studies, and Cultural Studies. Currently a faculty member at Kristu Jayanti College, Dr. Surjit also serves as an Editor, reviewer, and author for prominent global publications and journals, including being on the Editorial review board of Information Resources Management Journal and a contributor to IGI Global. With over 13 years of experience in Administration, Teaching, and Research, Dr. Surjit is dedicated to imparting knowledge and guiding students in their research pursuits. As a research mentor, Dr. Surjit has nurtured young minds and fostered academic growth. Dr. Surjit has an impressive track record of over 75 publications, including articles, book chapters, and textbooks, holds two US Copyrights, and has successfully completed and published two fully funded minor research projects from Kristu Jayanti College.

Sandeep Tripathi is the Associate Professor of Biochemistry and Director, Institute of Public Health and Nutrition. His research degree was based on “Metal ion neurotoxicity” which was awarded as “Best PhD thesis” among the batch 2010 in the King George’s Medical University, Lucknow, India. He has published 68 research articles and many book chapters. He has awarded Mrs. Abida Mehdi Award for Neuroscience Research by Indian Academy of Biomedical Sciences and Young Scientist Award by centre for education growth and research. He has established “National referral centre for fluoride poisoning (NRCFPI) in India”, it was first fluoride referral centre in the country and continuously leading by Dr. Tripathi as Head, Research and Development and he is the recipientof Niloufer Chinoy Award- 2013 presented by the International Society for fluride Research. Dr. Tripathi is the member of editorial board of many journals. He is the member of various International and National Societies (IBRO, ISNR, SOT, IAN, ACBI, SFRR, SOPI, SPGHTN and InSLAR). He has attended more than 50 conferences and workshops as speaker/ chairperson / moderator or as delegate.

G. Sangeetha Vani currently holds the position of Associate Professor in the Department of Microbiology at Ethiraj College for Women in Chennai, Tamil Nadu, India. She obtained her Master of Science degree in Applied Microbiology in 2004, Master of Philosophy in Microbiology in 2006, Master of Science in Bioinformatics in 2018, and Doctor of Philosophy in 2019. She has successfully finished numerous NPTEL courses. In 2005, she began her job as a Microbiologist and Analyst, lasting one year. She held the position of lecturer from 2005 to 2007. Since 2007, she has been working at Ethiraj College for Women. She has accumulated more than two decades of scientific experience. She has worked in Bacteriology, Virology, Bioinformatics, Environmental Microbiology, Agricultural Microbiology, and biofilm-related research. She has contributed articles to scholarly journals that undergo peer review and some are indexed in Scopus. She has delivered academic presentations at multiple conferences. She successfully finished three Faculty Research projects funded by Ethiraj College Trust. She is a member of various national and international organizations. She is also a reviewer in peer-reviewed and Scopus-indexed journals. In 2019, she was awarded the Ph.D. Certificate of Award from the University of Madras, specifically the Madanagopalan Memorial Prize, with a financial prize of Rs 3000. She has served as the state coordinator of the Microbiologists Society, India (2021-22). She serves as a member of BOS, Presidency College, Chennai. She has organized conferences, webinars, and workshops and also attended various conferences, seminars, workshops, and FDP.

Aashish Verma is working as Assistant Professor in the Department of Chemistry at Adarsh Institute of Management & Science Dhamnod India. He has more than 2 years of research and 10 years teaching experience. He has worked in the area of Natural Products in Chemistry. He has published research papers in peer reviewed Journals and book chapters in various books of International repute.

Sonam Verma is working as Assistant Professor in the Department of Zoology at Adarsh Institute of Management & Science Dhamnod India. Sonam has more than 2 years of research and teaching experience. She has worked in the area of Fishes in Zoology at Gawla Pond of Maheshwar Dist. Khargone, M. P. She has published research papers in peer reviewed Journals and book chapters in various books of International repute.

Hemendra Wala is working as upper middle teacher in madhya Pradesh Govt as a Biology teacher, district lab and biology master trainer. Wala has more than 10 years of research and teaching experience. He has worked in the area of limnology, ichthyology, neuro science etc. He has published research papers in peer reviewed Journals and book chapters in various books of International repute.

Yogesh Kumar Walia was born in Hamirpur, Himachal Pradesh, India in 1980. He received his B.Sc. degree from the Himachal Pradesh University Shimla in 2000. In 2004 he received his M.Sc. degree from the Barkatullah University (formerly Bhopal University), Bhopal, India. In 2010 he received his Ph.D. degree from the Barkatullah University (formerly Bhopal University), Bhopal, India. His contribution in synthetic bioorganic chemistry, environmental protection and natural products published in peer review journals and published more than forty research papers. **Presently** he is **working as Professor in Organic Chemistry at Career Point University Hamirpur**, India. He has supervised Twenty-Nine Post Graduate projects and Eight Ph.D. research scholars and currently he is supervising Six Ph.D. research scholars at this University.

Aaq Majid Wani, is presently working as Head and Associate Professor, Department of Forest Biology, Tree Improvement and Wildlife Sciences, College of Forestry, Sam Higginbottom University of Agriculture, Technology and Sciences, Prayagraj (Uttar Pradesh), India. Beside this, he has more than 15 years of experience in teaching and research in Forestry and guided Six Ph.D. and twenty seven M.Sc. students. Dr. Wani has published more than 90 research papers in National and International journals along with different Book chapters and three books. Dr. Wani has been awarded best teacher award by ICAR New Delhi in year 2016. Dr. Wani has shared many ideas and knowledge to the students as well as to the farmers coming to college of Forestry for exposure visit.

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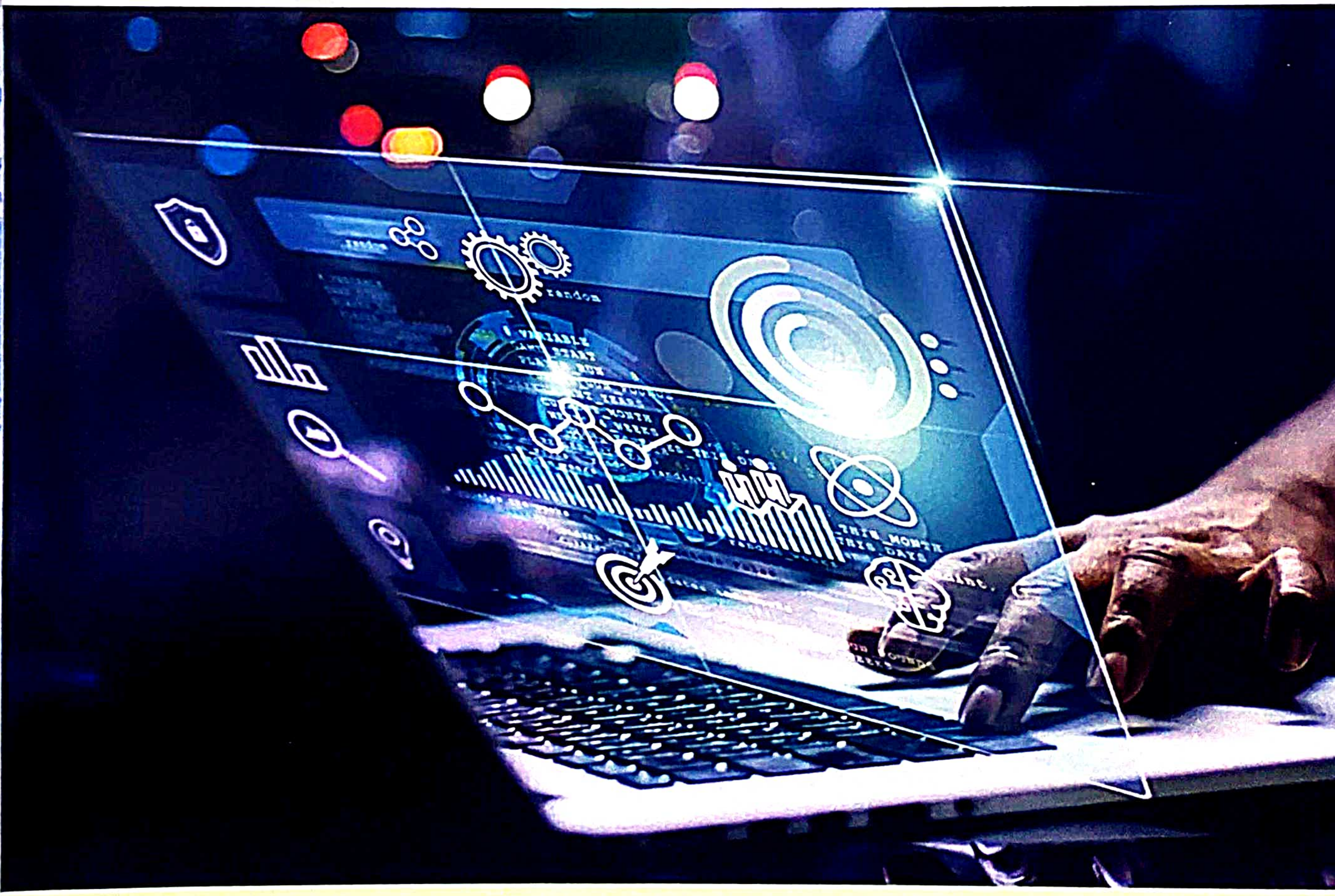

About The Author

Prof. Shyam S. Khinchi obtained his U.G. and P.G. degrees from Department of Geography, University of Rajasthan, Jaipur and Ph.D. from M.D.S. University, Ajmer (Rajasthan). Dr. Khinchi is presently working as a Professor & Head, Department of P. G. Studies in Geography, since 1996 at Dr. B. R. Ambedkar Govt. P.G. College Sri Ganganagar (Raj.). Prof. Khinchi has written 19 books and number of research papers published in National and International journals of repute. He has registered as Ph.D. guide, 3 of research scholar has got Ph.D. degree and 11 students got M. Phil. Degree under his supervision. He has also been working as member of the Board of Studies of Geography in M.G. S. University, Bikaner (Raj.). He has attended International Conference held in Bangkok (Thailand) also presented a paper on the same. He was awarded with the Life Time Achieve Award for his cordial participation at the research work. He has also organized 2 International & 5 National level conferences and Workshops. His area of specialization is Biodiversity, Environment Studies, Occupational Health Hazards, and Agricultural Geography. He has completed Two Minor Research Projects funded by UGC (CRO), Bhopal and Government of Rajasthan awarded him as state level Best Programme Officer Award of National Service Scheme (N.S.S.). He is also a life member of ISCA, NAGI, IIG, RGA, DRA and APG.

Mrs. Shilpi Yadav is an educationist working as an Assistant Professor, P.G Department of Geography, Sophia Girls' College (Autonomous), Ajmer, Rajasthan, India. She is engaged in teaching and research for the last 9 years contributing in Remote Sensing & GIS Environment, Climate Change, Urban Infrastructure, Border Disputes and Geopolitics. Presently, she is pursuing Ph.D. on Geo-Spatial Analysis of Soil Erosion Risk Modelling Using Land Use Land Cover, RUSLE & Morphometric Parameters: A Case Study ff Ajmer District, Rajasthan. Due to a long experience in working with GIS tools, she has a strong command on handling various formats of GIS software and working with their respective data dependencies. Mrs. Shilpi Yadav has to her credit 1 book published by National Publisher and more than a dozen research papers published in National and International journals of repute. She has also acted as a member of organizing committee for "Capacity Building Training Programmes in Geospatial Technologies" sponsored by DST (Department of Science and Technology) in Sophia Institution and acted as a Resource Person in this Geospatial Training Programme. She has also completed Institutional Projects on "Geo- Spatial & Temporal Analysis of Urban Heat Island using Remote Sensing and GIS: A Case study of Ajmer City" & Sewage Treatment Plant: A Boon for The Polluted Anasagar!!! (Evidence-Based Holistic Restoration of Lake Anasagar, Ajmer, Rajasthan, India). She has also done various advanced certification courses from Indian Space Research Organization, Indian Institute of Remote Sensing and ESRI.

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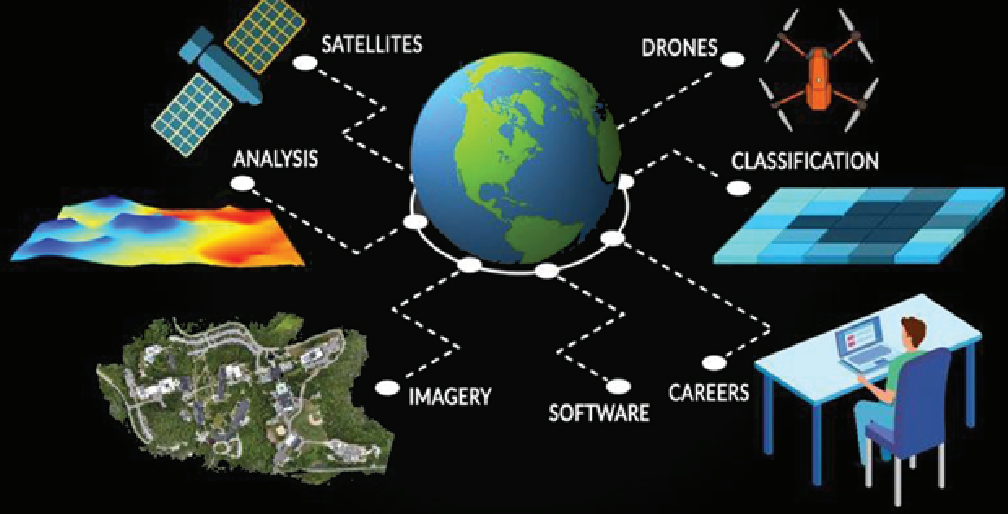

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Pavan Kumar
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Technological Approaches for Climate Smart Agriculture

Springer

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Pavan Kumar • Aishwarya
Editors

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Editors
Pavan Kumar
Rani Lakshmi Bai Central
Agricultural University
Jhansi, UP, India

Aishwarya
Banaras Hindu University
Varanasi, UP, India

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Foreword

In the face of the unprecedented challenges posed by climate change, agriculture stands at the forefront of adaptation and resilience. The book *Technological Approaches for Climate Smart Agriculture* is a timely and useful contribution to the discourse on sustainable agricultural practices in a changing climate. As our global population continues to grow, so does the urgency to secure food production while mitigating the environmental impacts of agriculture.

The pages within delve into a spectrum of technological innovations, from precision farming and remote sensing to data analytics and smart irrigation systems. Each chapter is a testament to the transformative power of technology when applied judiciously to the agricultural landscape. Beyond the realm of theory, the book offers practical insights into the application of these technologies, emphasizing their tangible benefits for farmers, ecosystems, and the broader community.

This book may be a guide for policymakers, researchers, and practitioners alike. It may inspire collective action, fostering a shared commitment to harnessing technology for the betterment of agriculture, preservation of environment, and the resilience of rural communities.

I extend my sincere appreciation to the authors for their dedication to this critical subject matter. Their collective wisdom and insights have resulted in a resource that not only informs but also inspires to embrace technological approaches that can steer agriculture towards a climate-smart and sustainable future.

Hon'ble Vice-Chancellor
Rani Lakshmi Bai Central Agricultural University
Jhansi, India

Ashok Kumar Singh

Foreword

In a world where climate change continues to exert its formidable impact on agriculture, the need for innovative and sustainable solutions has never been more pressing. *Technological Approaches for Climate Smart Agriculture* stands as a testament to the collective effort and dedication of experts and practitioners in tackling this critical challenge.

This book serves as a beacon, illuminating the pathways that merge cutting-edge technology with the wisdom of agricultural practices. The marriage of these two realms holds promise – a promise of resilience, adaptability, and sustainability in the face of a changing climate. Within these pages, readers will embark on a journey through a landscape of technological marvels, from precision farming techniques and sensor-based monitoring to predictive analytics and AI-driven solutions. Each chapter unfolds as a testament to human ingenuity, showcasing how technology not only confronts the challenges posed by climate change but also cultivates opportunities for a more robust, efficient, and environmentally conscious agriculture sector.

The authors, with their depth of knowledge and commitment, present a mosaic of ideas, research findings, and practical applications. Their contributions serve as a clarion call to action – an invitation for policymakers, farmers, scientists, and entrepreneurs to harness the power of technology in reshaping our approach to agriculture. As we delve into the realms of smart sensors, big data analytics, genetic engineering, and sustainable farming practices, let us not forget the essence of this pursuit: to ensure food security, safeguard the environment, and empower communities around the globe.

I extend my deepest gratitude to the contributors for their invaluable insights and commend their dedication to fostering a future where agriculture thrives in harmony with nature. May this book ignite conversations, inspire innovations, and serve as a guiding light in our collective journey towards a more resilient and sustainable agricultural landscape.

Dewayany Sutrisno

Spatial Information System
Geospatial Research Center
National Research and Innovation Agency
Indonesia

Preface

Climate change poses significant challenges to global food security and agricultural sustainability. To address these challenges, the concept of climate-smart agriculture (CSA) has emerged as a comprehensive approach that seeks to enhance agricultural productivity, resilience, and sustainability while mitigating greenhouse gas emissions. Technological advancements play a pivotal role in enabling climate-smart practices, empowering farmers to adapt to changing climatic conditions and contribute to climate change mitigation.

This book is a collection of peer reviewed range of technological approaches that have been developed and implemented to promote climate-smart agriculture. Precision farming, a data-driven approach utilizing advanced technologies like Global Positioning Systems (GPS), remote sensing, and Geographic Information Systems (GIS), enables farmers to optimize resource use through precise decision-making on irrigation, fertilization, and pest management. Furthermore, the adoption of drought and heat-tolerant crop varieties, developed through biotechnology and breeding techniques, provides resilience against extreme weather events and improved water-use efficiency.

Conservation agriculture practices, such as minimum tillage, crop rotation, and mulching, reduce soil erosion, conserve soil moisture, and sequester carbon, fostering both climate change adaptation and mitigation. Integration of climate information services, utilizing various technologies, ensures timely and accurate weather forecasts, climate outlooks, and advisories, supporting farmers in making climate-resilient decisions. Moreover, improved irrigation techniques, such as drip irrigation and sensor-based systems, enhance water management, reducing water wastage and improving water-use efficiency.

In the livestock sector, climate-smart breeding programs focus on developing resilient animal breeds capable of withstanding heat stress and optimizing feed conversion efficiency, thereby reducing methane emissions. The integration of renewable energy sources, such as solar-powered water pumps and biomass-based energy, promotes sustainable energy use in agricultural operations, further contributing to greenhouse gas emissions reduction. Mobile applications, revolutionizing information dissemination, provide farmers with access to climate and market information, best practices, and pest and disease monitoring. Such applications empower farmers to make informed decisions, optimize productivity, and manage risks effectively. Additionally, climate-smart agroforestry systems combine trees with crops or livestock, providing multiple benefits such as carbon sequestration, enhanced soil fertility, and diversified income sources for farmers. Carbon farming practices offer further potential for climate change mitigation, as strategic land management techniques enhance carbon storage in agricultural soils and vegetation. Practices such as cover cropping, agroforestry, and rotational grazing contribute to sustainable agriculture while mitigating climate change impacts.

The overall objective of this book is to bring together a unified presentation for managing challenges of technological approaches for climate-smart agriculture. However, successful adoption of these technological approaches for climate-smart agriculture requires comprehensive knowledge transfer, capacity building, and supportive policies at local, national, and international levels. Collaboration among governments, research institutions, private sectors, and farmers' organizations is essential to scale up these technologies and ensure their equitable distribution across diverse agricultural landscapes. In conclusion, technological approaches play a critical role in the transformation of agriculture into a climate-smart sector. By embracing innovative tools and practices, farmers can increase resilience to climate change, reduce environmental impacts, and contribute to global efforts in mitigating climate change while sustaining agricultural productivity and food security. An integrated approach that combines technology, knowledge dissemination, and policy support will be instrumental in building a climate-resilient and sustainable agricultural future.

This book is a collection of peer reviewed contributions from researchers of diverse fields. The book is truly interdisciplinary, with a research and application-oriented dimension. The whole book is divided into two parts. Part 1 explores the *climate change and global food security* with 9 chapters, whereas Part 2 deals with the *advanced technology in agriculture for climate smart farming* with 10 chapters.

The chapters in each section of this book are innovative and have practice-based experiences. Part 1 deals with tracing of climate-smart resilient agricultural practices, soil management, crop production, land use land cover change, soil organic carbon, and smart nutrient practices. The chapters of this part examine the broader issues associated with climate smart agriculture in economic systems and focus on the smart farming-related aspects of sustainability. Part 2 of the book takes in account the impact assessment of climate on agricultural production, adaptation and mitigation strategies, precision farming, simulation modeling, strategic intervention, climate policies, drone technology and renovation conservation agriculture.

The book proposes some pragmatic options for managing smart farming within these limits and provides an integrated approach which finally creates an enabling environment that offers hope of transformational change in the management of socio-ecological systems. Thus, this book aims to make available the reader with ground information and examples to sustain localized approach, facilitating practitioners to illustrate an appropriate way of action.

Jhansi, India Pavan Kumar
Varanasi, India Aishwarya

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About the Editors

Pavan Kumar is Assistant Professor at the Department of Forest Biology and Tree Improvement, College of Horticulture and Forestry, Rani Lakshmi Bai Central Agricultural University, Jhansi, UP, India. He obtained his PhD degrees from Faculty of Natural Sciences, Jamia Millia Islamia, New Delhi. He did BSc (Botany) and MSc (Environmental Science) from Banaras Hindu University, Varanasi, India, and subsequently obtained Master's degree in Remote Sensing (MTech) from Birla Institute of Technology, Mesra, Ranchi, India. His current research interests include resilient agriculture and climate change studies. He is recipient of Innovation China National academy award for Remote Sensing. Dr. Kumar has published 70 research papers in international journals and authored several books. He has visited countries like USA, France, the Netherlands, Italy, China, Indonesia, Brazil and Malaysia for various academic/scientific assignments, workshop and conferences. Dr. Kumar is member of International Associations for Vegetation Science (IAVS), USA, and Institution of Geospatial and Remote Sensing, Malaysia.

Aishwarya is student cum researcher of the Department of Agronomy, Institute of Agricultural Sciences, Banaras Hindu University, Varanasi, UP, India. She obtained her BSc degrees from the College of Agriculture, Rani Lakshmi Bai Central Agricultural University, Jhansi, UP, India. She has professional knowledge in the major disciplines of agriculture. Aishwarya has authored several peer-reviewed scientific research papers and presented works at many national and international conferences. In addition, she has actively engaged in South Africa's World Climate Research Programme (WCRP). She was honoured with best posters as well as presentation awards in Rani Lakshmi Bai Central Agricultural University and best volunteer during Science and Engineering Research Board (SERB)-DST Workshop. She is member of National Environmental Science Academy (NESA), New Delhi, India. She has authored several journals of Springer, Elsevier and Wiley-Blackwell.

Part I
Climate Change and Global Food Security

Environmental Crisis: Nourishment at Risk

Aishwarya and Pavan Kumar

Climate change is a critical factor affecting global food security, with far-reaching consequences for agricultural systems and food production. This section examines the complex relationship between climate change and food security, highlighting the challenges faced by farmers and vulnerable communities worldwide. It delves into the impacts of changing climatic conditions on agricultural productivity, water availability, pest and disease patterns, and biodiversity loss. The chapter explores the vulnerabilities of smallholder farmers and discusses the implications of global food trade and price instability. Moreover, it presents a comprehensive analysis of adaptation strategies and sustainable solutions to enhance climate-resilient agriculture and promote food security in the face of a changing climate.

Climate change is a growing concern that poses significant challenges to global food security. This research chapter explores the complex interactions between climate change and agricultural systems, critically examining the impacts of changing climatic conditions on food production, distribution, and access. It analyzes the vulnerabilities of smallholder farmers, particularly in developing countries, and the implications of climate-induced extreme weather events on crop yields and food availability. Additionally, the chapter investigates the role of sustainable agricultural practices, adaptation strategies, and international cooperation in mitigating the adverse effects of climate change on global food security. By highlighting the urgency of the issue and proposing comprehensive solutions, this research chapterr contributes to the ongoing efforts to build climate-resilient food systems and ensure food security for all in a changing climate.

Aishwarya (✉)
Banaras Hindu University, Varanasi, UP, India

P. Kumar
Rani Lakshmi Bai Central Agricultural University, Jhansi, UP, India

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One of the most important problems facing humanity right now is climate change, which has a significant impact on many facets of daily life, including the security of the world's food supply. Global agricultural systems are being impacted by the earth's climate change, causing serious difficulties for food production, distribution, and availability. The consequences of climate change are far-reaching and affect various aspects of life, including agriculture and food security. The agriculture sector is highly sensitive to changes in weather patterns, as it relies heavily on suitable climatic conditions for successful crop growth and livestock rearing. With the ever-increasing global population, ensuring food security becomes even more critical. In this article, the complex relationship between climate change and world food security is examined. The main problems are outlined, and some solutions are suggested to help reduce the effects and ensure that food production can continue in the future.

1 Climate Change's Effect on Agricultural Productivity

Environmental changes brought on by climate change include increased temperatures, altered precipitation patterns, and an increase in the frequency of extreme weather occurrences like droughts and floods. Crop yields and livestock productivity are impacted by these modifications, which disturb established agricultural methods. Farmers find it challenging to anticipate planting and harvesting dates due to unpredictable weather, which results in crop failures and decreased food availability.

2 Agricultural Smallholders' Vulnerability

Smallholder farmers, who make up a sizable share of the agricultural labor force worldwide, are especially susceptible to the effects of climate change. Their capacity to adjust to shifting climatic circumstances is hampered by a lack of resources and access to cutting-edge technologies. As a result, they face greater threats to their way of life and food security.

2.1 Changing Patterns of Pest and Disease

Pest and disease distribution and behavior are affected by climate change, which has an effect on crop health and productivity. The reappearance of some illnesses and new pest infestations makes it harder to produce food, which could result in losses of expensive crops.

2.2 Agriculture and Water Scarcity

Water scarcity is a problem in many areas due to altered rainfall patterns and higher rates of evaporation. Water use in agriculture is high, and a lack of water restricts irrigation methods and lowers farm productivity as a whole.

2.3 Biodiversity and Food Diversity Are Being Lost

Numerous plant and animal species are in danger due to climate change's impact on ecosystems and biodiversity. A reduction in crop genetic variety due to biodiversity loss increases the susceptibility of agricultural systems to pests and disease. Additionally, it reduces traditional food sources, which has an effect on the diversity of foods around the world.

2.4 Instability in Food Prices and Global Trade

Because of the interdependence of the world's food supply, disturbances in one area can have a global impact on food costs and availability. Extreme weather conditions and crop failures in significant food-producing regions can raise food prices, making it more expensive for needy populations.

3 Strategies for Climate-Resilient Agriculture Adaptation

Adaptation solutions are crucial to enhancing global food security in the face of climate change. Promoting climate-resilient agricultural methods, funding climate-smart technology, and providing smallholder farmers with better access to resources and information are a few examples.

3.1 Reduced Food Waste and Sustainable Food Systems

Food security may be assured in a changing environment by creating sustainable food systems that minimize waste, encourage effective distribution, and lower greenhouse gas emissions. Taking steps to reduce food waste along the entire supply chain can also increase the availability of food.

This section provides an overview of climate change and global food security and their challenges and future directions. Modern technology like Remote

Sensing (RS) and Geographical Information System (GIS) with timely and accurate information helps to monitor and analyze a wide range of phenomena like water, vegetation, land, and human activities. Interdisciplinary studies are also noticed in human–environment interaction between stakeholders and decision makers for real-world applications. Remote sensing data products and their limitations are also discussed in the book. To overcome this situation, artificial intelligence (AI), along with cloud computing and big data analytics, is the need of the hour. Decision support system based on the AI in remote sensing and GIS is key to the implementation of decision-making and planning in a sustainable manner. The section is segregated into nine chapters. Chapter 2 discusses the "A perspective way to climate smart Agriculture." It lessens climate change while boosting productivity and resilience. To hasten the shift to climate-smart agriculture (CSA), smallholder use of farming technology is required. Here, authors evaluated the factors that influence the adoption of five technologies that can aid in achieving some CSA outcomes on Tanzanian smallholder farms. Chapter 3 is devoted to "An insight on different climate smart and resilient agricultural practices." Chapter 4 presents "Soil management in sustainable agriculture: principles and techniques". "Dynamics of nutrients, soil organic carbon, and smart nutrient management practices" is discussed in Chap. 5 in which ***g***lobal climate change is a major concern for all developing and developed countries that has resulted in major changes to earth geological, ecological, and biological systems, and poses serious threats to existence of human civilization and sustenance of agricultural productivity and food security. Chapter 6 discusses "Impact on agricultural crop production under climate change scenario" because climate change and accompanying human activities and natural hazards pose significant challenges to sustainable agricultural production. Increasing agricultural productivity to feed the burgeoning population in the face of changing climate and degraded land resources leads to additional degradation and depletion of soil nutrient stocks. Chapter 7 presents "Metal(oid) source and effects on peri-urban agriculture/aquaculture sediments." Sediment plays a significant role as a source of metal (loids) in peri-urban agriculture, particularly in areas where agricultural land interfaces with urban and industrial activities. Chapter 8 is devoted to "Monitoring and forecasting of land use and land cover changes in paddy cultivation." "A bioinformatics insight on agriculture" in discussed in Chap. 9.

4 Conclusion

Global food security is significantly threatened by climate change, which also jeopardizes the livelihoods of millions of people and exacerbates already-existing inequities. Governments, international organizations, corporations, and communities must work together to address the effects of climate change on agriculture. We can work toward a future where food security is guaranteed despite the challenges of a changing climate by implementing climate-smart behaviors, investing in research and innovation, and promoting sustainable agricultural systems. This book chapter aims to provide a comprehensive understanding of the challenges posed by climate change to global food security. By exploring potential solutions and adaptation strategies, it seeks to empower policymakers, researchers, and communities to take proactive measures towards building climate-resilient agricultural systems and ensuring a sustainable food supply for future generations.

A Perspective Way to Climate Smart Agriculture

Aishwarya and Pavan Kumar

1 Introduction

In many parts of the world, millions of people's livelihoods, food security, and agriculture are now seriously threatened by climate change (Sharma & Ravindranath, 2019). According to a number of studies, changes in rainfall patterns (Lobell & Gourdji, 2012; Aggarwal & Perrin, 2009; Shiferaw et al., 2014; Mall et al., 2006), temperature changes, and variations in the frequency and intensity of extreme climatic events like floods and droughts (Brida & Owiyo, 2013; Singh & Kumar, 2013) could all have a significant impact on agriculture production. According to estimates of the effects of past and future climate change on cereal crop yields in various regions, the yield loss can range from 35% for rice to 60% for maize, depending on the location, future climate scenarios, and projected year (Garnett, 2011; Porter et al., 2014). Some of the main causes of climate change impacts on agriculture include changes in crop cultivation appropriateness and associated agricultural biodiversity, a decline in input usage efficiency, and an increase in the incidence of pests and diseases (Zabel et al., 2014; Norton, 2014). To ensure the food and livelihood security of farming communities, agricultural production systems must be adapted to these changes.

To lessen the moderate to severe climatic hazards to agriculture, there are a number of potential adaptation solutions. Climate-smart agriculture (CSA) technology, practices, and services are adaptation choices that sustainably boost productivity, improve resistance to climatic shocks, and lower greenhouse gas

Aishwarya (✉)
Department of Agronomy, Institute of Agricultural Sciences, Banaras Hindu University, Varanasi, UP, India

P. Kumar
Forest Biology and Tree Improvement, College of Horticulture and Forestry, Rani Lakshmi Bai Central Agricultural University, Jhansi, UP, India

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emissions (FAO, 2010). According to Vermeulen et al. (2012) and Lipper et al. (2014), the main objective of CSA is to build resilient food production systems that ensure both food and financial security in the face of ongoing climate change and variability. Numerous agricultural techniques and technologies, including minimum tillage, various crop establishment techniques, nutrient and irrigation management, and residue incorporation, can increase crop yields, increase the efficiency of the use of water and nutrients, and lower greenhouse gas (GHG) emissions from agricultural activities (Branca et al., 2011; Jat et al., 2014; Sapkota et al., 2015). The use of better seeds, ICT-based agro-advisories, crop/livestock insurances, and rainwater harvesting can all assist farmers in lessening the effects of climate change and variability (Mittal, 2012; Altieri & Nicholls, 2017). The CSA alternatives generally include conventional and cutting-edge methods, tools, and services that are pertinent for a specific place to adapt to climate change and variability (CIAT, 2014). In this study, a technology or practice is deemed to be climate smart if it can assist in achieving at least one pillar of CSA (either by increasing production, increasing resilience, or lowering GHG emissions). Farmers must consider all adaptation alternatives ex ante under the influence of climate risk and make short- and long-term expenditures based on the degree of current climate variability and anticipated future climate change (Callaway, 2004).

The application of CSA technologies (hereinafter referred to as CSA technologies) singly or in combination has a significant potential to lessen the effects of climate change on agriculture. For instance, Finger & Schmid (2007) predicted that straightforward adaptation strategies like shifting agricultural planting dates and implementing irrigation technology might lead to higher yields with fewer fluctuations than those achieved without adaptation. According to a meta-analysis of agricultural simulations conducted under various climatic scenarios (Challinor et al., 2014), farm-level modifications can boost crop yields by an average of 7–15% when compared to those without adaptation. According to numerous research, the advantages of adaptation depend on the crop as well as on variations in temperature and rainfall (Easterling et al., 2007). Similar to this, multiple farm-level studies (Gathala et al., 2011; Khatri-Chhetri et al., 2016; Sapkota et al., 2014) indicate that adoption of CSA technology can improve crop yields, boost input usage efficiency, raise net income, and reduce GHG emissions.

Despite the many advantages of CSA technology, farmers are currently adopting them at a rather low rate (Palanisami et al., 2015). The socioeconomic makeup of farmers, the biophysical context of a specific place, and the characteristics of new technology are only a few of the many variables that affect how widely CSA technologies are adopted (Below et al., 2012; Campbell et al., 2012; Deressa et al., 2011). Major obstacles to scaling out CSA in various agro-ecological zones include the identification, prioritizing, and promotion of accessible CSA technologies while taking into account local climatic hazards and technology demand.

Basically, by creating an investment portfolio across multiple agro-ecological zones, the identification and prioritization of CSA technologies enable climate change adaptation strategy in agriculture. Designing CSA implementation methods at the farm level requires taking into account adaptation alternatives that have been thoroughly assessed and prioritized by local farmers with respect to the key climate hazards in that region (FAO, 2012). Despite the necessity of prioritizing CSA technology at the farm level, there is a lack of such data in the current climate change adaptation programs, which hinders improved adaptation planning. Evidence on farmers' prioritizing might help important stakeholders make decisions that are in conformity with institutional rules and government regulations.

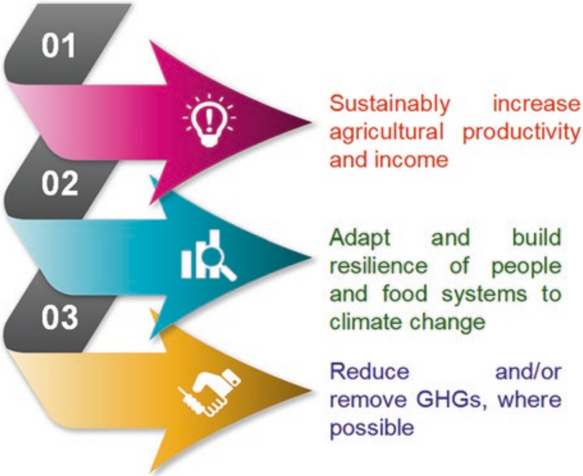
In response to the rapid acceleration of climate change, scientists and researchers have created CSA technologies. While some of these technologies are updated versions of traditional methods, others are brand-new to the system. In addition to other desirable characteristics, appropriate technologies to adapt to the changing climatic conditions will need to be drought-tolerant, grow and produce well within a short period of time, tolerant to numerous pests and diseases, able to produce well under low soil fertility conditions, and high yielding. In order to help with the mitigation of climate change, these technical features should be complemented by appropriate agronomic practices (Agarawal et al., 2018; Agarawal, 1995, 2008). Wide-ranging mitigation initiatives frequently take place at higher echelons of ecosystem management and governance (Chhetri, 2011; Chhetri & Easterling, 2010). Long-term advocacy for behavioral change among the people in the communities within the regions in SSA will be necessary for practices that minimize carbon output, such as restricting the use of fossil fuels, decreasing bush burning (Gentle et al., 2014; Khatri-Chhetri et al., 2019). The adoption rates of CSA technology and practices by smallholder farming households in SSA were examined and addressed in this study. To gauge and ascertain the degree of CSA technology acceptance, the possibilities, and the future projection of the agriculture system in terms of climate change, we use both qualitative and quantitative analysis methodologies (Gentle et al., 2018).

1.1 Climate-Smart Agriculture's Function

"Climate-smart agriculture (CSA) is an approach that helps to guide actions needed to transform and reorient agricultural systems to effectively support the development and ensure food security in a changing climate." This occurred at a period when the idea and methods of sustainable agricultural development were the subject of intense debate (Newell et al., 2019; Paudel et al., 2017). Other authors have improved upon these earlier definitions by heavily integrating elements like mitigation, adaptation, and management to provide a more coherent understanding of the notion. CSA is an integrated strategy that deals with the interconnected problems of food security, climatic variability, and other systemic factors like demography that affect agricultural output. In order to support equitable increases in farm incomes, food security, and development, CSA's three main goals are (Fig. 1):

(a) Sustainably increase agricultural productivity
(b) Adapt to and strengthen the resilience of agricultural and food security systems to climate change at multiple levels
(c) Reduce greenhouse gas emissions from agriculture (including crops, livestock, and fisheries)

Fig. 1 CSA's three pillars



CSA is an approach that helps guide actions to transform agri-food systems towards green and climate resilient practices. It emphasizes the necessity of achieving national food security and reducing GHG emissions (Adger et al., 2003; Agarawal et al., 2012; Chhetri et al., 2012). As a result, it should be highlighted that the definition of CSA depends on its goal, target audience, project type, institutional structure, and individual interest. Recent evidence suggests that the growing population and the activities that go along with it are causing climate change and its consequences. There are no definitions of CSA that take demography into account as of yet. Demographic management in SSA will therefore benefit from increased attention if demography is incorporated into the CSA definitions. Designing comprehensive mitigation and adaptation solutions for the changing climate will, in general, only be possible through CSA. As manual labor declines dramatically, agricultural production would rise and more technologies would be created and used in the industry.

1.2 Main Elements of Climate-Smart Agriculture?

CSA is a method that includes several elements entrenched in local settings rather than a collection of procedures that can be used everywhere. CSA includes investments, institutions, regulations, and technologies that are used both on and off the farm (Fig. 2). The following are some components that can be incorporated into climate-smart farming approaches:

(a) Agricultural, crop, livestock, aquaculture, and fisheries management to better manage resources, produce more with less, and increase resilience

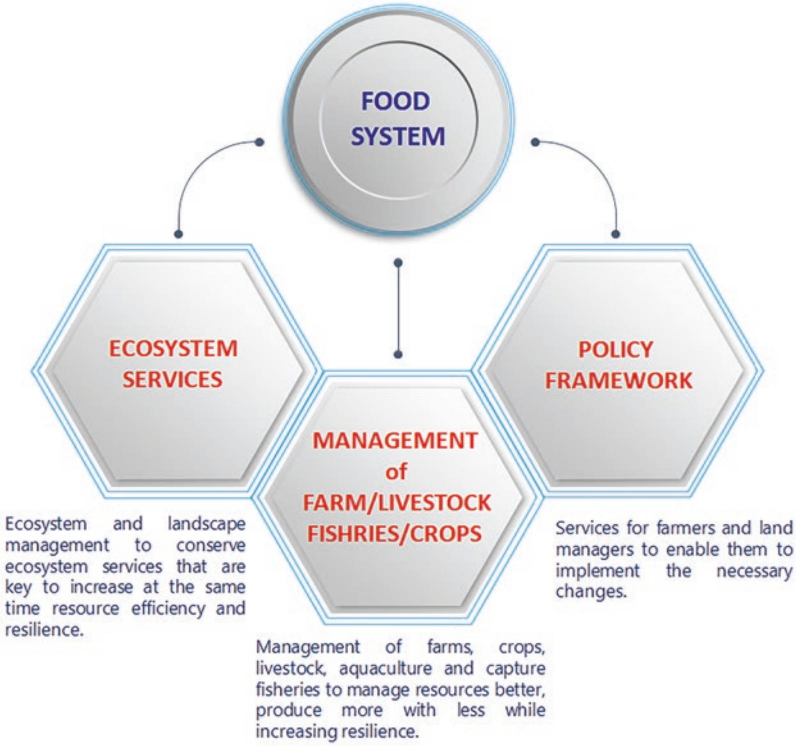


Fig. 2 Elements of climate-smart agriculture

(b) Management of ecosystems and landscapes to preserve ecosystem services necessary to simultaneously increase resource efficiency and resilience
(c) Services for landowners and farmers that help them make the necessary improvements

1.3 Why Does Agriculture Need to Be Climate-Smart?

The population of the globe will rise by one-third by the year 2050. The majority of these extra 2 billion individuals will reside in developing nations. Additionally, more individuals will reside in urban areas. According to Food and Agriculture Organization (FAO) estimates, in order to meet anticipated demands for food and feed by 2050, agricultural production will need to rise by 60%. This is assuming that present income and consumption growth trends continue. Therefore, agriculture must change if it is to feed a growing global population and serve as the foundation for economic progress and the eradication of poverty. Under a "business as usual" scenario, climate change will make this effort more challenging because of its negative effects on agriculture, which would necessitate spiraling adaptation expenses. Lower emission intensities per production and climate change adaptation are required to meet the goals of food security and agricultural growth. The natural resource base must not be depleted in order for this change to be successful. Because extreme events are more common and weather patterns are more unpredictable, climate change is already having an effect on agriculture and food security. Reduced production and poorer incomes in vulnerable areas may result from this. The cost of food globally may also be impacted by these changes. Smallholder farmers and pastoralists in developing nations are particularly heavily struck by these changes. Many of these small-scale farmers already struggle with a depleted supply of natural resources. They frequently lack awareness of the options available for changing their production methods, and they have few resources and a low risk tolerance level, making it difficult for them to obtain and use financial services and technology. The transition to agricultural production systems that are more productive, use inputs more efficiently, have less variability and greater stability in their outputs, and are more resilient to risks, shocks, and long-term climate variability is necessary to increase food security while also protecting the natural resource base and essential ecosystem services. To ensure that these resources are used more effectively, a significant change in how land, water, soil nutrients, and genetic resources are managed is necessary for more productive and resilient agriculture. Significant adjustments in national and local governance, legislation, policies, and financial structures are necessary to make this move. Access to markets for producers will also be improved as a result of this transformation. These adjustments will greatly aid in the mitigation of climate change by lowering greenhouse gas emissions per unit of land and/or agricultural output and raising carbon sinks.

1.4 Why Is Climate-Smart Agriculture Necessary?

By the year 2050, the world's population will have increased by one-third. Most of the additional 2 billion people will live in underdeveloped countries. Urban areas will also see a rise in population. According to FAO predictions, agricultural production will need to increase by 60% by 2050 in order to meet predicted demands for food and feed. This is presuming that the current trends in income and consumption growth hold. Because of this, agriculture must adapt if it is to feed a growing global population, support economic development, and end poverty. In a "business as usual" scenario, climate change will make this effort more difficult due to its detrimental effects on agriculture, which would need skyrocketing adaptation costs. To achieve the objectives of food security and agricultural growth, lower emission intensities per unit of production and climate change adaptation are needed. For this adjustment to be effective, the natural resource base cannot be depleted. Climate change is already having an impact on agriculture and food security because extreme events are becoming more frequent and weather patterns are becoming more unpredictable. This could lead to decreased productivity and lower revenues in vulnerable areas. These changes could potentially have an effect on the price of food globally. In poorer countries, smallholder farmers and pastoralists are particularly hard hit by these developments. A reduced quantity of natural resources already causes hardship for many of these small-scale farmers. It is challenging for them to get and use financial services and technology because they typically lack awareness of the possibilities available for changing their production processes, they have little finances, and they have a low risk tolerance level. To increase food security while also safeguarding the natural resource base and crucial ecosystem services, it is necessary to switch to agricultural production systems that are more productive, use inputs more efficiently, have less variability and greater stability in their outputs, and are more resilient to risks, shocks, and long-term climate variability. For more productive and resilient agriculture, a fundamental shift in how land, water, soil nutrients, and genetic resources are managed is required to ensure that these resources are used more effectively. To make this change, significant changes in national and local governance, legislation, policies, and finance institutions are required. The upshot of this transition will be an improvement in manufacturers' access to markets. By reducing greenhouse gas emissions per unit of land use or agricultural output and increasing carbon sinks, these changes will significantly help with climate change mitigation (Nelson et al., 2010; Padgham, 2009).

1.5 Impact of Agriculture on Climate Change

The agricultural industry must increase food production, and climate change will undoubtedly have an influence. It has also been asked to help reduce climate change due to its importance to the economy (UNFCCC, 2008). The issue is how and to what degree agricultural and food systems can aid in reducing climate change without jeopardizing the security of food and nutrition. About 13.5% of the world's GHG emissions in 2005 were directly attributable to agriculture (livestock and crop production) (IPCC, 2007). This statistic is based on work done with cattle and in the fields. However, a broader view of "food systems" should be taken into account when analyzing agriculture's contribution to climate change, as well as its potential for mitigation. This covers the effects these systems have on transportation, the energy industry, and the forest industry. Expanding our analysis of agriculture's contribution to climate change is necessary since some emissions from on-farm sources, such as power used in farm buildings, fuel used for farm equipment, and transportation of food, are not accounted for in the 13.5% number. Deforestation, which contributes to an extra 17% of world GHG emissions, is also greatly influenced by agriculture (IPCC, 2007).

According to a research from 2006, the food system was thought to be responsible for 31% of the GHG emissions in the European Union (European Commission, 2006). Therefore, it is crucial to look beyond the farm, vertically into the entire food chain, and horizontally across impacted land-uses like forests when examining difficulties and potential to reduce GHG emissions using agriculture. Carbon dioxide

(CO2) is only one of the primary direct sources of GHG emissions in the agriculture industry. Nitrous oxide (N2O), which accounts for 58% of total emissions due to soil and fertilizer use, and methane (CH4), which accounts for 47% of total emissions due mostly to livestock and rice production, are both produced in agriculture. These emissions are more challenging to regulate and measure since they depend on agricultural practices and natural processes. On the other hand, agriculture is a crucial industry that, when combined with forestry, can result in the biological capture and storage of carbon in biomass and soil, serving as "sinks" if it is managed efficiently. In the long run, especially, their management may be crucial to controlling climate change (IPCC, 2007). In developing nations, it is expected that both agricultural production and emissions would rise. By 2030, N2O emissions are predicted to rise by 35–60% and CH4 emissions by 60%, according to the IPCC (IPCC, 2007). Figure 3 shows some of these points, but it also calls attention to something that may be even more important: the fact that the GWP100 doesn't give a clear picture of how emissions affect heat. This figure was made with a simple emissions-based climate model, FaIR v.1.0, is presented, which calculates atmospheric concentrations of greenhouse gases and effective radiative forcing (ERF) from greenhouse gases, aerosols, ozone and other agents (Smith et al., 2018) in its default setting, by adding the stated CO2-equivalent emissions as either nitrous oxide, methane, or CO2 (or balances thereof) to RCP4.5 emissions, then subtracting the modeled warming from the baseline RCP4.5 conditions to show the effects of these emissions alone (Lynch et al., 2021).

The IPCC predicts that more land will be used for agriculture. According to the goal of "food security first," agricultural production can help to reduce climate change in two different ways. The first method is to increase efficiency by separating the rise of emissions from the expansion of output. This entails lowering emissions per kilogram of produced food (emissions from decreased deforestation per kilogram of food are also taken into account in this calculation). The second method involves improving soil carbon sinks. According to the IPCC's estimations (IPCC, 2007), by 2030, the worldwide technical mitigation potential from agriculture might

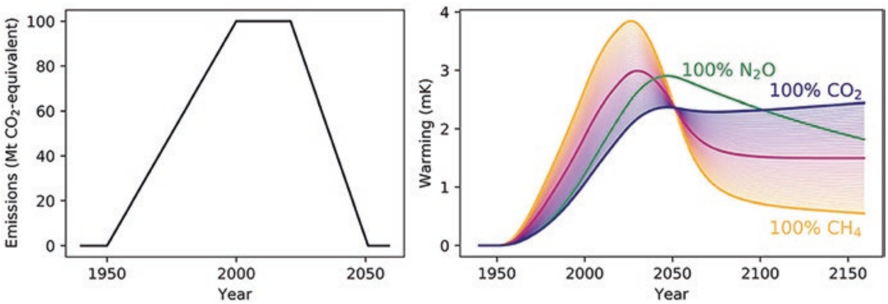


Fig. 3 A single emissions pathway (left) reported as CO2-equivalents using the 100-year global warming potential (gwp100) can have very different effects (right) depending on the gas-specific composition. (Source: Smith et al., 2018)

equal 5,500–6,000 tons of CO_2 annually. This is roughly comparable to 8 200 tons of CO_2 or three-quarters of the sector's projected emissions in 2030. About 70% of this potential has been identified in developing nations, 20% in Organisation for Economic Co-operation and Development (OECD) nations, and 10% in Economies in Transition (EIT) nations. According to IPCC estimations, controlling land carbon stocks rather than reducing agricultural GHG emissions (mostly CH_4 and N_2O) accounts for nine out of ten of agriculture's global mitigation potential. This entails improved grazing management, less tillage, improved soil carbon sequestration, the recovery of organic soils, and the regeneration of degraded areas. One of the primary goals for agriculture and food security may very well be to reduce emissions per kilogram of a given output. Increased efficiency also implies a number of indirect gains in addition to direct gains. Because less land is required to produce the same amount of food, these indirect gains also include decreased emissions from deforestation (which were not taken into account in the IPCC's 90% estimations). Reduced emissions from the production of fertilizer or energy inputs used on the farm are also indirect gains. If all other factors remain constant, it has been estimated that reducing the use of fossil fuels through increased on-farm energy efficiency might result in a decrease of 770 tons of CO_2 annually by 2030 (IPCC, 2007). Additionally, there may be savings through increased food chain efficiency, such as a decrease in post-harvest losses.

1.6 Climate-Smart Agriculture

CSA is an approach that aims to sustainably increase agricultural productivity, adapt to climate change impacts, and reduce greenhouse gas emissions. It involves implementing practices and technologies that are resilient to climate variability and contribute to climate change mitigation. Various perspectives on the key ways to achieve climate-smart agriculture:

1.6.1 Sustainable Intensification

Sustainable intensification is an agricultural approach that aims to increase productivity and food production while ensuring the long-term sustainability of natural resources and minimizing negative environmental impacts. This includes optimizing the use of resources like water, fertilizers, and pesticides, and promoting integrated pest management and precision agriculture techniques. Sustainable intensification is a key strategy to meet the growing global demand for food while safeguarding the environment and promoting agricultural resilience. By combining technological advancements, ecological principles, and social inclusivity, sustainable intensification offers a pathway to achieve food security and environmental sustainability in the face of climate change and population growth.

1.6.2 Climate-Resilient Crop Selection

Climate-resilient crop selection is a crucial aspect of climate-smart agriculture that involves choosing and promoting crop varieties that are better adapted to current and future climatic conditions. These resilient crop varieties can withstand various climate stressors, such as drought, heatwaves, floods, and pests, and still maintain satisfactory yields and quality. Promote the adoption of climate-resilient crop varieties that are better adapted to changing climatic conditions. Breeding and promoting drought-tolerant, heat-tolerant, and disease-resistant crop varieties can enhance the resilience of agricultural systems. By actively promoting and adopting climate-resilient crop varieties, farmers can increase agricultural productivity, improve food security, and enhance their capacity to adapt to the challenges posed by climate change. It is important to continuously monitor and update crop selections as climate conditions evolve, ensuring a dynamic and responsive approach to climate-smart agriculture.

1.6.3 Conservation Agriculture

Encourage conservation agriculture practices such as minimum tillage, crop residue retention, and cover cropping. These practices enhance soil health, reduce erosion, and help retain soil moisture, making agriculture more resilient to climate shocks. Conservation agriculture (CA) is a sustainable farming approach that aims to improve agricultural productivity, protect natural resources, and promote environmental sustainability. It involves three main principles: minimum soil disturbance (no-till or reduced tillage), permanent soil cover (mulching or cover cropping), and crop rotation or diversification. Conservation agriculture is designed to enhance soil health, conserve water, reduce erosion, and mitigate the negative impacts of agriculture on the environment. In CA, farmers minimize soil disturbance by avoiding or reducing conventional plowing. This helps preserve the soil structure, organic matter, and beneficial soil microorganisms. Reduced tillage also reduces soil erosion and carbon dioxide emissions from the soil. Adopting conservation agriculture practices requires a shift in farming techniques and mindset. Extension services, farmer training, and supportive policies are essential to encourage widespread adoption of conservation agriculture and to realize its numerous benefits for farmers and the environment.

1.6.4 Improved Water Management

Implement efficient water management techniques such as rainwater harvesting, drip irrigation, and micro-irrigation. These practices help conserve water resources and ensure more efficient use of available water during periods of water scarcity. Improved water management is a critical component of sustainable agriculture and is essential for addressing water scarcity, increasing agricultural productivity, and adapting to climate change. Implementing water-efficient irrigation techniques can significantly reduce water wastage and increase the efficiency of water use. Drip irrigation, sprinkler irrigation, and subsurface irrigation are examples of water-efficient irrigation methods that deliver water directly to the root zone, minimizing losses through evaporation or runoff. Improved water management in agriculture not only conserves a precious resource but also enhances agricultural productivity, food security, and resilience to climate change. Integrating water management with other sustainable agricultural practices ensures a holistic approach to sustainable and climate-smart farming.

1.6.5 Agroforestry and Afforestation

Integrate trees and forests into agricultural landscapes through agroforestry and afforestation initiatives. Trees can improve soil fertility, provide shade for crops, and contribute to carbon sequestration, thus mitigating climate change. Agroforestry and afforestation are two important practices that involve integrating trees and forests into agricultural landscapes (Nirola et al. 2015). Both approaches contribute to sustainable land use, environmental conservation, and climate change mitigation and adaptation. Both agroforestry and afforestation play essential roles in sustainable land management, environmental conservation, and climate change mitigation and adaptation. Integrating trees into agricultural landscapes and restoring forests on degraded lands contribute to a more resilient and sustainable future for agriculture and ecosystems alike.

1.6.6 Climate Information Services

Enhance the accessibility and usability of climate information services for farmers. Timely and accurate climate data, weather forecasts, and early warning systems can assist farmers in making informed decisions and adapting their agricultural practices accordingly. Climate Information Services (CIS) are systems that provide timely and relevant climate-related information to individuals, communities, and organizations. These services offer valuable data, forecasts, and advisories related to weather, climate patterns, and climate change impacts. The aim of climate information services is to help users make informed decisions, plan for climate variability, and build resilience to climate-related risks. Climate information services are crucial for supporting climate-resilient practices, disaster preparedness, and sustainable development. By providing timely and accurate information, these services empower individuals and communities to make informed decisions, adapt to climate variability, and reduce vulnerability to climate-related risks.

Climate-Smart Livestock Management: Encourage climate-smart livestock practices, such as improved feeding, breed selection, and manure management, to reduce methane emissions and enhance livestock productivity. Climate-smart livestock management refers to practices and strategies that aim to make livestock production more sustainable, resilient, and environmentally friendly in the face of climate change. Livestock farming is a significant contributor to greenhouse gas emissions and can be vulnerable to climate-related impacts. Climate-smart livestock management involves adopting practices that mitigate greenhouse gas emissions, enhance livestock productivity, and adapt to changing climate conditions. By adopting climate-smart livestock management practices, farmers can enhance the sustainability and productivity of livestock systems while reducing their environmental footprint. These practices not only contribute to climate change mitigation and adaptation but also support the livelihoods and resilience of livestock-dependent communities.

1.6.7 Community-Based Adaptation

Promote community-based approaches to adaptation by involving local farmers in decision-making and co-designing climate-smart agricultural strategies. This ensures that the solutions are context-specific and tailored to the needs of the communities. Community-Based Adaptation (CBA) is an approach to climate change adaptation that focuses on empowering local communities to identify, plan, and implement adaptation strategies that suit their unique needs, priorities, and vulnerabilities. CBA recognizes that communities, especially those in vulnerable and marginalized areas, are often the first to experience the impacts of climate change and are best positioned to design context-specific adaptation solutions. Community-based adaptation has proven to be effective in building resilience and enhancing the adaptive capacity of communities facing climate change impacts. It fosters a sense of ownership and empowerment among community members and promotes sustainable, context-specific, and people-centered adaptation measures. As climate change continues to pose challenges, CBA remains a crucial approach to ensure that adaptation efforts are both effective and inclusive.

1.6.8 Capacity Building and Training

Capacity building and training are essential components of sustainable development and effective response to various challenges, including climate change, poverty reduction, environmental protection, and social inclusion. These processes focus on enhancing the knowledge, skills, and abilities of individuals, organizations, and communities to tackle complex issues and drive positive change. Provide farmers with training and capacity-building programs on climate-smart agricultural practices. Extension services and knowledge-sharing platforms can play a crucial role in disseminating information and best practices. Capacity building and training are integral to achieving the United Nations Sustainable Development Goals (SDGs) and advancing climate change adaptation and mitigation efforts. These processes enable individuals and communities to build resilience, make sustainable choices, and contribute to positive social, economic, and environmental outcomes.

1.6.9 Policy Support and Incentives

Create an enabling policy environment with supportive regulations, incentives, and subsidies for adopting climate-smart agriculture. Governments can play a significant role in encouraging sustainable practices through targeted policies and financial support. Policy support and incentives play a crucial role in driving positive change, encouraging desired behaviors, and promoting the adoption of sustainable practices and actions. In the context of climate change, policy support and incentives are vital for advancing climate action, encouraging mitigation and adaptation efforts, and transitioning toward a more sustainable and low-carbon future. By providing policy support and incentives, governments can create an enabling environment for sustainable practices and climate action. These policies not only drive environmental benefits but also offer economic opportunities, promote innovation, and contribute to the overall well-being and prosperity of society.

1.6.10 Public-Private Partnerships

Public-private partnerships (PPPs) are collaborative arrangements between government entities (the public sector) and private companies or organizations (the private sector) to jointly address societal challenges, deliver public services, and implement development projects. These partnerships combine the strengths and resources of both sectors to achieve shared objectives and promote sustainable development (Smith & Myers, 2018). Foster collaboration between the public and private sectors to scale up climate-smart agriculture initiatives. Private sector involvement can bring in technology, innovation, and market linkages to support farmers' transition to climate-resilient practices. While PPPs offer numerous benefits, they also come with challenges, including potential conflicts of interest, risk allocation complexities, and the need for transparent governance and regulation. Therefore, it is essential to carefully design and manage PPPs to ensure that they deliver sustainable and equitable outcomes for society.

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An Insight on Different Climate Smart and Resilient Agricultural Practices

Anwesha Dey, Shubhi Patel, Avdhesh Sharma, and H. P. Singh

1 Introduction

Feeding the billions without stretching thin the natural resource base is a challenge to world agriculture. In the year 2020, 8.9% (nearly 690 million people) of the total global population fell under the hunger category and in near future, the problem will intensify as agriculture will be burdened to produce 70% more food by 2050 to fill the empty stomachs of an estimated 9 billion people (World Bank, n.d.; Barman et al., 2022). Disruption in agriculture due to climate change has been faced by farmers in every corner of the world. Eighty-four percent of the impact of extreme events like drought, flood, and heavy rainfall is borne by agriculture and its vulnerability to climate change has resulted in reduction in crop and livestock productivity, decrease in nutritional quality, increase in pest infestation, etc. (FAO, n.d.). By 2080, it is estimated that 5–26% of the global population will face undernourishment posing a serious threat to food security (Patel et al., 2021; Schmidhuber & Tubiello, 2007). In third-world countries, 22% of the total economic impact of climate change at all scales is borne by agriculture (FAO, n.d.) evident from consequences such as 15–25% reduction in agricultural income (Srinivasarao, 2021), 11% decrease in global crop yield, and 20% rise in average producers' price by 2050 (Nelson et al., 2014; Patel et al., 2021). Climate change has devastating effects on densely populated areas of developing nations in South Asia as they are

A. Dey (✉) · H. P. Singh
Department of Agricultural Economics, Institute of Agricultural Sciences, Banaras Hindu University, Varanasi, Uttar Pradesh, India

S. Patel
Narain College, Shikohabad, UP, India

A. Sharma
Narayan Institute of Agricultural Sciences, Gopal Narayan Singh University, Sasaram, Bihar, India

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envisioned to suffer ~20% loss in crop productivity by 2050 (Cairns et al., 2013; Chaudhary et al., 2016). In reverse, agriculture also adds to this adversity by producing 21–37% of total greenhouse gas emissions (Lynch et al., 2021; Mbow et al., 2019); the scenario worsens with the fact that one-third of the global food production is either wasted or lost adding to the danger of climate change (World Bank, n.d.). To combat this global menace, integration of finance and adaptation efforts through approaches such as climate-smart and climate-resilient agriculture is required.

2 Climate-Smart Agriculture versus Climate-Resilient Agriculture.

Climate-smart agriculture and climate-resilient agriculture are approaches to fight against the negative impacts of climate change. According to FAO, climate-smart agriculture is an integrated approach to transforming and reorienting agri-food systems based on three major objectives: increase agricultural productivity and incomes sustainably, reduce vulnerability to climate-related shocks by strengthening resilience against climate change, and reduce or eliminate greenhouse gases where possible. Thus, climate-smart agriculture leads to sustainable crop production, enhances adaptation, reduces the emission of greenhouse gases, and promotes food security and economic development (Jat et al., 2020; Lipper et al., 2014). On the other hand, climate-resilient agriculture is an adaptive and composite approach that encourages higher productivity through crop and livestock systems via sustainable use of natural resources. Both the agricultural approaches aim at methods that can endure both short and long-term shocks of climate change and ensure food security. The four better's that provide the base for these methods are better production, better nutrition, a better environment, and a better life for all without leaving no one behind (FAO, n.d.). These practices have the potential to reverse the current scenario and produce sustainably from the local to the global level, thus, reducing hunger and poverty for future generations (Srinivasarao, 2021). Thus, both climate-smart agriculture and climate-resilient agriculture are sustainable pathways to work towards resilience and food and nutrition security while curbing greenhouse gases.

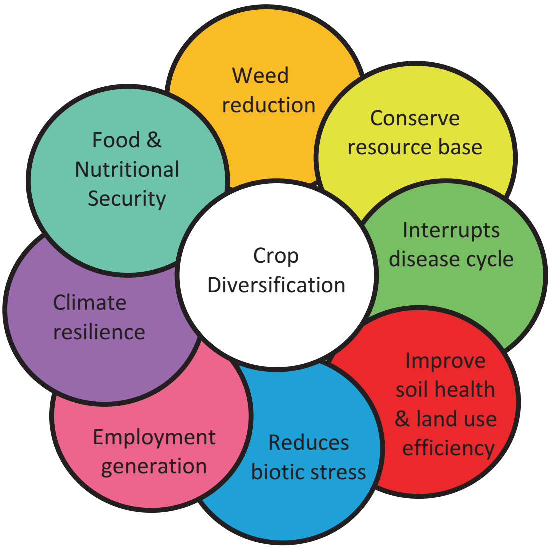
Agricultural systems have a complex and direct relationship with climate change. The rising climate variability has led to a shift in the average temperature range, uneven precipitation patterns, an increase in extreme weather events such as severe floods, prolonged droughts, storms, heat waves (Lakhran et al., 2017), and changes in cropping season which had a significant impact on crop productivity (Kiani et al., 2021). The other biophysical effects borne by agriculture are changes in nutrient cycle and soil moisture level, a shift in occurrence pattern of pests and pathogens, alteration in crop planting dates, and weak resilience of agroecosystems (Fuhrer, 2003; Kiani et al., 2021; Lin, 2011). Various mitigation strategies are adopted by farmers to face the climate change adversities; some of them under the rubric of climate-smart and -resilient agriculture are described below:

2.1 Crop Diversification

In the era of climate change, crop homogenization has jeopardized the global food and nutrition security scenario (Labeyrie et al., 2021). Current cropping technologies have resulted in wear and tear of the environment through loss of biodiversity, groundwater depletion and contamination, and rising levels of carbon dioxide in the atmosphere calling for serious attention to the dialectical connection between diversification and specialization (Barman et al., 2022). Diversification is a rationale, cost-effective, and widespread method used by farmers to cope with climate change effects (Fig. 1). The change in product (or enterprise) choice and input use decisions based on market forces and the principle of profit maximization is known as diversification (Lakhran et al., 2017). In other words, it is a transformation from a low-income generating cropping system to a higher profitable one. Crop diversification is a demand-driven, need-based situation-specific, region-specific, a dynamic, and iterative concept that incorporates spatial, temporal, value addition, and resource-complementary techniques (Barman et al., 2022; Singh et al., 2018).

Crop diversification refers to the addition of new crops or cropping systems to agricultural production taking into account the different returns from value-added crops with complementary marketing opportunities (Ignaciuk et al., 2018; Khanam et al., 2018). Crop diversification improves climate resilience in different ways such as by suppressing pest outbreaks and dampening pathogen transmission and by

Fig. 1 Basic concept of crop diversification



safeguarding crop production from future climate varsities (Lin, 2011). Thus, this cropping system has the potential to be a tool for climate resilience by improving the crop portfolio. There is a negative relationship between the level of diversification and the probability of being poor and undernourished (Anuja et al., 2022), making crop diversification the most relevant and affordable climate-resilient strategy for small and marginal farmers. For the proper functioning of agroecosystems, crop biodiversity acts as the link between stress and resilience (Heal, 2000; Lin, 2011). There are two different approaches to crop diversification namely horizontal and vertical diversification. The horizontal approach is the addition of more crops (or multiple cropping) carried through crop substitution and crop intensification process. This method is beneficial for small farmers as production increases due to amplified cropping intensities. Crop substitution is growing a different crop replacing the previous crop which was grown as a monoculture crop. This is necessary to break the trend and shift the farmers from growing staple cereal crops to diverse high-value horticultural and other minor cereal crops. It results in improved resource-use efficiency, higher income, interruption in the disease cycle, etc. Crop intensification is an increase in total production per unit of inputs used (such as land, labor, time, and cost) (FAO, n.d.). In other words, crop intensification is the addition of new value crops to the existing mono-cropping system to increase the overall productivity (Barman et al., 2022). On the other hand, the vertical approach is the production of crops along with degrees of industrialization. In other words, vertical diversification includes post-harvest activities such as processing, grading, packaging, and transporting to domestic as well as foreign markets. It also includes practicing other activities such as agro-forestry, bee-keeping, and dryland horticulture along with the main cropping system. Thus, to reduce the negative climate change impacts, crop diversification is a viable option keeping in mind the diverse agroecological scenario of the country which is suitable for growing several diverse crops such as oilseeds, fruits, vegetables, pulses, aromatic, and medicinal crops.

2.2 Conservation Agriculture

Climate change and its drastic effects have threatened agricultural productivity as agriculture is crucial for food security as well as economic development. Age-old traditional heavy tillage practices had not only resulted in decreased soil productivity but had been a prime contributor to the emission of greenhouse gasses such as methane and nitrous oxide resulting in anthropogenic climate change (Lynch et al., 2021). Carbon dioxide emitted from soils adds to this menace of human-driven agriculture (O'Dell et al., 2020; Smith, 2008). Thus, if not practiced sustainably, agriculture has the potential to cause heavy destruction to the environment and contribute to climate change. Conservation agriculture is an approach that ensures food security, conserves biodiversity and promotes economic growth. This method has the potential to reduce the global crop production system's greenhouse gases emission and enrich their role as carbon sinks through sequestration of soil organic carbon (UNEP, 2016; Chaudhary, 2016). Conservation agriculture is a bunch of crop management technologies that are widely known for promoting a boost in crop yield, reducing soil degradation and developing resilience against weather-induced stresses (Kassam et al., 2009; Powlson et al., 2016). The approach is based on three pillars: minimum tillage and soil disturbance, permanent soil covers with crop residues and live mulches, and diversification through crop rotation and intercropping (Hobbs, 2008; FAO, 2008; Stanojevic, 2021; Dey et al., 2022). Conservation agriculture has numerous benefits such as:

- Agronomic benefits—increase in soil organic matter, reduction in surface runoffs, replenishment of groundwater levels (Shrestha et al., 2020), enhancement in nutrient use efficiency and water use efficiency (Jat et al., 2012), reduction in weed incidence (Bhan & Behera, 2014), increase in crop production and yield and early sowing of crops (Malik et al., 2005).
- Economic benefits—low input cost, time and labor saving, low overall cost of production, and saving on fuel cost due to less use of machinery.
- Environmental benefits—conservation of resource base, reduces soil erosion, improves air and water quality, reduces carbon dioxide by carbon sequestration, helps to regenerate the lost biodiversity, reduces the emission of greenhouse gases, and develops resilience against climate change.

Globally, conservation agriculture is widely practiced over 12.5% of the world's total cropland (Dey et al., 2022) starting from the Arctic circle in the northern hemisphere to the Falkland Islands in the southern hemisphere, spreading over the tropics, to countries situated at 3000 m above sea-level and also over a wide range of climatic variations such as in dry regions with 250 mm to wetlands with 3000 mm rainfall (Friedrich et al., 2012; Kassam et al., 2019). Such wide adoption of this method demonstrates its potential to fight the challenges of climate change at the global level. Conservation agriculture is a collection of various kinds of technologies and practices, some of the major practices are discussed in Table 1.

2.3 Soil and Nutrient Management

Soil systems are critical to sustainable development as they play multifunctional roles such as biomass production, providing habitat to living organisms and gene pools, purification of air and water, reducing greenhouse gases emission, aiding carbon sequestration, protecting precipitation extremes, and providing the base to various recreational and cultural activities (Hamidov et al., 2018; Montanarella, 2015). Climate change directly or indirectly affects the soil systems. Climatic variations directly lead to changes in soil processes such as organic carbon transformations and nutrient cycling through changes in moisture levels and T regimes in the soil and a rise in soil erosion rate due to increased frequency of high-intensity rainfalls (Hamidov et al., 2018). To make agriculture more resilient to climate change, proper and responsible soil management is a necessity. Soil is the source of air,

Table 1 Different kinds of conservation agriculture technologies

Crop management technology	Method of practice	Advantages
Zero tillage/no tillage	Seeds are directly placed into the soil with previous crop stubbles without any prior land preparation.	Early planting, nutrient management, less weed incidence, better grain quality, less water requirement, reduction in air pollution caused due to burning of rice stubbles
Minimum tillage	Tillage activities are reduced by eliminating high-cost operations in two ways: Remove operations whose costs are more than the returns and combine the operations that can be carried out together.	Soil structure is improved; increment in water infiltration rate; facilitate smooth root growth; less soil compaction; reduced soil erosion by wind and water
Surface seeding	Seeds of Rabi cereal crop (usually wheat) are broadcasted on wet soil surface either before or after the standing Kharif crop (usually rice) is harvested.	No use of machinery saves fuel cost; condensed input use; suitable for any farm size; reduces irrigation water use; prevents weed infestation; doubles cropping intensity (in wheat)
Precision farming	Inputs are applied in precise amounts to soil and crop by the use of information technology.	Improves resource use efficiency; boosts agricultural productivity; reduces soil degradation; less use of chemicals for plant protection; improves water use efficiency; reduces in cost of cultivation
Bed planting	Raised beds and furrows are made manually or by bed planting machine after land preparation then seed & fertilizer are sown together on top of the bed and intercultural operations are done through furrows.	Easing growing of high-value crops like cotton, maize, wheat, and soybean; avoids wastage of irrigation water; decreased pest infestation; increased fertilizer use efficiency; promotes intercropping
Direct seeded rice	Paddy seeds are directly sown in the field thus eliminating the transplanting process.	Saves energy, time & cost; enhances water productivity; minimizes labor requirement; reduces greenhouse gas emission; promotes better growth of succeeding crops

water, and nutrients for the crop. Usually, the soils have their nutrient reservoir to provide both macro- and micronutrients to the plant but for better growth, they are often supplemented with external doses, that is, fertilizers (CTCN, 2016) to replenish the nutrient deficiency. To achieve sustainable food production, the balanced use of nutrient inputs from fertilizers is essential. To amplify the production levels, farmers use both mineral/inorganic and organic fertilizers. Inorganic/chemical fertilizers not only deteriorate soil health (Bayu, 2020) but also put additional monetary pressure on farmers. To mitigate the negative impacts of fertilizers on the environment and to diminish the threats of climate change, Integrated Nutrient Management (INM) is the key. Integrated Nutrient Management is a holistic approach to obtaining the desired level of crop productivity through maintenance of soil fertility and plant nutrient supply up to optimum levels (Lamessa, 2016; Mahajan & Gupta, 2009). In other words, it is the technique of using balanced dose of both organic and inorganic fertilizers mixed with some specific microorganisms to increase the nutrient availability to the crop and reduce soil pollution (Selim, 2020). The prime components of INM are inorganic fertilizers, organic manures, crop residues, legumes, and bio-fertilizers (Mahajan & Gupta, 2009). A detailed summary of all the components is stated below:

- *Fertilizers*—fertilizers are a key component of INM. With rising demand for food fertilizer consumption had scaled up to supply large amounts of nutrients in intensive farming systems (Mahajan & Gupta, 2009). Thus, the quickest way to sustainably boost crop production levels is use of chemical fertilizers in balanced ratio and recommended amounts. Plants only utilize 30–40% of the nutrients supplied (i.e., 30–50% nitrogen, 15–20% phosphorus, and < 5% micronutrients) (Vinay et al., 2020); rest substantial amount is lost through various pathways like leaching, surface run-off, volatilization, denitrification, soil erosion, and the fixation mechanism in soil (Mahajan & Gupta, 2009). Lone use of chemical fertilizers for long-term results in poor soil health (Mahajan et al., 2002); thus, an ideal way to enhance soil health as well as crop productivity is through integration of fertilizers with organic manures, compost, biofertilizers, etc.
- *Organic manures*—organic manures are made from plant residues and animal wastes. Various kinds of organic manures such as compost, FYM, vermicomposting, biogas slurry, edible and non-edible oil cakes, sewage sludge, human excreta, pressmud, and other agro-industrial wastes have immense nutrient potential (Sharma et al., 2016). In comparison to inorganic fertilizers, organic manures directly affect plant growth without harming the soil biome. Traditionally compost and FYM have been used in bulk to maintain soil fertility and ensure yield stability. The rising cost of fertilizers and their limited supply have raised the need to find renewable alternatives leading to major interest in organic manures. Improvement in soil's physical, chemical, and biological properties due to proper balanced supply of macro and micronutrients is achieved through organics. Integration of different organic sources with inorganics depending on their availability in different cropping systems leads to improved water holding capacity, better nutrient supply to plant, enhanced soil organic matter, and higher yield.
- *Crop residues*—crop residues have several other uses such as feed for the livestock, etc.; so their availability for INM may not be continuous. Nowadays, burning of crop residues is a major problem that destroys the plant nutrients and also cause destruction to the environment through pollution. In regions where harvesting is done through machinery crop residues are left in the field adding to the nutrient pool through the decomposition process. Practically a huge amount of residues of crops like vegetables, potato, and sugarcane goes wasted; these residues could be an excellent source of nutrients to plants as well as provide stability to soil. If the cereal crop residue is in excess it can be used as a component of INM in addition to its use as a cattle feed (Vinay et al., 2020). In manual

harvesting, the stubbles left in field range from 0.5 to 1.5 t/ha varying from crop to crop; the amount increases in case of mechanical harvesting (Sharma et al., 2016). Thus, crop residues are key ingredient in the nutrient recycling process.

- *Legumes*—Nitrogen plays a crucial role in the development of plants as it ensures energy availability within the plant to optimize yield. For several years, legumes in symbiotic collaboration with nitrogen-fixing bacteria convert atmospheric nitrogen into its usable forms, and this process is known as nitrogen fixation. Legumes is a multipurpose crop used for both food and fodder as well as for green manuring. Grown in any form, legumes adds to the yield productivity and replenish nitrogen levels in soil.
- *Biofertilizers*—Biofertilizers are materials containing living microorganisms that promote growth when applied to seed, plant surface or soil through processes such as nitrogen fixation, potassium and phosphorus solubilization, excretion of phytohormones, production of phytopathogen suppressing substances, protecting plants from abiotic and biotic stresses, and detoxification of underground pollutants (Macik et al., 2020). They promote growth by enhancing plant nutrient uptake by colonizing the rhizosphere, improve supply of nutrients, and increase accessibility of nutrients to plant root hairs resulting in increased root biomass (Dasgupta et al., 2021; Vessey, 2003). Biofertilizers are non-toxic alternatives to chemical fertilizers. Nitrogen fixation is done by bacteria like *Rhizobium, Azospirillum, Bradyrhizobium,* and *Azotobacter* (Wagner, 2011); phosphorus solubilization is carried out by bacterial cultures like *Pseudomonas, Bacillus, Micrococcus,* and *Fusarium* (Saritha & Tollamadugu, 2019). The symbiotic association of rhizobia-legume fixes nitrogen up to 100–300 kg/ha in a single crop season (Sharma et al., 2016).

2.4 Water Management

Water is a renewable resource that is crucial for the survival of all living organisms on this planet, but the availability of this resource is scarce in recent times. Climate change affects the hydrological cycle and its components in many dimensions such as variations in patterns and intensity of precipitation; rise in atmospheric humidity; increased evaporation rate; changes in soil moisture level (Bates et al., 2008; Hoanh et al., 2016; Rao et al., 2011); rise in sea level; and melting of ice leading to extreme weather events such as floods and droughts (Mostafa et al., 2021). By the 2050s, the area under water stress will increase at twice rate than the area under decreasing water stress (Hoanh et al., 2016). According to FAO, for producing food for an individual around 3000 L of water is required, out of which 1500 L is used for production of plant-based food. Agriculture withdraws 70% of the total water available for use (Chartzoulakis & Bertaki, 2015; UN Water, 2009). With the necessity to increase food production, irrigated agriculture will also grow along with rain-fed agriculture, ensuring increased water use. Over-extraction of groundwater not only depletes the groundwater levels but also increases carbon emissions. Both forms of agriculture bear the negative effects of climate change, water availability in rain-fed agriculture varies with the changed rainfall, and temperature pattern, whereas irrigated agriculture faces the additional risk of varying groundwater levels (Hoanh et al., 2016). Thus, there is an urgent need for sustainable water management which ensures to match the quantity of water needed with water available in a particular space and time at reasonable cost without deteriorating the environment. Chartzoulakis and Bertaki (2015) enlisted some water management methods which are discussed below:

- Localized irrigation is an approach in which water is supplied from plant to plant and is an efficient method of irrigation, and the method includes drip irrigation and sprinkler irrigation. In drip irrigation, water is slowly dripped into the soil wetting the area where roots grow, water comes out at a rate of 2–20 L/hour through small outlets in plastic pipes known as emitters (FAO, n.d.). In sprinkler irrigation, water is discharged as rainfall under high pressure that wets the whole soil profile. For more efficient water application, microsprinklers are used to spray water over the soil surface surrounding the plant at a rate of 12–200 L/hour (Chartzoulakis & Bertaki, 2015). Localized irrigation methods save water wastage during and after water discharge, reduce irrigation costs, improve water-use efficiency, and amplify the yields.
- Irrigation scheduling is the process of decision-making on when to give irrigation and how much water should be given. It aims to achieve the dual goal of enhancing agricultural production and water conservation. The factors that determine the irrigation scheduling are soil-crop characteristics (water holding capacity of soil, crops' water requirements, and rate of infiltration), climate (precipitation pattern, temperature, and evaporation rate), irrigation practices (irrigation method, amount of water available and water delivery systems), and management (technical support to farmers from experts). Water scheduling has numerous advantages such as deep percolation of fertilizers and agro-chemicals to the root zone, saves water by avoiding water-logging, maintains optimum growth of plant due to proper maintenance of soil water conditions, and avoids saline water table to rise.
- Fertigation is a modern-day agricultural practice of applying fertilizers, soil amendments, and other water-soluble products together through the irrigation system. This method has several benefits over the traditional broadcasting method, such as frequent nutrient supply to plants due to improved nutrient concentration in soil, effective and précised nutrient application as crops' requirements, nutrients can be applied when soil and crop conditions are appropriate otherwise entry can be restricted (Kafkafi & Kant, 2005), and it also reduces the chance of plant salt injury (Machado & Serralheiro, 2020).
- Deficit irrigation is a water management strategy that is prevalent in semi-arid and arid regions where the water available for agriculture reduces due to its need for other purposes. The method involves application of seasonal water to the crop only during moisture-sensitive growth stages in a controlled manner to optimize water uptake by the crop. This method enables effective and rational use of water.

Deficit irrigation is further carried out in two ways: regulated deficit irrigation and partial root drying.

- Subsurface drip irrigation is suitable irrigation system for arid areas. In this method, irrigation is applied through network of pipes laid under the soil surface; the depth of the laterals depends on the crop to be irrigated and the tillage practices. This method is more water efficient in comparison to conventional drip irrigation system. The major advantages of this system are uniform water application under high degree of control, reduced evaporation, minimized water loss due to run-offs, maintenance of optimum soil moisture level, and preventing airborne drifts.

2.5 *Integrated Pest Management*

Globally, 40% of the total crop production is annually lost due to pest infestation which costs about $220 billion (FAO, 2021). These losses are estimated to increase due to climate change effect on crop production, as any change in the host plant species directly impacts the insects that feed and thrive on them (Skendžić et al., 2021). Climate change events such as global warming are predicted to cause major changes in the geographical distribution and population dynamics of the insect, insect–host interactions, altered profiles of pollinators/scavengers, reduced activity and abundance of biological enemies, effects on expression of resistance to insect pests, reduced efficacy of bio-pesticides and chemical insecticides (ICRISAT, n.d.), increased survival rate during extreme winters, changed interspecific interactions, higher risk of invasion by migratory pests, and rise in the incidence of insect-transmitted plant diseases (Skendžić et al., 2021). Thus, rise in pest infestation leads to high economic losses along with challenging food security. Integrated pest management (IPM) is the key to mitigate the impact of climate change on insect pests by reducing their invasion. Integrated pest management is a long-term ecosystem and effective approach that relies on the combination of chemical, cultural, mechanical and biological methods to control insect pests to optimize agricultural production. The different tools of IPM are briefly discussed below:

2.5.1 Cultural Methods

Cultural methods are a non-chemical management strategy to destroy the pest establishment by altering the soil and crop environment. These methods include regularly practiced farm operations to eliminate the pests by either killing the pests or by destroying their habitat to prevent them from causing destruction. These control methods are based on the biology of the pest and its development. Some of the popular cultural methods employed by the farmers are: removal of previously infested plant debris, soil treatment, summer ploughing, adjusting the sowing and harvesting time to avoid the peak season of particular pest attack, crop rotation with non-host crops, maintaining proper plant space, selecting and planting resistant varieties, avoiding excess fertilizer use, proper water and weed management, practicing intercropping or mixed cropping, growing trap crops on sides of fields, harvesting near to the ground surface to avoid infestation for next cropping season, and removinge the infected part during pruning.

2.5.2 Mechanical Methods

These are physical methods to reduce the population of desired pest in order to protect the crop. Various mechanical control methods are used, and some of the major ones are handpicking and removing the insects or other toxic materials; use of hand nets and bag nets to catch adult insects such as green leaf hoppers, grasshoppers, and rice hispa; beating household insects like houseflies, cockroaches with broomsticks or paper or killing insects like rhinoceros beetle by hooking via crooked hooks; installation of bird perchers; use of pheromone traps; use of light traps; use of rope for dislodging larvae on the leaves, etc.

2.5.3 Biological Methods

Biological control methods are significant tools of IPM. In this biocontrol method, natural enemies of pests are used to eliminate them. In other words, predators, parasitoids, pathogens, and weed-feeders are used to kill and maintain the pest population below the desired level to reduce the economic loss. Parasitoids are living organisms that lay eggs in or on host bodies and complete their life cycle on the host, which ultimately results in the death of the host pest. Examples of parasitoids are *Trichogramma, Pseudogonotopus*. Predators are organisms that kill and feed on other living organisms. Examples of predators are ladybird beetles, spider, and dragon flies. Bio-pesticides are comprised of pathogens that are responsible for infesting and causing diseases in their host pests and killing them. Examples of biopesticides are *Metarhizium*, nuclear polyhedrosis virus (NPV), and *Bacillus thuringiensis*.

2.5.4 Chemical Methods

Chemical pesticide use is the last step in pest management. These methods are employed at last when all the above control methods fail to control the pest population. Use of pesticides in a sustainable way can be practiced by judicious, need-based application of pesticides after proper pest surveillance to minimize the economic loss. Spraying of pesticides should be done after considering what, when, where, and how to spray. Use of safer pesticides such as neem-based pesticides or biopesticides that will have less harmful effects on the crop environment should be promoted.

2.6 Crop Improvement

The rising global demand for food security has put pressure on crop productivity in two major ways: one is meeting the calorific as well as nutritional needs together and second developing resilience to climate change (Mohd. Saad et al., 2021). If the productivity of major cereals grown across the globe, that is, wheat, rice, maize, and soy, increases then they will be capable to meet only two-thirds of the total calorie consumption needs despite boosted production levels in the past few decades (FAO, 2017). Plant breeding is a holistic approach of crop improvement that involves selecting the wild relatives for transferring a particular trait over years of the continuous selection process (Razaq et al., 2021). Quality seeds and planting materials obtained from well-adapted varieties are the first step in climate-smart crop production (FAO, 2011). Breeding methods that include multilocational trials are carried out to develop climate change–resistant crop varieties that are more resource efficient. Climate-resilient crops with the ability to withstand broad-spectrum extreme events such as floods, droughts, heat, salinity, and pests are the need of the hour (Kole et al., 2015). Molecular breeding is the modern plant breeding technique in which gene(s) with desirable genetic modification or specific trait are inserted into the plant. Genetically modified crops are the outcomes of modern genetic engineering methods which involve transfer of DNA into plant cells. The prime purpose of these modification is to develop resistance against some pests, pathogens, environmental extremity, or particular chemicals. Some of the famous examples of genetically modified crops are Bt cotton, Bt brinjal, GM mustard, and potato (protein-rich potato).

3 Conclusion

Our current food system is bestowed with the duty to feed as well as provide livelihood to a population of more than 1 billion (Mbow et al., 2019). Climate change is a long-term threat to mankind as it has already begun to affect the food and nutritional security of the planet through rising temperatures, fluctuating precipitation patterns, and increased frequency of extreme events. Agriculture is a prime contributor to greenhouse gas emissions, but indeed it is the key to global climate change responses. Climate-smart and climate-resilient agriculture are holistic approaches to amplify food production sustainably. They are basically a cluster of agricultural practices that ensure food and nutritional security while curbing the adversities of climate change. These practices majorly include crop diversification, conservation agriculture, soil and nutrient management, water management, integrated pest management, and crop improvement; all these practices are pathways to overturn the current scenario by providing healthy food and environment to our future generation. Protecting our natural resource base, particularly soil and water, can directly impact our small and marginal farmers both socially and economically.

Thus, climate-smart agriculture is an interlinked approach to manage the growing food demand by connecting the climate change resilience, sustainable increase of agricultural production and incomes, and greenhouse gas reduction into the same thread.

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Soil Management in Sustainable Agriculture: Principles and Techniques

Dipti Grover, Ajay Kumar Mishra, Pinki Rani, Neha Kalonia, Anjali Chaudhary, and Sheetal Sharma

1 Introduction

Soil is not a renewable natural resource, as forming a centimeter of soil may take hundreds of years. So, the soil is a complex ecosystem where microorganisms and plant roots work to bind organic matter and mineral particles into a dynamic framework that controls nutrients, air, and water. "A healthy soil should be capable of supporting life processes such as plant anchorage and nutrient supply, retain optimal water and soil properties, support soil food webs, recycle nutrients, maintain microbial diversity, remediate pollutants, sequester heavy metals, and contribute to disease suppression" (Hooks & Wang, 2010). Healthy soil is the foundation for profitable, productive, and environmentally sound agricultural systems. The major challenge is maintaining soil health with sustainable food production for the ever-increasing population. Sustainable management of soils is crucial for improving global food security because it is the most fundamental resource. To satisfy the demands of the expanding population and shifting dietary preferences towards animal-based over plant-based foods, food production must double between 2005 and 2050. Better soil management offers a low-cost solution for all the challenges

D. Grover · P. Rani · N. Kalonia
Institute of Environmental Studies, Kurukshetra University, Haryana, India

A. K. Mishra (✉)
International Rice Research Institute South Asia Regional Centre (ISARC), Varanasi, Uttar Pradesh, India
e-mail: a.k.mishra@irri.org

A. Chaudhary
School of Interdisciplinary and Transdisciplinary Studies (SOITS), Indira Gandhi National Open University (IGNOU), Delhi, India

S. Sharma
International Rice Research Institute, Delhi, India

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that hinder food security. Crop productivity, environmental sustainability, and human health are all directly and indirectly impacted by soil management. The management of soils will be more crucial than ever in the upcoming years due to the anticipated rise in the global population and the resulting need to intensify food output.

Soil management affects the soil's nature, properties, processes and functions. It is possible to design a crop and soil water management system that enhances and sustains soil health over time by understanding how management practices impact the soil processes that support plant growth and regulate environmental quality. Farming operations can do soil management like amendments in soil and optimizing soil health and adopting soil management strategies. Farming operations include precise/site-specific nutrient management, precision agriculture, soil amendments to improve soil productivity by biochar, specific nutrient amendment, straw incorporation, and biological and hydrological amendments (Kumar et al., 2022). To optimize soil health, first identify the workability and trafficability of soil to enhance agricultural productivity. Adopting soil conservation techniques, such as crop rotation, cover cropping, establishing windbreaks, contour farming, and strip cropping, along with integrated pest management, bank stabilization, and sediment control, is vital. Additionally, embracing conservation tillage, effective crop residue management, and advanced digital technologies for crop monitoring significantly enhances sustainable agricultural practices (Mishra et al., 2018). These conservational practices are region-specific and site-specific. So, site-specific nutrient management and conservational strategies should be adopted (Mishra et al., 2021b). Today's agricultural technologies may increase productivity to meet world food demand, but they may also threaten agricultural ecosystems by intensifying pesticides (Mishra et al., 2021a). Certain agricultural practices like crop residue burning affect the air quality (Grover & Chaudhry, 2019), soil quality and human health (Grover et al., 2015). Such faulty agricultural practices need to be managed.

Above all, sustainable management approaches showed the potential to increase soil carbon and improve nutrient and water use efficiencies (Chaudhary et al., 2022). All the management strategies have variant effects on SOC (soil organic carbon) accumulation and climate change adaptation. Increases in mean temperature, changes in rain patterns, increased frequency and intensity of extreme events, sea level rise and salinization, and disturbance in ecosystems are all apparent signs of climate change and environmental stresses, which significantly impact agriculture globally (HLPE, 2012; Thornton, 2012). Agriculture land is a significant source of all three biogenic GHGs: carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). Soils contribute a significant share (37%, mainly as N_2O and CH_4) of agricultural emissions (Tubiello et al., 2015), while land use contributes 25% of the total global anthropogenic GHG emission (Smith et al., 2014). Agriculture is facing a severe climate change. When soil quality is restored, extreme events (like drought, heat waves, and flooding) and unpredictable and variable climates can be more easily resisted by the soil. In order to reduce the risks of a changing environment, adaptation is essential. Implementing agricultural methods that lessen risks and take advantage of any new opportunities that may result from climate change is necessary.

Agricultural soil management is quite diverse, develops over time and is continuously adapted, driven by socio-economic, biophysical and technological factors. Agricultural systems are shifting to degenerative agricultural methods as a result of intensive and exhausting resource exploitation, soil nutrient mining, rising cultivation expenses, and the cropping system's contribution to greenhouse gas emissions (Mishra et al., 2021a, 2022a). To address these challenges, soil research must identify research challenges and conduct systemic and interdisciplinary studies.

2 Emerging Challenges in Soil Management

The functioning of novel management practices involves multiple spatial scales, from the microbiome to the landscape level, creating knowledge gaps and challenging soil study (Ludwig et al., 2018). Soil management depends upon the root-soil interface, nutrient uptake, water uptake and accessibility, and pest regulation. Moreover, it also depends on root crops competing for water, energy, and nutrients aboveground and in the soil and the arrangement of the crops, such as agriculture, agroforestry or agri-silviculture (Giri et al., 2019). So, in the same way, strategies and management practices may vary according to agroecology, geographics, and physico-chemical and social conditions. In this chapter, we have highlighted key challenges and prospects of soil health management (Fig. 1).

2.1 Human Growth and Food Security

At around 7 billion people, the world's population is expected to increase exponentially to about 9 billion people by 2050. So, the major confront is to feed the ever-increasing population and attain sustainable hunger and food security goals in the present scenario. Only 10–12% of natural soils are suitable for agriculture. It is a big challenge to attain food security with such a vast population. About 75% of the world's population is estimated to be deficient in one or more essential minerals. At the same time, 2 billion people experience nutritional deficiencies that result in a variety of diseases or concealed hunger (Gebrehiwot et al., 2022). All that is because of soil degradation, so now it is high time to conserve the soil and make it healthier and only then food security issues can be resolved. The year 2015 was designated as the International Year of Soils. The motto "Healthy soils for a healthy life" emphasizes soil's significance for food security, economic development, and critical ecosystem functions. Their objectives are directly or tangentially related to soil sustainability (Hurni et al., 2015). The situation will worsen if serious actions are not taken to mitigate soil threats with the urgent need to ensure food security and eliminate hunger and nutrition. It is crucial to involve in soil management practices actively. The full potential of soil should now be unlocked to address problems with food security and others like providing clean water, preserving biodiversity, sequestering carbon, and boosting climate change resilience.

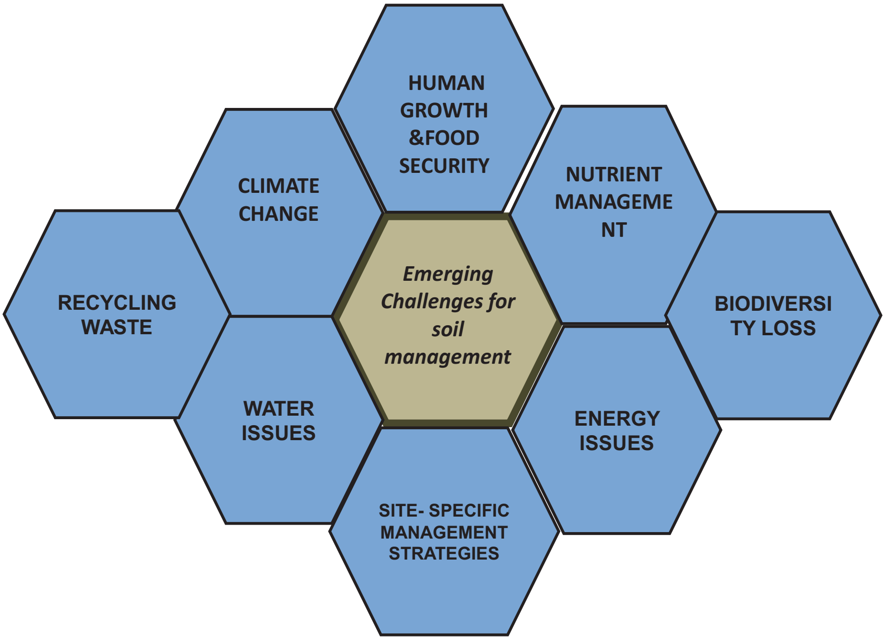

Fig. 1 Emerging challenges and constraints for soil management

2.2 Impact of Climate Change on Soil Health

Climate change will have a far-reaching impact on soil, water and crop nexus. Soil parameters such as soil organic pool, available water capacity, soil fertility, soil salinity, and erosion and crop parameters such as crop strands, plant pests and disease, and productivity grain quality directly affect the food production system. Indirect impacts due to changes in agricultural productivity, shifting in the growing season, post-harvest losses, land use patterns, and distribution of food commodities on the cropping system are likely to be affected (Mishra et al., 2022a). The regularity and severity of cyclones, floods, hailstorms, and droughts may hamper crop yields and regional food supplies. Additionally, the intensity and magnitude of soil degradation are increasing drastically at the global scale and are attributed to several anthropogenic factors (Fig. 2).

Soil ecosystem has a significant role in the world carbon budget and regulation of greenhouse gases. If the world's soil is not revitalized, it could discharge 850 billion tons of carbon dioxide into the atmosphere, adding to climate change, as carbon stored in soil is three times that in living plants and two times in the atmosphere. Improved soil management practices reduce GHG emissions and sequester carbon, increasing soil organic matter (SOM) content and tightening the soil's nutrient cycle. This improves fertility and productivity, increases soil biodiversity, and can help build resistance to the harmful effects of climate change (Mishra et al., 2022b). So, many countries are adopting climate-smart agriculture practices to adapt and mitigate climate change.

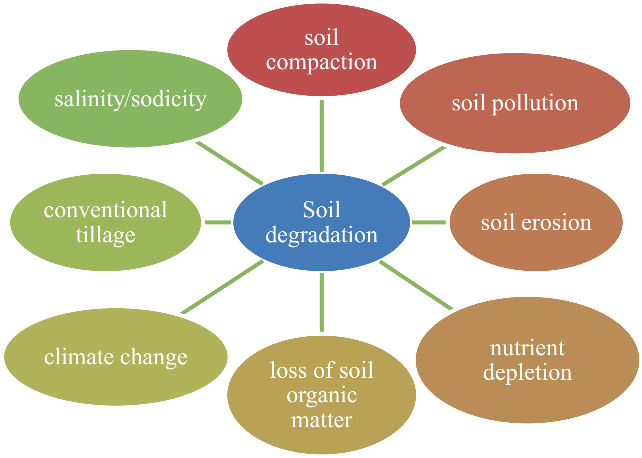

Fig. 2 Anthropogenic causes of soil degradation leading to reduced productivity and profitability

2.3 *Water Challenges*

The current changing climate scenario significantly affects the hydrological cycle. Environmental resources have been experiencing significant stress, especially in water and soil degradation in various regions all around the globe. In such a situation, water productivity and security must be increased so crop damage can be prevented under extreme climatic conditions. Hydrological extremes (floods, drought, soil/water erosion) significantly affect soil and crop productivity. Depleted soils are unable to absorb and regulate water flows. Lack of water retention leads to water scarcity, droughts and floods. Organic matter can retain up to 90% of its weight in water, which it releases gradually. This characteristic is particularly beneficial in drought-prone areas. However, the decreasing levels of SOC are exacerbating drought conditions. Additionally, enhancing farm water use efficiency by carefully managing soil disturbance, optimizing plant populations, and efficiently managing nutrient pools can further mitigate these challenges (Hatfield & Dold, 2019; Passioura & Angus, 2010).

2.4 *Nutrient Management*

Nutrient management involves carefully regulating all nutrient sources to prevent unintended yield increases. This includes the management of fertilizers, organic manures, recyclable waste materials rich in nutrients, soil reserves, and processes like biological nitrogen fixation and biofertilizers. In addition, every effort is made to reduce nutrient losses to the environment. The intake of soil nutrients and crop needs must be balanced. The crop will yield its highest potential if the nutrients are applied properly and in sufficient amounts. Numerous factors affect the uptake of nutrients by plants. Ions might be readily available to roots or could be "bound" by other substances or within the soil matrix, influencing their accessibility. Alkaline or acidic soils with pH levels that are too high or low prevent plants from accessing certain elements (Mishra et al., 2021b). In order to slow down climate change, nutrient management decreases methane (CH_4) emissions from rice production and improves carbon sequestration in agricultural soils (IFPRI, 2009). The soil's biological, chemical, and physical characteristics that are impacted by the local soil degradation processes also affect soil fertility and plant nutrient availability. It is crucial to comprehend these interactions and processes to maximize plant nutrient availability and reduce nutrient losses to the ecosystem. Nutrients in the soil are depleted as plants are removed from an area or soil sediments are transported elsewhere (Halvin et al., 2014). Depleting nutrient stock in the soil is a significant but hidden form of land degradation.

It is frequently advised to use integrated nutrient management (INM) techniques to maintain soil nutrients and health (Baruah & Baruah, 2015). Additionally, it improves agronomic productivity (Wu et al., 2020), which has been suggested as a successful alternative method for producing sustainable crops (Navarro-Noya et al., 2013, Zhang et al., 2018). Whether a substance is a poison or medicine, the destiny of the recipient depends on the dosage. Therefore, the exact application of fertilizer and pesticides (site-specific nutrient management) is essential for sustainable agriculture.

2.5 Energy Challenge

Energy is an essential component of agriculture. We have to manage our lands to accommodate increasing demands with various other challenges like changing climate affecting agricultural production. In agriculture, a range of energy-intensive processes are involved, excluding the fuel-dependent agricultural equipment used for irrigation, transportation of produce, livestock maintenance, and food processing. These processes include intensive tillage, chemical fertilizers and pesticides, indiscriminate water management practices, and burning crop biomass (Kumar et al., 2022). Now, it is essential to adopt energy-efficient agriculture management practices. This will help to achieve and maintain the balance. As fossil energy sources diminish, the need for plant-based liquid fuel will increase. Plant-based biofuels have become one of the most important strategies for reducing global warming while ensuring energy security. Typically made from grain maize or sugarcane, ethanol is the most common processed biofuel. For instance, more than 20% of the maize crop is used to make ethanol in the United States (Tollefson, 2008). A higher energy economy could be achieved with cellulose-based ethanol, but the technology is still in its infancy.

2.6 Soil Biodiversity

The diversity of underground life is represented by soil biodiversity, which interacts with plants and tiny animals to create a web of biological activity. Soil organisms drive the transformations of nutrients that make them available to plants. It helps improve water entry and storage, resistance to soil erosion, control soil pests and diseases and facilitate the recycling of organic matter in the soil. Soil biodiversity involves every transformation of carbon and nitrogen. It is challenging to pinpoint the various feedback responses of soil microbes to global warming as it contributes to the emission of greenhouse gases and sequestering carbon and fixing nitrogen (Khursheed, 2016).

Soil biodiversity is sensitive to agricultural practices (intensive tillage, residue burning) and climatic parameters (temperature, humidity). So, its disturbance can create a significant problem with the soil ecosystem. To preserve biodiversity and its associated processes, it is essential to implement targeted strategies such as mulching, effective residue management, crop rotation, selecting appropriate crop species, and landscape management tailored to the specific characteristics of each site.

2.7 Recycling Wastes

Soils can be better used as biogeochemical reactors; soils are recycling agents and the soil benefits from the recycling. Decomposition in the soil can improve the soil's physical structure, supply the soil and plants with nutrients and promote an energy and substrate-loaded environment to host biodiversity (Barrios, 2007; Abiven et al., 2009). Animal wastes, green manures, and farm waste-derived products like biochar and compost are typically alkaline and have a high pH buffering capability, which can counteract soil acidification (Cai et al., 2021; Rayne & Aula, 2020). Additionally, the presence of basic cations like Mg^{2+} and Ca^{2+} and organic anions in these substances raises the pH of the soil (Cai et al., 2021). Agricultural wastes have long been known to improve soil health, including physical, chemical, and biological characteristics, and raise soil pH (Bhatt et al., 2019; Cai et al., 2021; Rayne & Aula, 2020). Plant residues enhance soil health and crop yield by regulating soil temperature, increasing soil moisture content, supporting soil microbial activities, and increasing the availability of nutrients. They also control weed growth and soil erosion (Chatterjee et al., 2017; Kader et al., 2017). Agricultural wastes, particularly agricultural residues, have long been regarded as a significant cause of pollution. Biomass burning has a substantial impact on the chemistry of the planet's atmosphere since there is a noticeable rise in concentrations of pollutants (SO_x, NO_x, and $PM_{2.5}$) in the agricultural residue burning season (Grover & Chaudhry, 2019). Burning agricultural waste may significantly add to the creation of atmospheric brown clouds in many Asian nations, impacting local air quality, atmospheric visibility, and the planet's climate (Mishra et al., 2014). There are many ways to turn agricultural waste into wealth, including growing green manure, mulching organic residues, composting, vermicomposting, energy conversion, pulp and paper formation, particle board and furniture preparation, green cutlery preparation, producing alcohol, biogas, and using biofuel, among many other cutting-edge uses.

2.8 Site-Specific Management Strategies

Crop output is affected by variations in soil texture, type, and other important elements within and between production areas, and these variations significantly impact management tactics. A uniform rate of input applications across the full field may therefore be expensive and underutilize the advantages. Agriculture site-specific management (SSM) is the variable management of crops and soils in response to localized field circumstances. SSM is a rapidly evolving group of technologies that allow farmers to manage their crops and soils as machinery traverses a field. Numerous other titles are also used for it, such as "Grid Farming," "Farming by Soils," or "Variable Rate Technology (VRT)." In essence, SSM is about doing the right thing, at the right time, in the right place, and in the right way. SSM, in basic terms, is a two-step process: the first involves assessing variability and the second deals with managing that variability. As a result, site-specific management techniques that use sensor-based and variable rate inputs can enhance environmental quality, soil health, and agricultural profitability.

Precision agriculture tools can handle variations in the production system to improve plant growth and crop yield. Applications would precisely use inputs' quantity, timing, and method based on variables in an ideal precision farming practice (management of a single plant). The type and quantity of nutrients can be determined by soil characteristics such as structure, texture, organic matter, and electrical conductivity (EC) (fertilizer need, irrigation scheduling, seeding rate, seeding depth). VRA and SSM are the techniques that modify input applications in response to soil variations.

3 Concept of Soil Management

Soil is a crucial resource that can be managed effectively to enhance or diminish its quality and productivity. In the soil's complex ecology, plant roots and living microorganisms bind organic matter and mineral particles into a dynamic framework that controls water, air, and nutrients. The cycling of nutrients, biological control of plant pests, and regulation of water and air supply are just a few functions healthy soil performs to support plant development. The interrelated biological, chemical and physical characteristics of soil affect these processes, and many of these characteristics are highly responsive to soil management techniques. Soil management is an integral part of land management and is coupled with different good

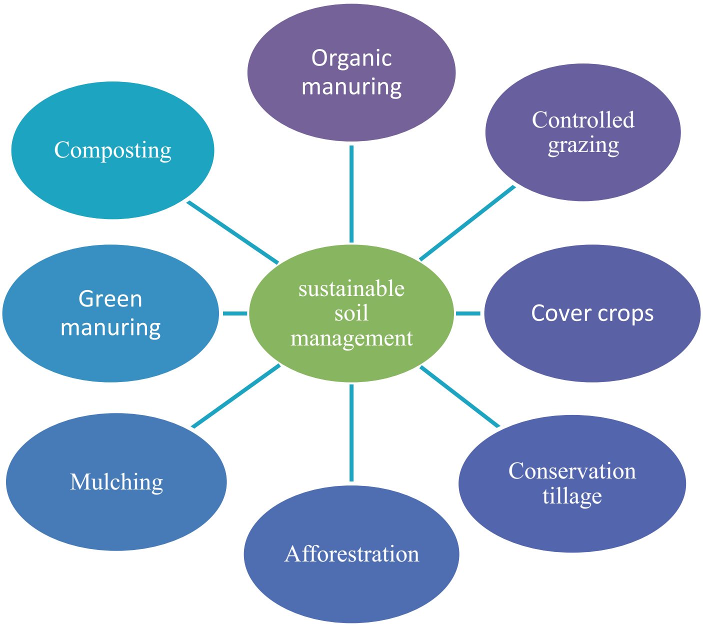

Fig. 3 Various soil management techniques that promote soil health and increase productivity and profitability

agricultural practices (Fig. 3). Defining specific interventions to enhance soil quality for a chosen land use involves considering the variations in soil types and their distinct characteristics. To preserve and safeguard soil resources, SSM practices are required. Sustainable soil management preserves or enhances the supporting, provisioning, regulating, and cultural functions that soil serves without substantially affecting the soil function that supports those functions or biodiversity. It is essential to strike an equilibrium between the regulating services for water availability, quality, and greenhouse gas composition and the supporting and provisioning services provided for plant production.

3.1 Principles to Improve Soil Health

(a) Reduce disturbance: There are many methods to disturb the soil from plows to hooves. While some disturbance is inevitable, reducing disturbance events across processes creates healthier soils. Limiting tillage, maximizing chemical intake, and rotating animals can accomplish this.
(b) Maximize soil cover: Increase soil cover by cultivating cover crops, applying organic mulch, and allowing plant debris to remain on the ground.

(c) Maximize biodiversity: Increasing diversity can help break the disease cycle, promote plant development, and provide habitat for soil organisms and pollinators. It can be accomplished by integrating livestock, using various crop rotations, and planting various cover crops.
(d) Maximize the presence of living roots: The nutrient-cycling creatures like earthworms and microbes are fed by living roots, which also help to prevent soil erosion.

3.2 Approaches for Soil Management

3.2.1 Soil Management by Conservation of Soil

The following measures are adopted for soil management by conservation of soil:

1. Crop rotations: The cultivation of various products in succession to prevent fallow land.
2. Agroforestry: The establishment of new forests or the growth of trees.
3. Synthetic soil conditioners: Polymers or soil additives utilized for improving soil aggregation.
4. Minimal soil disturbance for agricultural output through reduced or zero tillage.
5. Riparian buffers: Planting trees, shrubs, and grasses along the sides of rivers and streams to prevent land erosion.
6. Crops grown in fields to act as "cover crops" to stop soil erosion.
7. Natural or constructed vegetative buffers, such as vegetative filtration strips, can improve soil water permeation, filter sediments, and help recharge groundwater by filtering drainage water (Humberto & Lal, 2008).
8. Leaving crop residues in the ground is essential to maintain soil aggregates bound together through the root crowns.
9. Management of canopy cover: Covering the ground with the top or canopy of trees to protect it from wind and raindrop splashes.
10. Contouring: Planting vegetation to cover the slope, which might cut down on erosion losses by roughly 50%.
11. Mulching: The process of covering top soil with debris or plastic to increase soil carbon pools, reduce water and carbon dioxide losses, and increase soil productivity (Dumanski & Peiretti, 2013).

3.2.2 Soil Management by Soil Amendments

Any substance that helps to improve the soil's physical qualities—such as water retention, permeability, water infiltration, draining, aeration, and structure—can be used as a soil amendment. A few examples of physical alterations are subsoiling, heavy cultivating, sanding, horizon mixing, profile reversal, and trenching. These activities improve the soil's permeability. The deep plow is advantageous when gypsum or lime is in the ground (Ahmed et al., 2019).

In biological amendments, flowering crops like dhaincha (*Sesbania aculeata*) and kallar grass (*Leptochloa fusca*) are cultivated on problematic soils. The sodic soils undergo significant organic matter addition during restoration. Furthermore, efforts are made to incorporate straw and agricultural residues. With its 1 m-deep fibrous roots, kallar grass increases soil permeability and aeration while aiding in the leaching of soluble Na ions. The fibrous root system of kallar grass proliferates, and substantial amounts of organic matter are incorporated into the soil, which, in addition to improving physical conditions, causes the formation of organic acids. Other organic manures also enhance the physical properties of soil and generate organic acids (such as humic and fluvic acid), which aid in soil reclamation.

Gypsum, calcium carbonate, phospho-gypsum, and other direct and secondary calcium suppliers: Elemental sulfur, sulfuric acid, pyrites, and $FeSO_4$ gypsum are among the most widely utilized chemical amendments for providing calcium, primarily sourced from gypsum, calcium carbonate, and phospho-gypsum, along with other direct and secondary calcium suppliers. Calcium carbonate is intractable and useless in calcareous sodic soils (where $CaCO_3$ has already precipitated). However, it can be used in non-calcareous sodic soils (where $CaCO_3$ has not yet precipitated) because the soil pH there is low, which encourages the solubilization of $CaCO_3$. Calcareous sodic soils also use some secondary sources of calcium, such as elemental sulfur, sulfuric acid, and iron sulfate. Applying these materials causes the precipitated $CaCO_3$ in sodic soils to dissolve, releasing Ca for restoration (Latha & Janaki, 2020).

For the effective reclamation of salty or sodic soils, leaching and drainage are crucial conditions in hydrological amendments. Artificial draining is not needed if the soils are permeable, but this is uncommon in saline-sodic soils. Utilizing tube wells to create vertical drainage, horizontal drainage, tile drainage, and surface drainage are some drainage methods used for soil reclamation (Shankar & Evelin, 2019).

4 Key Practices for Better Soil Management

4.1 Sustainable Intensification

The only way to achieve sustainable intensification (SI), which entails producing more from less by decreasing losses and improving use efficiency, is by enhancing soil quality, including chemical quality or soil fertility. Although it is not the only method of boosting soil fertility, integrated nutrient management is a successful strategy for accomplishing SI. In many developing nations, nutrient depletion and declining soil fertility are the leading causes of poor productivity. Utilizing organic

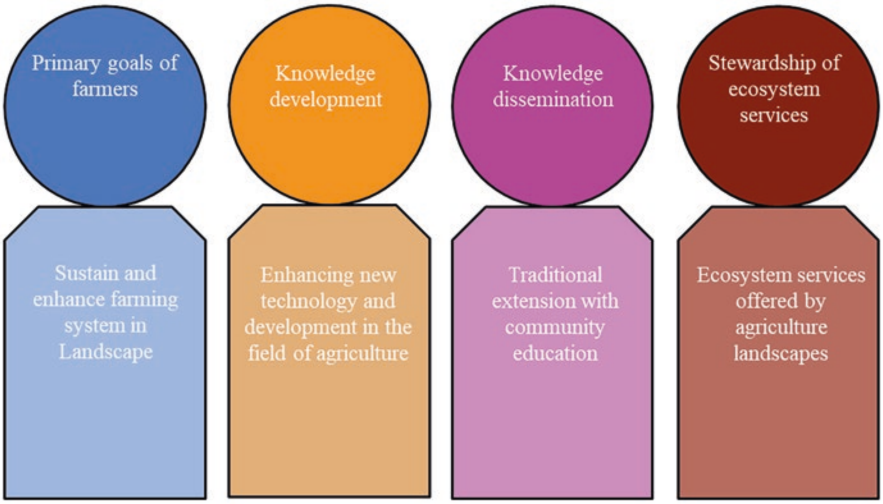

Fig. 4 Approaches for sustainable intensification

amendments made from recycled organic refuse, such as urban waste, is a practical way to increase soil fertility and aggregate structural stability. SI can be achieved through a participatory approach and capacity building (Fig. 4).

4.2 Soil Restoration and Its Significance

Improving compacted soils' porosity and nutrient retention is known as soil restoration (SR). The process includes mechanical loosening through tilling, biological enrichment using macro and micro-soil organisms, combined biological and mechanical aeration, cultivation of dense vegetation, and the application of soil amendments. Urban soils disturbed and compacted must have mature compost distributed and mixed in.

4.2.1 Strategies for Soil Quality Restoration

The following are three basic strategies for restoring soil quality (Fig. 5):

1. Minimizing losses from the pedosphere or soil solum.
2. Creating a positive soil C budget while enhancing biodiversity.
3. Strengthening water and elemental cycling.

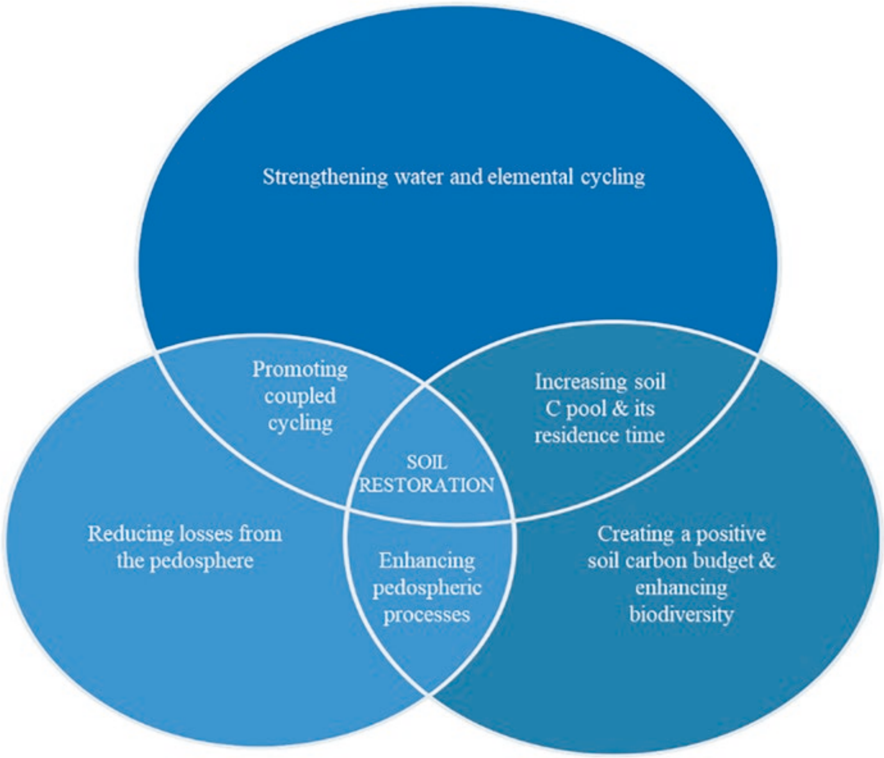

Fig. 5 Significance of soil restoration in escalating soil health

4.3 Soil Organic Matter Management

According to Dexter et al. (2008) and Schjnning et al. (2012), soil organic carbon (SOC) is essential for determining and sustaining the physical conditions and functions of soil. SOC, which manifests as soil organic matter (SOM), affects plant nutrient fluxes and, consequently, the agronomic yield of soils (Dexter et al., 2008; Whitbread et al., 1995; Smith et al., 2016). By creating stable aggregates, soil carbon also significantly affects soil structure and associated characteristics (such as water retention, bulk density, friability, and tillage) (Dexter et al., 2008; Lefroy et al., 1995).

A decrease in soil quality, or the ability of soil to operate, is implied by a decline in SOC content due to the loss of organic matter (Karlen et al., 1997). As a result, some of its fundamental characteristics would change, adversely affecting crop productivity and lowering the soil's ability to keep C from being mineralized. SOC management techniques aim to improve and maintain soil C, but their efficacy relies on the soil properties (i.e., soil quality) and the level of SOC at the time. Adopting a method that increases the amount of organic carbon in the soil might have an unintended effect because the extra C would be gone (Dexter et al., 2008).

Two Approaches to Building Soil Organic Matter

(a) Reduce soil disruptions to slow down the rate of decomposition (zero tillage, reduced tillage, direct drilling) (Snapp & Grandy, 2011).
(b) Increase carbon inputs from organic materials by using capture crops, green manure, crop rotation, residue control, multiple cropping, mulching, alley cropping, fallowing, and farmyard manuring (Snapp & Grandy, 2011).

The quantity and regularity of residue applications, the type and C:N ratio of the mulching material, the amount, intensity, and spread of rainfall, the soil's moisture content and the amount of clay in the soil all affect how well these practices increase soil organic matter. Different methods can be used to sequester carbon in different parts of the globe (Table 1).

Table 1 Drivers of carbon sequestration in different regions of the world

Strategy	Regions	Process	References
Litter turnover	Tropics	The rate of nutrient cycling, carbon input and organic matter reactivation. Reducing erosion, boosting biodiversity and water infiltration	Loaiza-Usuga et al. (2013)
Forestry plantations	Tropics	Silvopastoral system for nutrient cycling	Kholi et al. (2008)
Woodlot islets	Degraded drylands	Silvopastoral systems in drylands	Nair (2012)
Soil carbon sequestration	Agroecosystems	Optimal management strategies	Gutrich and Howarth (2007)
Integrated nutrient management	Sub-Saharan Africa	Soil quality management	Bationo et al. (2007)
Nutrient management for SOC sequestration	Sub-tropical red soils (China)	Soil carbon build-up	Xie et al. (2013)
Manuring	Indus plains	Application of farm manure	Mirza et al. (2005)
Residue retention as mulch	Mexican highlands	Improvement of soil structure	Lal (2015a, b)
Regular organic inputs	Western Kenya	Improvement of soil structure, nutrient retention and soil structure improvement	Lal (2015a, b) and Mbau et al. (2015)
Urban waste	Mediterranean Europe	Enhancing soil fertility	Debiase et al. (2016) and Míguez et al. (2019)
Soil biological management	Global soils	Enhance ecosystem services provisioned by SOC pool	Lal (2015a, b)

4.4 Soil Degradation Processes

Degradation of soil is a natural or human-caused process that negatively impacts the land's ability to operate appropriately within an ecological system. It could be explained as the reduction, loss or modification of features or organisms in soil that cannot be replaced, as well as the loss of utility or prospective utility (Barrow, 1991). Agriculture-related factors make up the majority of anthropogenic sources of land degradation. Intensification of farming, cultivable land expansion, animal husbandry expansion, changing cropping without needed fallow periods, a lack of soil conservation practices, crop cultivation in fragile or marginal lands, imbalanced use of chemical fertilizers and pesticides, potential issues resulting from improper planning or management of irrigation and the use of high-yield hybrid crops are just a few of the issues that affect agriculture today. According to estimates, up to 40% of the world's arable territory is degraded (Kertész, 2009). Physical, chemical, biological, and natural processes are the most prevalent culprits behind surface soil and soil resource degradation (Fig. 6).

4.4.1 Processes of Soil Degradation

Some elements that contribute to soil degradation include deforestation, shifting cultivation, excessive grazing, mono crop cultivation, intensive use of agrochemicals, inaccurate irrigation management, heavy agricultural machinery, mineral extraction, war or careless waste disposal (Dragovic & Vulevic, 2020). Land degradation not only reduces crop yields but also reduces agroecosystems' carbon content and may reduce biodiversity.

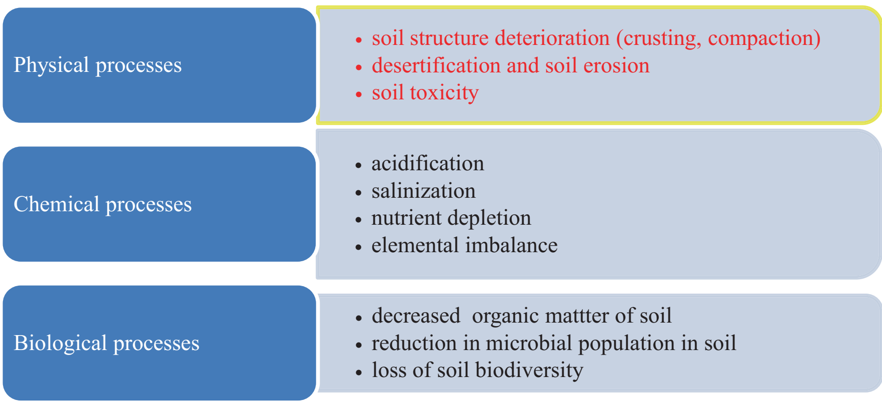

Fig. 6 Different soil degradation processes leading to reduced soil health

4.4.2 Land Degradation Scenario Globally

Globally, more than 33% of the ground is degraded (FAO, 2015). The cost of land degradation to the world economy is between $18 and USD 20 trillion annually. By 2050, the loss of soil organic carbon due to irresponsible land management and conversion is predicted to hit 212 Gt. A gauge of soil vitality is soil carbon. Due to the loss of ecosystem services brought on by land degradation, which is expected to account for 10–17% of global GDP, global net primary productivity has decreased by at least 5%.

4.4.3 Land Degradation Scenario in India

In India, soil degradation affected 97.85 million hectares (29.7%) of the country's 328.72 million hectares total geographical area (TGA) in 2018–19. In 2018–19, about 83.69 Mha of land became desertified (ISRO Altas, 2021).

4.5 Ecosystem Services (ES) Offered by Soil

Terrestrial ecosystems are built on top of the soil, and most ecosystem functions essential to human survival are provided by soil (Kibblewhite et al., 2008). Ecosystem services are goods obtained from ecosystems that benefit people's well-being (Table 2). Soil can provide ecosystem services that are either regulatory, such as sustaining primary production and biodiversity, or supportive (e.g., infiltration of

Table 2 Ecosystem services offered by soil

Services	Key functions
Support services	Biodiversity pool Nutrient cycling Soil formation Water cycling
Regulating services	Biological control of pest and disease Climate regulation Water infiltration and storage Recycling of waste and detoxification Filtering of nutrients and contaminants Erosion control Carbon sequestration and greenhouse gas regulation Neutralization, filtering and buffering of pollutant
Provisioning services	Biomass production (production of food, fiber, and energy) Clean water provision Raw material Physical environment
Cultural services	Heritage Recreation

water, preservation of nutrients, gases in the atmosphere regulation, pest control, and erosion control). Ecosystem services contribute to human well-being and are nature's capital (Costanza et al., 1997; Robinson et al., 2012).

The advantages of soils have significance in decreasing poverty and preventing climate change because they are directly or indirectly related to creating clean air, water, and food. These are some of the most critical issues facing our civilization today. The particular environmental factors that determine the features and applications of soil rely on the type, quantity, and quality of soil ES (Pereira et al., 2018). Agriculture has harmed ecosystems by increasing soil erosion, releasing more greenhouse gases into the atmosphere, polluting the environment with nutrients and reducing species. Therefore, minimizing the harm produced by agriculture is necessary to realize the potential of soil to provide ecosystem services (Power, 2010). The soil biota's abundance, diversity, activity, and composition control various ecosystem processes that support the ecosystem benefits that soil provides (Wagg et al., 2014). To anticipate how the soil biota will contribute to the resilience of the ecosystem services that soil provides in the face of numerous environmental changes on a global scale, it is necessary to understand the variety and redundancy of the soil biota.

4.6 Soil Erosion Management

4.6.1 Planting Vegetation

Planting plants with extensive roots can stabilize the earth. It is important in places more prone to erosion, like streams, hillsides, and riverbanks. Vegetative barriers block the passage of water because of their thick, densely packed stems. These barriers allow water to flow gently without eroding while dispersing the run-off—natural prairie grasses, woody perennials, and wildflowers.

4.6.2 Contour Farming

The erosion problem can be solved using the contour farming method, in which farmers plant across a slope along the contour lines. Crop rows, wheel tracks over hills, and furrows can all be used to accomplish these goals.

4.6.3 Applying Mulches

Mulch is spread out to cover the exposed earth and prevent it from being washed away. When seedlings or shrubs first develop, mulching primarily serves as an erosion control measure. While organic mulches can feed and protect your garden in the spring and autumn, wood mulch can be used in gardens and landscapes.

4.6.4 Avoiding Overgrazing

In this state, soils become vulnerable to erosion due to water run-off, a risk that can be mitigated through the implementation of sustainable grazing practices and effective pasture management techniques. For example, rotational grazing and shifting cattle between various paddocks can lower erosion, enhance the forage quality, and enable pasture plant recovery.

4.6.5 Reforestation

Enough soil erosion control is provided by restoring a damaged ecosystem and preserving the current ones. Actively eroding gullies, earth flows, and shallow landslides can be effectively stabilized with its aid.

4.6.5.1 Use Plastic Sheeting

There should be placement of geotextiles, plastic covers, erosion control mats, and blankets to prevent soil erosion caused by wind or precipitation. They mainly aid newly planted crops in taking root on slopes where water is flowing.

4.6.5.2 Improving Drainage

Every building should have gutters or pipes that can efficiently channel water from the garden into a water-gathering system. Underground perforated drainage pipelines may need to be installed in areas with high water run-off.

4.6.5.3 Avoiding Soil Compaction

Soil is compressed into a hard layer when a machine, an animal or a person constantly moves over it. Topsoil will be carried downwards due to water having difficulty draining through the smaller spaces between the compacted soil particles. Instead of trampling the ground, creating a route on paving stones or cleared pathways is essential, especially when wet. You can also benefit from adding manure or compost because it attracts worms, which split up the soil clumps.

4.6.6 Soil Restorative Farming/Cropping Systems

The SOC pool, structural morphology, and other properties of farming and cropping systems (rotations, soil fertility management, erosion control, grazing/stocking rate, and water management) influence the type, rate, and severity of soil degradation.

Crop rotations and grazing, in particular, can significantly affect the SOC pool and the associated soil properties. Like managing the quality of arable lands, controlling the quality of rangeland soils is crucial for lowering degradation risks. Rangeland soil management is complicated due to high variability, harsh environments, and the desire for overgrazing. Some of the constraints that need to be removed include a decrease in the percentage of palatable perennials, an increase in densification (compaction), and a drop in SOC. Conserving and effectively managing rangeland soils is a critical measure to reduce the dangers of their degradation.

4.7 Climate-Smart/Strategic Agriculture

It refers to using agricultural methods that minimize risks and take advantage of any new opportunities brought forth by climate change. A major threat to the livelihood and food security of millions of people around the world is developing from climate change (IPCC, 2014). Some of the important effects of climate change on agriculture include changes in biodiversity, increased pest and disease prevalence, and decreased input usage efficiency (Zabel & Putzeniechner, 2014; Norton, 2014). These impacts have a considerable influence on agricultural production. Hence, mitigating the effects of climate change on agriculture is a challenge. Agricultural production systems must be adapted to these changes to ensure farming communities' food and livelihood security. Fortunately, several potential adaptation strategies can be used to lessen the moderate to severe climatic hazards to agriculture.

Adaptation strategies that serve as climate-smart agriculture (CSA) technologies, practices, and services sustainably boost production, improve resistance to climatic shocks, and lower greenhouse gas emissions (FAO, 2010). Generally speaking, CSA focuses on creating resilient agricultural production systems that result in financial stability and access to food in the face of advancing climate change and variability (Vermeulen et al., 2012; Lipper et al., 2014). In order to adapt to climate change and variability, it combines established and cutting-edge methods, technology, and location-specific services (CIAT, 2014).

The use of residue incorporation, nutrient and irrigation management, minimal tillage, and other climate-smart agricultural techniques and technologies can increase crop yields, optimize the use of water and nutrients, and lower greenhouse gas (GHG) emissions from agricultural operations (Branca et al., 2011; Jat et al., 2014; Sapkota et al., 2015). Improved seeds, ICT-based agro-advisories and crop/livestock insurance can assist farmers in reducing the impact and variability of climate change (Mittal, 2012; Altieri & Nicholls, 2013). Many studies show that CSA technologies offer a great deal of potential to lessen the effects of climate change on agriculture. For instance, straightforward adaptation strategies like shifting the dates crops are sown and implementing irrigation technology can produce higher yields with fewer changes than those achieved without adaptation (Finger & Schmid, 2007). According to a meta-analysis of crop simulation under various climatic scenarios, farm-level adjustments can boost crop yields by an average of

7–15% compared to those without (Challinor et al., 2014). According to numerous research, adaptability advantages depend on the crop and variations in temperature and rainfall (Easterling et al., 2007). According to several farm-level studies, CSA technology may also enhance crop yields, boost input usage efficiency, boost net income, and lower greenhouse gas emissions (Khatri-Chhetri et al., 2016; Sapkota et al., 2014; Gathala et al., 2011).

The World Bank defines CSA as a comprehensive management strategy for landscapes, including agriculture, forestry, livestock, and fisheries, that addresses the interrelated issues of food security and accelerated climate change. Now let us talk about a few management techniques that use climate-smart techniques to increase agricultural productivity sustainably (Fig. 7).

4.7.1 Climate-Smart Water Management for Sustainable Agriculture

Climate change's effects on the water cycle have the most prominent effects on agriculture. Crop evapotranspiration is accelerated by changing climatic circumstances, which alter rainfall patterns and increase the magnitude of changes in groundwater recharge. Like the extreme effects of exceptional floods and droughts, inadequate groundwater management harms agricultural water use.

The soil, weather, and crop conditions can all be continuously monitored using farm management (FM) systems. In order to precisely determine the water requirements for each plot, farmers can use this information to use clever water algorithms. Alternatives like alternate wetting and drying, rainwater collecting, and automated irrigation systems can speed up irrigation processes while ensuring significant water

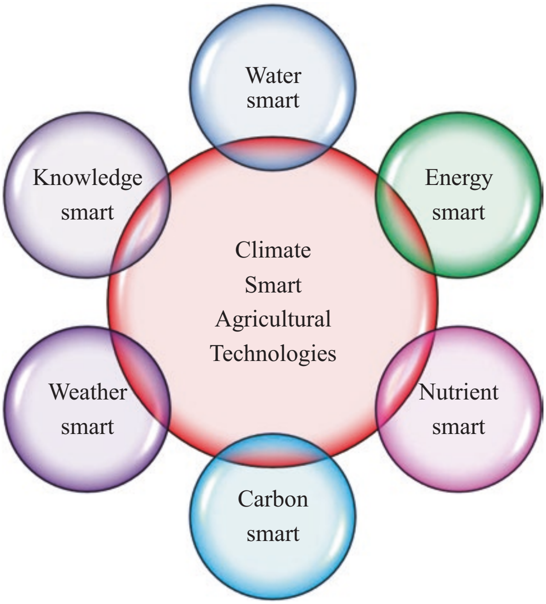

Fig. 7 Basic tenets of climate-smart technologies

conservation. Water loss is reduced through drip irrigation (DI), which applies water directly to the root zone of crops. When the land is leveled using the laser land leveling (LL) method, water is distributed evenly and less water is lost. The furrow irrigated bed planting (FIBP) approach effectively manages irrigation, drainage, and monsoon rains. Drainage management (DM) uses a water control structure to help remove extra water (flood). The cover crops technique (CCM) enriches the soil with nutrients while reducing soil water loss through evaporation. Therefore, a sound farm management system may effectively support water conservation initiatives and provide a climate-resilient future.

4.7.2 Tackling Climate Change with Sustainable Soil Management

A balanced mixture of minerals, organic matter, living things, and water guarantees that the crops receive vital nutrients. Improved agricultural and land management techniques can increase soils' capacity to store carbon and combat climate change. By matching the needs of crops with the appropriate product, rate, time, and location, site-specific integrated nutrient management (SINM) enables the best possible supply of soil nutrients over time and space. Green manuring (GM), which incorporates the growing of legumes in a cropping system, is another method. Similarly, intercropping with legumes (ICL) involves growing legumes alongside other major crops in mixed or alternate rows. Both methods raise soil quality and nitrogen availability.

The leaf color chart (LLC) calculates the amount of nitrogen needed based on how green the crops are. It can be used for wheat and maize crops and rice and is mainly used for split-dose applications in rice to identify nitrogen deficit. Farm management systems can assist farmers in successfully retaining the natural health of the soil by providing crucial recommendations on user-friendly composting procedures and real-time soil testing. Farm management systems can also accelerate bio-composting by utilizing cutting-edge technology advancements. In order to provide climate-resilient farm productivity, this can assist in increasing the soil's micronutrient and carbon content.

4.7.3 Carbon Smart

The need for creating technologies to address the effects of greenhouse gas emissions has never been more pressing since they have reached a critical threshold. This can be accomplished by preserving soil organic matter (SOM), which holds soil carbon and makes soils resistant to extreme weather events. Agroforestry (AF), which encourages carbon storage and appropriate land use management, is another intervention that aids in lowering GHG emissions. For animals, concentration feeding (CF) lowers nutrient losses and requires little feed. Similarly, FM encourages carbon sequestration through sustainable land use management. IPM (integrated pest management) is environmentally friendly because it uses fewer chemicals.

4.7.4 Energy Smart

It comprises energy-saving measures like zero or minimal tillage (ZT/MT). They aid in lowering the energy required for land preparation. Long-term, this approach also leads to enhanced retention of organic matter in the soil and improved water infiltration.

4.7.5 Integrated Pest Management to Cope with Rising Pest Attacks and Diseases

Pest and disease attacks are considerable among the many difficulties in farm productivity. With the dramatic climatic changes, the dynamics of pest inflow and crop illnesses are changing quickly. Many insects, pests, illnesses, and weeds are growing and becoming established due to the variable temperature and humidity conditions. Hence, pest management is growing in importance for the agricultural industry.

In order to improve soil health and stop pests from spreading, extended crop rotations can be a fantastic approach to combat the pressures of weed and insect invasions that are becoming increasingly intense. An effective farm management system can also assist with farm condition analysis, crop rotation, crop selection, and pest control strategy implementation. Farm management systems also provide farmers with a comprehensive perspective of the farm environment. This allows them to manage risks and track better and plan their pest management actions, keeping their crops resistant to climate change.

4.7.6 Weather Smart

Farmers can take advantage of services related to income security and weather advisories provided by weather innovation technology. For instance, weather-based crop agro-advisories provide farmers with value-added agro-advisories based on climatic information. Similarly, cutting-edge climate housing for livestock (CSH) shields animals from harsh weather conditions (such as heat or cold shocks). Another technique for minimizing crop failure losses is crop insurance (CI). You can receive crop-specific insurance to make up for income loss brought on by weather fluctuations.

4.7.7 Knowledge Smart

A climate-smart approach can be used to improve agricultural systems, landscapes, and livelihoods by combining research and local knowledge. It will improve smallholder farmers' abilities to adapt to and mitigate climate change. Planning for uncertain crops, for example, is possible. A climatic risk management plan might be created to deal with significant weather-related contingencies such as drought, flood, and heat/cold pressures during the crop season. It is possible to use new and improved crop varieties (ICV) that are resilient to pressures like drought and flooding. Seed and fodder banks (SFB) can be established to manage climate hazards to preserve crops and fodder seeds. These methods, tools, and services boost resilience, lower greenhouse gas emissions and increase production directly or indirectly.

Technology and procedures that aid in improving at least one component are CSAs. The three CSA components can all be improved with the same technique. Despite the many advantages of CSA technologies, farmers now adopt them at a limited rate (Palanisami et al., 2015). The socio-economic qualities of farmers, the biophysical conditions of a specific place and the characteristics of new technologies are just a few of the many variables that affect how widely CSA technologies are adopted (Campbell et al., 2012; Below et al., 2012; Deressa et al., 2011). Scaling out CSA in various agroecological zones has considerable problems identifying, prioritizing, and marketing existing CSA technologies while considering local climate hazards and technology demand.

Evidence regarding farmers' priorities might assist important stakeholders in making decisions that align with institutional and governmental policies. As a result, we may conclude that climate-smart agricultural methods aim to proactively improve farmers' efforts to secure their food supply and create more stable livelihoods for the coming generation.

4.8 Soils and Global Food Security

Food security "exists when all people, at all times, have physical, social, and economic access to adequate safe and nutritious food that fits their dietary needs and food preferences for an active and healthy life," according to FAO. Access to wholesome food and appropriate nutrition for all people is the fundamental idea behind food security. The idea of food security is fundamentally impacted by nutrition. The four pillars or components of food security are accessibility, use, stability, and availability. Food accessibility and utilization refer to physical and financial access, adequate dietary intake and the body's capacity to use nutrients. Food availability and accessibility refer to the quantity and suitability of the food that is readily available.

According to the most recent State of Food Security and Nutrition in the World (SOFI) report (2021), jointly produced by five UN bodies, the epidemic and the state's failure to address its impacts have significantly increased the prevalence of hunger and food insecurity worldwide. Data from the SOFI Report 2021 show that severe food insecurity has increased in prevalence, with 11.7% of the world's population experiencing it at a severe level. In comparison, India saw a 6.8% increase in moderate to severe food insecurity prevalence during 2018–20. With the Covid epidemic in India, around 9.7 crore more people experience moderate to severe food insecurity. Over 3.1 billion people globally cannot afford a balanced diet, which is proof that more people lack access to sufficient amounts of safe, nourishing food.

A quarter of the world's hungry people live in India, where the UN-India estimates that there are nearly 195 million undernourished people. Moreover, 43% of Indian children suffer from chronic undernutrition. According to the Global Food Security Index (GFSI), which evaluated 113 nations in 2018 based on four factors—affordability, availability, quality and safety—India came in the 76th position. In the GFSI rankings for 2020, India came in at 71 out of 113 nations. The SOFI study for 2022 also emphasizes the aggravation of critical factors contributing to food insecurity and malnutrition, including population growth, armed conflict, extreme weather conditions, economic shocks, and expanding inequities. In Fig. 8, several other elements affecting food security are depicted.

Given that worldwide production of food and linked ecosystem services will grow by 70% by 2050 to feed a projected 9 billion people, ensuring food security will only get more complex. Our soil is under increasing strain to generate more goods and ecological services for the people who are getting more prosperous and more numerous. Our existence is based on the soil. According to estimates, our soils directly or indirectly provide 95% of our food (FAO, 2015). Soil fertility and productivity are essential for maintaining future food security on a global scale. Healthy soil is the cornerstone for growing nutritious food, which helps ensure local and global food security. However, nearly one-third of the world's soils have lost their ability to produce since the 1970s (Blanco-Canqui and Lal 2010). By soil erosion, nitrogen depletion, salinity, sealing, and contamination, global soils are subject to moderate to severe degradation. Topsoil has been deteriorating and eroding at

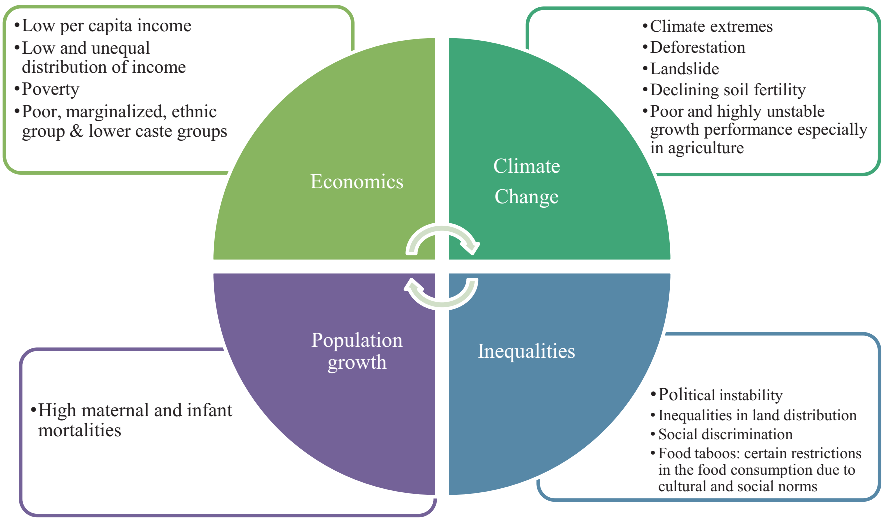

Fig. 8 Drivers and factors affecting food security

alarming rates due to agriculture, deforestation, and other issues. Our soils are being negatively affected by climate change.

Nutritional security is impacted by both soil degradation and food security. Bad nutrition results from poor soil. Fruits and vegetables today contain 90% fewer nutrients compared to past levels. Nutritional deficiencies affect 2 billion individuals and cause a variety of disorders. According to a US study, soil depletion caused a 27% decrease in calcium levels, a 37% decrease in iron levels, a 21% decrease in vitamin A levels, and a 30% decrease in vitamin C levels in fresh vegetables between 1975 and 1997. Between 1914 and 2018, the average amount of calcium, magnesium, and iron in cabbage, lettuce, tomatoes, and spinach decreased by 80–90% in the United States. Due to deteriorating soil, the protein content of beans fell by 60% in India in just 20 years. These statistics are pretty concerning, resulting from the fact that our soil cannot produce nutritious food. Technological advances like space farming, soil processing in hypergravity, and soilless agriculture are being driven by changing diets, food choices, and dietary needs. The mantra is:

Healthy soil = Healthy diet = Healthy people = Healthy ecosystems = Healthy processes.

Soil scientists and agronomists must look beyond traditional farming to highly efficient greenhouse or vertical farms using aquaculture, aquaponics, aeroponics, hydroponics, AeroFarms, and other soilless cultures in sky farming or vertical farming due to shrinking arable land, warming climate, increasing water scarcity, and growing urban and total populations. It will, however, take time for them to be adopted and scaled up. Because no ecosystem component acts in isolation, it is a misconception to believe that we can manage any part of our environment without addressing the entire system. No problem can be fully solved unless we accept that life is a single, intricate reality that co-occurs. Nearly every significant ecological catastrophe is, in some way or another, a result of or a symptom of degraded soil. Like good soil, practically any environmental or environment-related problem can be solved. We have the best chance of healing the whole if we fix the soil.

In order to handle the growing demands on soils brought on by the rapid global population development and climate change, sustainable soil management is a necessary prerequisite. To promote regenerative and, ideally, healthy soil and global food security, integrated pest control and soil fertility might be highlighted as key pathways. The objectives of UN Sustainability Goal (SDG) 2 to eradicate hunger, achieve food security, improve nutrition, and support sustainable agriculture could only be achieved after that.

4.9 Adoption and Scaling of Nature-Based Solution (NbS)

IUCN defines nature-based solutions (NbS) as "actions to protect, sustainably manage, and restore natural or modified ecosystems that address societal challenges effectively and adaptively, simultaneously providing human well-being and biodiversity benefits." Nature-based solutions are based on the notion that when ecosystems are healthy and well-managed, they provide essential benefits and services to people, such as reducing greenhouse gas emissions, securing safe water resources, making the air safer to breathe and providing food security.

In order to improve soil quality for increased agricultural output and sustainability, the NbS may be crucial. The numerous natural solutions for enhancing soil quality are covered in this article. Indigenous techniques like sheep pinning, applying tank silt, green manuring, and discarding from households and croplands may be able to keep and restore soil fertility. In addition to increasing the abundance of nutrients in the soil, biofertilizers can help with their solubilization and mobilization. Conservation agriculture practices will provide a new choice for sustainable agriculture in India with integrated organic amendment A frequently used substance called biochar can increase soil moisture availability by 8–10% and helps to slow down climate change by sequestering carbon. There may be a 1.8 Pg CO_2-C equivalent annual mitigation possibility for biochar. It serves as an amendment to the soil and a source of nutrients when applied. Cation exchange capability and SOC in soil are improved by biochar (CEC). Different types of biochar are prepared based on the numerous environmental applications in the field (Srivastava, 2020). The effluent from biogas reactors, known as biogas slurry, includes various nutrient components that can improve soil fertility (Mrunalin et al., 2022).

Using organic manures, such as farmyard manure (FYM), sheep manure, cow dung and urine, vermicompost, green manures, and biodynamic formulations, and avoiding the use of inorganic fertilizers and chemicals, is part of the natural method of farming. The natural way of farming involves the use of organic manures, including formulations like farmyard manure (FYM), sheep manure, cow dung and urine, vermicompost, green manures, and biodynamic formulations, as well as altogether avoiding the use of inorganic fertilizers/chemicals (Li et al., 2012; Wang et al., 2016). These techniques lessen environmental damage and help farmers achieve sustainable soil health (Li et al., 2012; Wang et al., 2016). Agri-ecotourism and natural farming are other ways to spread awareness of these practices and let people enjoy nature while learning how agriculture, livestock, waste, and applications are interconnected. This is also a cost-effective and environmentally friendly way to expand the village and open up the possibility of fostering climate resilience through ecotourism (Mishra et al., 2022c).

4.10 Regenerative Agriculture Practices for Soil Management in Diverse Landscapes

In order to meet the competing needs of increasing food production to feed a growing global population, improving the sustainability and health of agricultural landscapes and adjusting to the effects of climate change on agriculture, agricultural land managers are continuously under pressure (Smith, 2013; Foley et al., 2005).

It is suggested that synthetic fertilizers and other intensive farming techniques, which formerly helped to increase agricultural productivity quickly, have contributed to a decline in the global health of vital ecosystem services (Baude et al., 2019). Many people are now questioning the viability of conventional farming systems and calling for a switch to alternative agricultural systems that can produce food while promoting ecosystem health (Tilman et al., 2002; Dubey et al., 2021).

The transition is essential to preserving food security and human well-being into the future while adjusting to the stresses that global climate change places on agricultural systems (Maia et al., 2018; Patz et al., 2012). In order to address these issues, a sizable number of agricultural land managers (hence referred to as farmers) are implementing regenerative agricultural (RA) systems (Soloviev & Landua, 2016). The number of regenerative farmers is unknown, but interest in and investment in regenerative agriculture have recently increased (Newton et al., 2020; Gosnell et al., 2020).

Regenerative agriculture was identified as a "sustainable land management strategy" in an IPCC Special Report on "Climate Change and Land" that is centered on ecological processes and "may be successful in enhancing agro-ecosystems resilience"). In order to regenerate and contribute to numerous provisioning, regulating, and supporting services, RA is a farming method to enhance the environment and the economic and social components of sustainable food production (Schreefel et al., 2020). The core principles of RA include system-based conservation agriculture (CA), which incorporates no-till farming and residue mulching, cover crops, integrated nutrient and pest management, complicated rotations, and crops with trees and livestock (Lal, 2015a, b).

At its core, RA aims to restore severely damaged soil or increase the health of the soil, which benefits the water quality, the plants, and the productivity of the land. Using RA techniques, creating new soil and boosting the amount of SOC in existing soils is feasible (Fig. 9). In addition to increasing soil structure and health, crop yields, water retention, and aquifer recharge, this also reduces atmospheric carbon emissions. Therefore, implementing these strategies is crucial for reducing run-off and easing the erosion of various types of soil (Rhodes, 2017). Thus, RA is all about "holistic land management," which refers to farming methods that restore rather than deplete the land.

4.11 Regenerative Agriculture Techniques

Although carbon sequestration is simply one tool among many RA options, it is a common component of RA strategies. Farmers are also concerned with improving the overall health of the soil, increasing the biodiversity of the plants and animals, effectively managing rainwater to help the land withstand droughts and storms, and treating people and animals with respect. Below are just a few strategies for achieving these objectives.

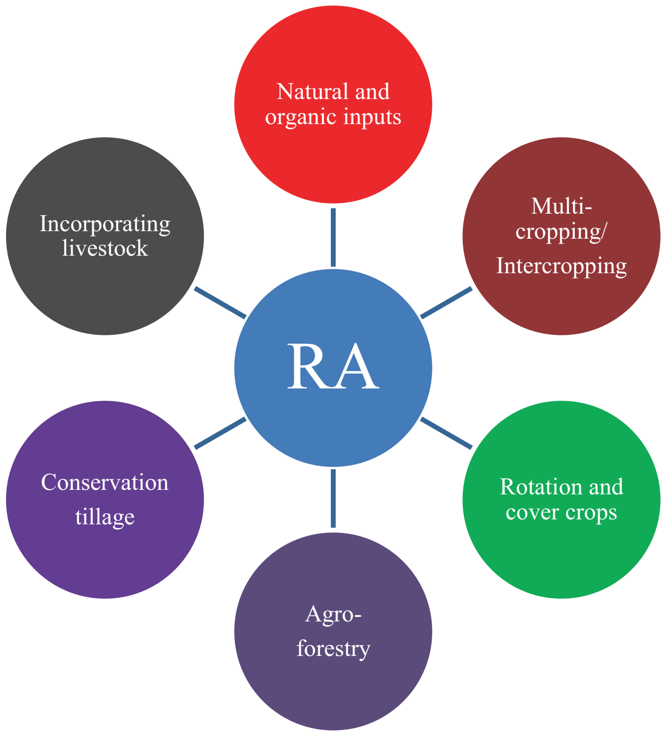

Fig. 9 Basic tenets of regenerative agriculture RA regenerative agriculture

4.11.1 Conservation Tillage

Before planting new crops, tilling is a standard method of soil manipulation that mixes organic matter into the soil and kills weeds. Tilling, however, causes the soil's carbon to be released into the sky. Using minimal or no-till methods leaves carbon in the soil, enriching it and lowering greenhouse gas emissions. Moreover, it encourages the growth of soil microbes, prevents soil erosion, and keeps soil moisture.

4.11.2 Integration of Natural and Organic Inputs

It is possible to create nutrient-rich compost for plants and the soil microbiome from animal, plant, and food waste. It can also be produced at home! Composting bags are frequently used in backyard gardens. However, some compost—such as animal dung and tree fall—is produced naturally on farms and can restore the soil's organic content without much intervention. Compost can be spread over fields or combined with soil to aid in crop growth. It lessens the need for additional fertilizers on farms, enriching the soil without increasing greenhouse gas emissions that may be linked to the production of substitute fertilizers. In some areas, the soil is amended with biochar to produce nutrient-rich soil without fertilizer, soil manipulation or carbon dioxide production. Biochar is a dark, fertile substance rich in carbon that is highly porous and formed by the pyrolysis of organic material like leaves and sticks. Moreover, the soil can better hold onto nutrients and water.

4.11.3 Perennial Crops

These plants grow complex, dense root systems that store rainwater and swiftly adjust to soil nutrient changes, enabling them to exist year-round. They contribute to the development of nutrient-rich soil and require less input for long-term life. Farmers frequently utilize them as cover crops in between growing seasons. In a farm, cover crops immediately boost biodiversity, stop soil erosion, and preserve the soil's integrity (including water use and nutrient levels) between growing seasons.

4.11.4 Agroforestry

As a comprehensive food production system with significant environmental, economic, and social benefits, agroforestry is becoming more widely accepted. Increased farmer income security, better soil health, higher biodiversity, and several other ecosystem services are all benefits of the agroforestry approach. Many agroforestry techniques can be incorporated into current agricultural systems. Known agroforestry practices include alley cropping, contour hedgerow, tree farming, green fence, multistory planting, riverside forest buffer, silvoarable structures, silvopasture, and windbreak (Torquebiau, 2000; den Herder et al., 2016). Several advantages include carbon sequestration, plant protection from adverse weather, and improved water quality. These advantages can be achieved by planting rows of trees between crops, in livestock pastures and over farmland or pastures.

Awareness of the variety of agroforestry systems and methods used worldwide is crucial. Agroforestry practices and systems produced globally are influenced by climatic, physiographic, and socio-economic variables (Nair, 1993; Bhardwaj et al., 2017; Thevathasan & Gordon, 2004). For instance, agroforestry is widely used in India's traditional land use systems. In the Western Ghats of Kerala, India, typical agroforestry systems involve the use of Erythrina indica trees, which support black-pepper (*Piper nigrum*) vines and also provide shade for coffee plants (Coffea spp.) In the northeastern Himalayan region of India, intercropping black pepper and pineapple (*Ananas comosus*) beneath areca nut palms is another popular practice (Singh et al., 2014). Over time, agroforestry's regeneration effects have been acknowledged and encouraged. Recent initiatives to create a regenerative agriculture certification provide a chance to think about how agroforestry can advance regenerative objectives (Elevitch et al., 2018).

4.11.5 Managed Grazing

While using controlled grazing, farmers consider the land's long-term viability, the requirements of the local fauna, and the need to safeguard the land and animals from hazards like fire and drought. Including livestock in these systems ensures the availability of sufficient local bio-inputs for agricultural use. The livestock is rotated across various pasture areas depending on the forage's growth rate and stage. This gives crops a chance to grow robust root systems and a reliable fuel supply for livestock. These root systems promote soil fertility and water retention. In a case study from the central Andes of Colombia, Hacienda Pinzacuá, a 45-hectare farm, underwent an agroecological transformation. Amidst a very fragmented landscape, it emerged as a beacon of regenerative agriculture. Pinzacuá has evolved into a high-quality matrix that serves as a refuge or sanctuary for different taxa, a drive to survive in the fragmented terrain. Currently, Pinzacuá stands out as an island of flora in a landscape bereft of trees. Important land management decisions were made throughout the 20 years of transition, and significant changes in land cover were implemented gradually through trial and error (Montes-Londoño et al., 2022).

4.11.6 Environmental and Nutritional Advantages

Soil RA techniques can reduce atmospheric carbon dioxide by 65–75 parts per million. That suggests that the 135 billion tons of carbon dioxide lost to the atmosphere can be returned to the soil, where it belongs, in 25–50 years (Lal, 2014). This has a favorable effect on how commonplace climate change is. While many businesses may tout lower greenhouse gas emissions, RA goes further by eliminating greenhouse gases from the farmland. Given that the world's population is predicted to reach 9 billion people by the year 2050, RA has the potential to boost the supply of nutrient-rich foods that are fed to people worldwide. Farmers in the RA are assisting in producing more food in less area to feed more people by investing in the soil.

4.12 Conclusion

The pivotal role of Soil Management in Sustainable Agriculture is underscored by the principles and techniques that form the foundation of the twenty first-century green revolution, rooted in Regenerative Agriculture (RA). This paradigm shift in agricultural practices emphasizes a soil-centric approach, prioritizing soil health as a cornerstone for sustainable yield. RA integrates enhanced eco-efficiency and a reduced dependence on external inputs, aligning with ecosystem-based strategies. It leverages modern science and managerial skills, illustrating a knowledge-based methodology. Furthermore, RA resonates with Howard's Law of Return (1943), advocating for the recycling of organic matter to enrich soil fertility and establish a favorable carbon budget within the soil and ecosystem. Regenerative Agriculture, while not entirely novel, represents an evolving ethos in farming that addresses the urgent need for site-specific, innovative, and resilient agricultural technologies. These practices are essential for achieving sustainable yield, combating climate change, and minimizing environmental footprints, marking a significant stride towards a more sustainable and ecologically harmonious future in agriculture (Howard, 1943).

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Dynamics of Nutrients, Soil Organic Carbon and Smart Nutrient Management Practices

Sudhir Kumar Rajpoot, Nikhil Kumar Singh, Pratik Sanodiya, Richa Chaudhary, Amit Yadav, S. Vijay Kumar, Gaurendra Gupta, Raghavendra, Utkarsh Singh, and Hanamant Halli

1 Introduction

Global climate change is a major concern for all developing and developed countries that has resulted in major changes to the earth geological, ecological and biological systems and poses serious threats to the existence of human civilisation and sustenance of agricultural productivity and food security (Ramesh et al., 2019). Anthropogenic and agricultural activities along with forestry and land use changes have resulted in increasing greenhouse gas emissions (GHGs) such as CO_2, CH_4 and N_2O on earth's surface and are one of the important growing concerns of this century. Therefore, many countries in the world have started developing various policies, technologies and methods to mitigate GHGs (Ross et al., 2016). Among the various mitigation solutions developed, organic carbon storage in soil as well as in terrestrial biosphere through proper land use and management practices is an important strategic option (Zhang & Ni, 2017). Soil is an important sink for carbon stock with global carbon storage of 1550 Pg (Batjes, 1996) and accounts for two or three times more carbon than atmosphere and vegetation, respectively (Scharlemann et al., 2014). Hence, little change in terrestrial carbon pools has a significant impact on climate change (Zhang et al., 2016). Soil organic matter (SOM) is a vital indicator of soil quality; therefore, maintaining SOM with quality and quantity is essential for sustaining long-term soil fertility (Zhao et al., 2015). There are several pools and fractions of soil organic matter such as total organic carbon, particulate and mineral-associated organic carbon, dissolved organic carbon, extractable organic carbon and

S. K. Rajpoot (✉) · N. K. Singh · P. Sanodiya · R. Chaudhary · A. Yadav · S. V. Kumar
G. Gupta · Raghavendra · H. Halli
Institute of Agricultural Sciences, BHU, Varanasi, UP, India
e-mail: sudhir.k.rajpoot@bhu.ac.in

U. Singh
Acharya Narendra Deva University of Agriculture & Technology, Ayodhya, UP, India

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microbial biomass carbon that may be useful in the study of short-term and long-term influences of land use and management on soil organic carbon dynamics. Soil nutrients are the chemical elements vital to biological functions, that is, for survival and reproduction of any living organisms in soil (DeAngelis et al., 1989). Further, nutrient dynamics is broadly defined as the way nutrients are taken up, retained, transferred and cycled over time and distance in an ecosystem (Harrison et al., 2016). Therefore, soil nutrients and organic carbon are interlinked to each other. It is well documented that the capacity of soils to sequester carbon is strongly influenced by nitrogen and phosphorus availability because of stoichiometric links between carbon, nitrogen and phosphorus biochemical cycles. Human disturbances (deposition, fertilisation and nutrient mining) continuously cause large imbalances between the biogeochemical cycles and changing nutrient availabilities identified as key uncertainty in predicting future ecosystem carbon sequestration (Macdonald et al., 2018). Land use change (LUC) is a major driving feature for the balance of soil organic carbon stocks and the global carbon cycle (Poeplau et al., 2011). Furthermore, land use and land use change are human activities with a major impact on the balance between the input and outputs of SOC and atmospheric CO_2 concentration (Houghton, 2003). A better understanding of LUC on the world's terrestrial carbon balance is thus a necessary part of the global effort to mitigate climate change (The Terrestrial Carbon Group, 2010). Therefore, understanding of mechanisms that drive the interactions between carbon and nutrient cycles and long-term predictions of changes in current and future organic carbon and nutrients in the soil through crop growth simulation models under varied management practices could pave the way to enhance productivity of different crops and cropping systems by maintaining soil quality under changing climate and land use change, which is much needed in current scenario.

Increased food and fibre output per area of land will be a result of future population growth. Growing crops deplete more nutrients from the soil; hence, it is crucial to replace soil fertility through effective and efficient fertiliser management. The availability of native soil nutrients depends on the soil's capacity to absorb nutrients lost during crop removal. N, S and micronutrient supplies from mineralisation of soil organic fractions are finite, whereas P, K, Ca, Mg and micronutrient supplies are replenished by mineral dissolution and surface exchange reactions (Halvin et al., 2020). The degree to which nutrients are mobile in soil affects ion transport to plant roots, assessments of the nutrients' availability to plants and ultimately decisions about nutrient management. There are many nutrient management techniques for crops that have been considered for proper nutrient management, such as the adoption of the 4R nutrient management strategy – application of the right nutrient source at the right rate at the right time in the right place – to improve nutrient use efficiency by the crop and to minimise nutrient losses to the surface and groundwater as well as to the atmosphere (Rates et al., 2008). By limiting negative environmental effects, effective soil nutrient management will guarantee crop output meets consumer demand. As a result, this chapter attempted to link how various nutrient management techniques for crops can affect nutrients, organic carbon and nutrient dynamics in the soil as a result of climate change.

2 Potential Impact of Climate Change on Plant Nutrients and Soil Organic Carbon

Soil organic carbon (SOC) is very important in the global C cycle since it constitutes the largest terrestrial reservoir of this element (Chabra et al., 2003). Soils store at least three times more carbon (in the form of soil organic carbon) than that found in the atmosphere or living plants (Schmidt et al., 2011). This reservoir of soil organic carbon is very sensitive to climate change and how climate change is likely to impact soil organic carbon has always been a matter of considerable debate. On the one hand, it is recognised that global warming and increasing CO_2 levels in the atmosphere can favour increased plant growth, which in turn could provide more organic matter for the soil. On the other hand, a rise in air temperature will lead to increase in decomposition and loss of soil organic matter. There is thus significant interest in the fate of such carbon, particularly the extent to which soils and land use can be used to regulate the sequestration of carbon from the atmosphere or the loss of soil organic carbon to the atmosphere (Fig. 1).

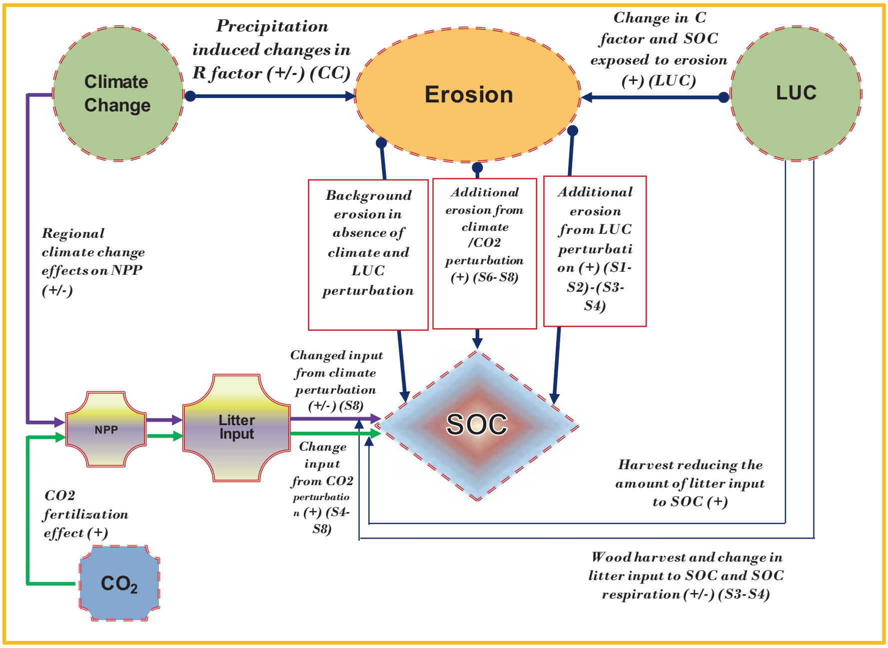

Fig. 1 Conceptual model on the impact of climate change and land use change on soil organic carbon. (Modified from Chabra et al., 2003)

2.1 Effect of Climate Change on Soil Organic Matter

2.1.1 Addition of Organic Matter in the Soil

One of the evident effects of climate change has been the ever-increasing atmospheric CO_2 levels as well as the temperature rise. Both of these have been believed to be a cause of increase in the net primary production, that is, plant biomass which has been causing the rise in the addition of carbon inputs into the soil. This is majorly due to the fact that photosynthesis is limited by atmospheric CO_2, especially in areas where nutrients and water are not a limiting factor. Moreover, soil moisture has also observed potential changes as the precipitation patterns have been altered due to the effects of climate change; for example, the water-limited areas are facing sudden increases in the precipitation again increasing the net primary production and its effects as mentioned in the above paragraph. However, the amount, location and quality of carbon inputs are likely to be affected by (i) changes in the above versus below allocation and (ii) species composition.

2.1.2 Soil Organic Matter Decomposition

The decomposition of soil organic matter is a complex series of biochemical reactions that are enzymatically controlled and hence is highly temperature regulated along with other factors which include changes in land use, soil temperature and moisture. In general, the decomposition process gets accelerated as the temperature gets warmer given the condition that other factors like soil moisture, oxygen concentration are not limiting. This increase in decomposition due to temperature rise is regulated by the following (Ågren & Wetterstedt, 2007; Conant et al., 2011):

(i) Rate of substrate availability in the environment
(ii) Rate of substrate depolymerisation by extracellular enzymes
(iii) Rate of diffusion of these substrates and their utilisation by microbes

The depletion of readily mineralisable components is expected to cause changes in the overall 'temperature sensitivity' of soil organic matter decomposition which is often described as a change in its (soil organic matter) overall quality or stability. According to Davidson and Janssens 2006, kinetic theory suggests that the decomposition rates of biochemically complex organic matter that decompose slowly should be more sensitive to temperature.

2.1.3 Soil Organic Matter Stabilisation

The isolation of the effects of temperature on stabilisation or destabilisation, independent of the soil organic matter, has been proven to be difficult. Just like decomposition, the protection of soil organic matter by occlusion within aggregates and association with the mineral surfaces are chemical processes and hence subject to the kinetic theory. Moreover, the data on chemical stabilisation proposes that there lies a complex relationship wherein warmer temperatures induce the net soil organic matter release from mineral surfaces but may simultaneously cause enhancement in the initiation of slower reactions which results in soil organic matter being tightly bound to mineral surfaces. Thus, it can be understood that the warming of temperature could lead to both the release of soil organic matter along with CO_2 efflux and the creation of tighter mineral-soil organic matter bonds for the remaining pool of chemically protected soil organic matter.

2.2 Climate Change Effects on Organic Carbon and Nutrient Dynamics in Soil

The availability of organic matter, temperature patterns, hydrology and potential changes in evapotranspiration are among the soil-forming variables that may change as a direct effect of global climate change. In a warmer soil temperature regime, both organic matter and the carbon to nitrogen (C:N) ratio will decrease. Dryer soil will slow down organic matter decomposition and root formation, making the soil more vulnerable to erosion. Stress on the soil's moisture levels is brought on by rapid plant transpiration and increased soil evaporation. On the dynamics of nutrients and soil quality, climate change is anticipated to have a variety of effects. Precipitation type, timing, intensity and quantity all have an impact on how soil forms. Temperature fluctuations on a daily and seasonal basis have an impact on vegetation types, biological activity, chemical reaction rates and moisture effectiveness. Climate change may affect mineral soils' ability to hold water, susceptibility to erosion and compaction, and workability. Certain soils may be more prone to erosion in regions with more winter rainfall. The leaching of nutrients and washing away of organic materials are two further alterations. In addition to affecting soil characteristics, climate also controls it by absorbing and releasing greenhouse gases such as carbon dioxide, methane and nitrous oxide. Depending on the use of the land and climatic circumstances, soil can serve as a source or sink for carbon. Other chemical and biological activities, which may also be influenced by climate, landscape position and land use, are founded on several soil physical qualities. According to Magdoff and Weil (2004), the cycling of nutrients, particularly N, is closely linked to the cycling of soil organic carbon. As a result, climate change drivers like increased temperatures, variable precipitation and atmospheric N deposition are likely to have an effect on the cycling of N as well as possibly other plant-available nutrients like phosphorus and sulphur. The presence of cation exchange capacity (CEC), an inherent soil feature that may be significantly impacted by high CO_2, is necessary for the soil to be available for nutrients to crops. According to Mareschal et al. (2010), an increase in organic matter content, root and mycorrhizal biomass and exudation, and soil aggregation status can all contribute to an increase in CEC under high CO_2. According to Hoosbeek et al. (2006) crops and trees growing in high CO_2 environments may be able to (indirectly) influence the soil's ability to provide nutrients and thereby control nutrient availability over time. As shown in Fig. 2, elements with cycles controlled primarily by biological processes (such as C and N) may respond to temperature changes differently than elements with cycles controlled by both biological and geological processes (such as P, S and K) or elements with cycles controlled primarily by geological processes (such as K, Ca, Mg, S or micronutrients [Wood et al., 2006, Watanabe et al., 2007]).

The biological conversion of organic to inorganic pools is significantly regulated by soil moisture and temperature; hence, global climate change may have a significant impact on the concentrations of nitrogen and sulphur in soil solutions. According to some experts, the size of the soil C pool won't alter since the increased levels of soil respiration and breakdown brought on by soil warming will be tempered by the increasing levels of C supply underneath (Kirschbaum, 2000). According to Pendall et al. (2004), rising CO_2 doesn't directly affect the mineralisation of nitrogen (N), but the heat that results from climate change can also promote N mineralisation, which raises the concentration of N in soil solution. With rising temperatures, the adsorption/desorption reactions will also speed up, and variations in soil moisture may further affect the reactions by changing the ionic strength of the soil solution.

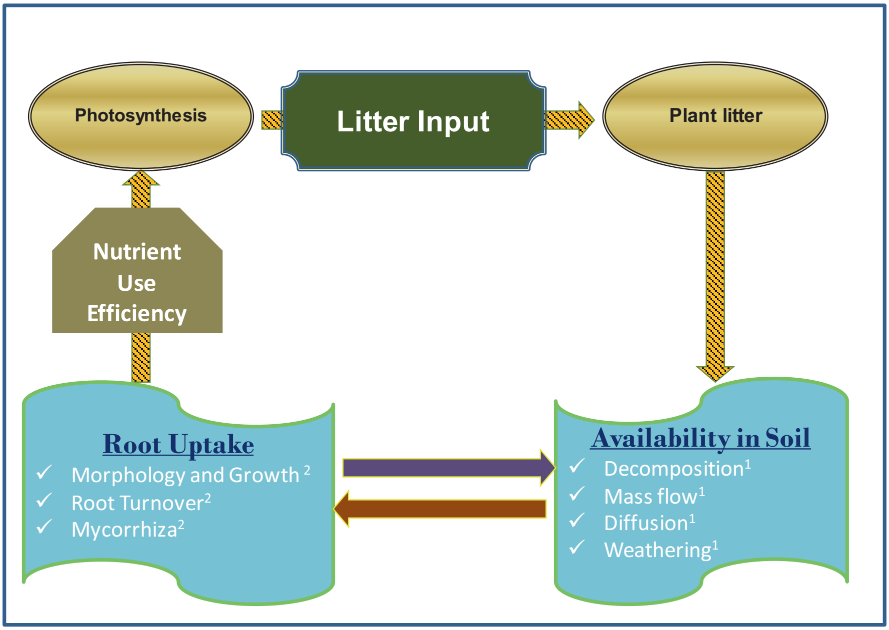

Fig. 2 Process of ecosystem nutrient cycle, directly (1) and indirectly (2) affected by climate change. (Modified from Wood et al. 2006; Watanabe et al. 2007)

3 Dynamics of Plant Nutrients and Organic Carbon in Soil

In soil, there are both live and dead organic materials, which together make up soil organic matter (SOM). It consists of an unlimited variety of organic substances, ranging from simple, easily mineralised organic wastes to complex, unusual products and microbial biomass. SOM includes 58% of the total organic carbon, which is the fraction of carbon stored in this organic matter. SOM are typically categorised as primary active, slow and passive carbon complexes, which vary in size and solubility (Tan et al., 2007). With an average resident time of between 1 and 5 years, active pools are very sensitive types of modified carbon. This carbon group plays a crucial part in supporting the soil food web and has an impact on a number of soil processes and activities, such as nutrient cycling and soil quality maintenance (Majumder et al., 2008). Whereas passive SOC pools often have a residence duration of 200–1500 years, slow SOC pools typically have a residence time of 20–40 years. Although they contribute to carbon fixation, the stable carbon fractions have a strong resistance to microbial activity and are hence not very good indicators of soil quality (Majumder et al., 2008).

3.1 Total Organic Carbon (TOC)

The carbon content of soil organic compounds is measured using TOC. These organic components come from both internal and external sources, including decomposing organic matter and metabolic by-products of microorganisms or living things. External sources include fertilisers, compost, bio-solids, insecticides and fertilisers. Physical fractionation of SOM can be broken down into three main categories: coarse organic matter (organic fragments smaller than 250 μm), fine organic matter (organic materials between 53 and 250 μm) and mineral-bound organic matter (organic materials smaller than 53 μm). Table 1 lists the additional crucial soil organic carbon (SOC) constituents.

3.2 Soil Nutrient Dynamics

The transformation processes have an impact on both organic and inorganic sources of important nutrients. The physical, chemical and biological characteristics of the soil regulate these processes. The dynamics of nutrients are significantly influenced by the amount of organic carbon in the soil as well as the quantity and kind of organic inputs. Major nutrients (N, P and K) are generally well predicted by crop models in various agroecosystems. As a result, the dynamics of important nutrients in the soil are thoroughly discussed.

Table 1 Soil organic carbon fractions and their important features

S. no.	Fractions of SOC	Features
1.	Particulate organic matter carbon (POM-C)	POM-C is the material that passes through a 2 mm sieve, but kept on a 53 um sieve, minus the sand Important for aggregate stability, nutrient cycling and water infiltration Abundant in topsoil compared to lower strata Prone to change with management practices
2.	Mineral organic carbon (MOC)	MOC includes the carbon fractions of the complex SOM that have been both physically and chemically stabilised. Represent negative carbon sinks with relatively longer spin times.
3.	Dissolved organic carbon (DOC)	DOC originates from a multitude of sources such as plant litter, root exudates, soil humus or microbial biomass. It is organic molecules of sizes that pass through a 0.45 µm filter. DOC is further divided into labile, semi-labile and non-labile parts. (1) labile carbon: Called extractable organic carbon. Primary energy source that can be readily degradable or consumed quickly by soil microorganisms. It is also identified as a short-lived carbon pool. Simple sugars (i.e. glucose, fructose) and protein degradation products (i.e. amino acids) are labile carbon compounds. (2) semi-labile carbon: Breakdown of intermediate products of cellulose or hemicellulose is an example of a semi-labile organic compound. This fraction can be decomposed into the labile carbon fraction with time. (3) non-labile carbon: It includes humic substances of high molecular weight. This fraction is resistant to microbial decomposition and can persist in the soil environment for several years.
4.	Microbial biomass carbon (MBC)	It represents the living components of soil organic carbon (SOC) and is considered as an estimate of biological activity of the soil. MBC has been proposed as an index of soil stress and disturbance, and its measurement is often essential for soil ecological studies.

Hanson et al. (2000), Cambardella et al. (2001), Marschner and Kalbitz (2003), Singh & Lal (2005), Marschner et al. (2008), Yadav et al. (2021)

3.2.1 Soil Nitrogen (N) Dynamics

The main source of plant-available nitrogen is soil organic N mineralisation, whereas soil inorganic N is obtained from applied fertilizers. It was discovered that four mechanisms, including biotic immobilisation-remineralisation, abiotic immobilisation, soil organic N mineralisation and plant residue organic N mineralisation, had an impact on the inorganic N routes in soils. The inorganic N that has been microbiologically immobilised promotes microbial growth and can be recycled in

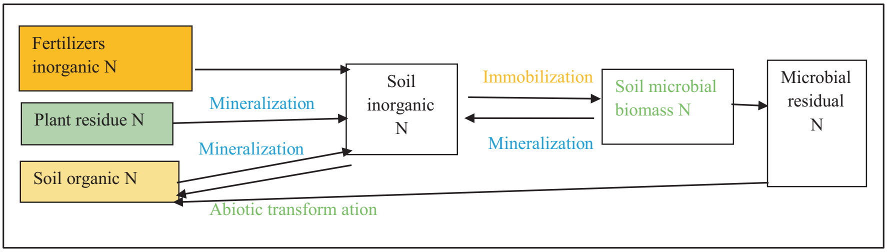

Fig. 3 Nitrogen (N) dynamics in soil

favourable settings. Remineralisation is the term for this process, which primarily happens as a result of microbial death (Fig. 3).

3.2.1.1 Forms of N in Soil

The three main types of nitrogen in the soil are nitrate nitrogen (NO_3-N), ammonium nitrogen (NH_4^+-N) and organic nitrogen (Org-N). Organic N cannot be utilised by plants. Only the ammonium and nitrate forms of nitrogen can be used by plants. Organic nitrogen is broken down during *mineralisation* to produce usable ammonium nitrogen for plants. Since ammonium is further transformed by bacteria into the nitrate form, which is likewise accessible to plants, nitrification takes place.

(a) Ammonium N (NH_4^+-N)

As organic N is broken down by bacteria, the first plant-usable form released is ammonium. Because warm, moist soils encourage microbial activity, this process, known as mineralisation, moves forward more quickly in the late spring, summer and early fall than it does in the colder months.

(b) Nitrate-N (NO_3-N)

The conversion of ammonium nitrogen (NH_4^+-N) to nitrate nitrogen (NO_3-N) is known as nitrification. Plants can utilise nitrate N, just like they can use ammonium N. Nitrate repels negatively charged soil particles because, unlike ammonium, it possesses a negative charge.

3.2.2 Phosphorus (P) Dynamics in Soil

Inorganic P (Pi) and organic P(Po) are two chemical types of P that are present in soil Turner et al. (2007). Pi typically makes up 35–70% of the total P in soil (Harrison, 1987). Al/Fe oxides and hydroxides can effectively absorb P in acidic soils, rendering it inaccessible to plants. Phosphate precipitation processes, where phosphate can precipitate with Ca to produce dicalcium phosphate (DCP), are the main source of P retention in neutral to calcareous soils. In the end, DCP can be converted into more stable forms like hydroxyapatite and octacalcium phosphate, which are less accessible to plants at alkaline pH. Po typically makes up 30%–65% of all the P in soils. Orthophosphate diesters, labile orthophosphate monoesters and organic polyphosphates are the main active forms of soil Po, which also exist in stable forms as inositol phosphates and phosphonates (Turner et al., 2002). By mineralisation processes mediated by soil organisms and plant roots in conjunction with phosphatase secretion, the Po can be liberated.

3.2.3 Potassium (K) Dynamics in Soil

The most predominant macronutrient in soils is potassium. Indian soils range in total K concentration from 0.5% to 3.0%. Around 98% of the total K in soils is found in primary and secondary minerals, with the remaining K being fixed or non-exchangeable, exchangeable (adsorbed), or being in soil solution. K exists in soil in four different forms: (i) solution K, (ii) exchangeable K, (iii) fixed or non-exchangeable K and (iv) mineral or structural K.

3.2.3.1 Soil Solution K

This K is found in the soil solution. The range of water-soluble K in soil is 1–10 ppm. For successful crop production, especially when the crop is mature, solution K concentration is crucial.

3.2.3.2 Exchangeable K

This is potassium held in a 2:1 layer silicate exchange complex. Soil can have between 40 and 600 ppm of exchangeable K.

3.2.3.3 Fixed or Non-exchangeable K

In contrast to mineral K, which is covalently bound inside the crystal structure of soil mineral particles, non-exchangeable K is held between adjacent tetrahedral minerals like micas, vermiculites and inter-graded minerals. K transforms from an immutable state to an exchangeable state. Fixed K, which cannot be exchanged, varies from 50 to 750 ppm in soil.

3.2.3.4 Structural or Mineral K

The majority of K in soil is found in form of minerals, mainly as K-containing primary minerals like feldspar, biotite and muscovite . The amount may vary generally from 5000 to 25,000 ppm in soil.

4 Nutrient Management Practices for Crops

One of the core Millennium Goals, and one that depends heavily on boosting crop output, is the accomplishment of food security. However, there are a number of limitations on crop output in underdeveloped nations. The lack of crop nutrients in the right amounts and forms is one of the main factors limiting crop productivity in the third world (Hussain et al., 2006; Havlin & Heiniger, 2020). Soil nutrient loss rises as crop productivity rises. Plants require a precise amount of a certain nutrient in a particular form at the appropriate time for growth and development. It is essential to comprehend the critical functions of macro- and micronutrients in crop nutrition if you want to increase yields (Arif et al., 2006). In order to successfully manage nutrients, soil testing is required to ascertain the crop's nutritional requirements and the soil's capacity to supply nutrients. Following their identification, the nutrient management plan adopts the 4R concept, which calls for determining the ideal nutrient rate, the right source of nutrients, the right placement of nutrients and the right timing of nutrients (nutrient application timing) (Havlin, 2020). Numerous nutrient application techniques, such as FYM and fertiliser applications to the soil, nutrient seed priming and foliar nutrient application, may be used to supply crop nutrients. Each of these application techniques has benefits and restrictions of its own. For instance, it has been demonstrated that applying FYM increases crop growth by enhancing the physical, chemical and biological characteristics of the soil (Sandhu et al., 2020). However, there is always a concern about insufficient availability of FYM. Similarly, applying nutrients through soil is frequently regarded as the most practical and efficient method (Kugbe et al., 2019). However, there are a number of restrictions on the use of fertiliser, mostly because it is expensive, adulterated and difficult to find on the market at the right time and at an acceptable price. Similar to this, the chemical and physical characteristics of the soil affect the availability of nutrients. These nutrients cannot be sufficiently absorbed by plant roots in dry soils (Graham et al., 1992; Ellis & Foth, 1996). As an alternative, the ideas of foliar nutrient spray and nutritional seed priming were created. According to reports, seed priming promotes robust early seedling growth and greater stand establishment (Arif et al., 2005; Ali et al., 2007). Crop production has been reported to increase with the foliar application of macro and micronutrients (Arif et al., 2006; Grewal et al., 1997).

4.1 Nutrient Management by 4Rs

Nutrient management is the first line of defence in the battle to regulate nitrogen and phosphorus. The 4Rs of nutrition management are right rate, right source, right location and right time. The 4Rs' consistent use will aid in reducing the amount of nutrients that agricultural crops lose into surface and groundwater resources (Fig. 4 and Table 2).

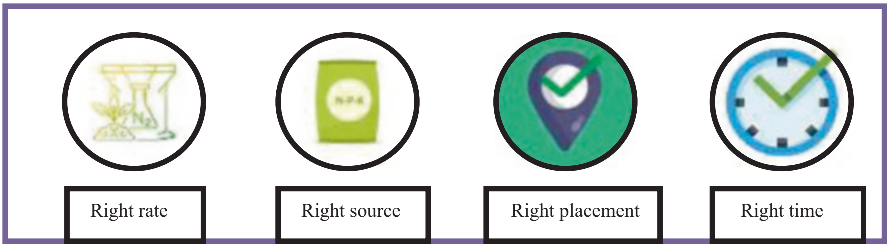

Fig. 4 Principle of 4Rs

Table 2 4R practices for nutrient management

	Practices	Description
1.	Right rate	Match the crop's needs with the amount of fertiliser used. Too little fertiliser results in reduced crop yields and crop quality as well as less residue to preserve and strengthen the soil, while too much fertiliser causes leaching and other environmental losses. The correct rate of fertiliser should be applied, and this can be determined with the aid of realistic yield goals, soil testing, omission plots, crop nutrient budgets, tissue testing, plant analysis, applicator calibration, variable rate technology, crop scouting, record keeping and nutrient management planning
2.	Right source	Match the supply and type of fertiliser to the soil's characteristics and the crop's needs. Balanced application of nitrogen, phosphorus and other nutrients while being aware of their interactions. One of the keys to improving nutrient utilisation efficiency is balanced fertilisation
3.	Right placement	Put and preserve nutrients in areas where plants can use them. The technique of application is essential for effective fertiliser use. The optimum application technique depends on the crop, cropping system and soil characteristics; however, integration is typically the best choice to preserve nutrients and boost their effectiveness. Other best management practices include conservation tillage, buffer strips, cover crops and irrigation management to assist in retaining fertiliser nutrients in their original locations and available to growing crops
4.	Right time	Make nutrients accessible to the crop when it requires them. When a crop's demand matches its availability, nutrients are employed most effectively. Best management strategies that affect the timing of nutrient availability include controlled release technologies, stabilisers and inhibitors, product selection and application timing (pre-plant or split applications)

4.2 Evaluating Outcomes of 4R Practices for Nutrient Management

Within the 4R nutrient, outcomes are evaluated on various levels (Fig. 5). Farmers and their advisors make judgments and put them into practice at the farm level based on local site considerations. A decision's outcome is always evaluated by progressive farmers. If they adhere to the 4R approach to nutrient stewardship, this evaluation of outcome is based on sustainable performance as informed by stakeholders, and it affects the subsequent cycle of decisions.

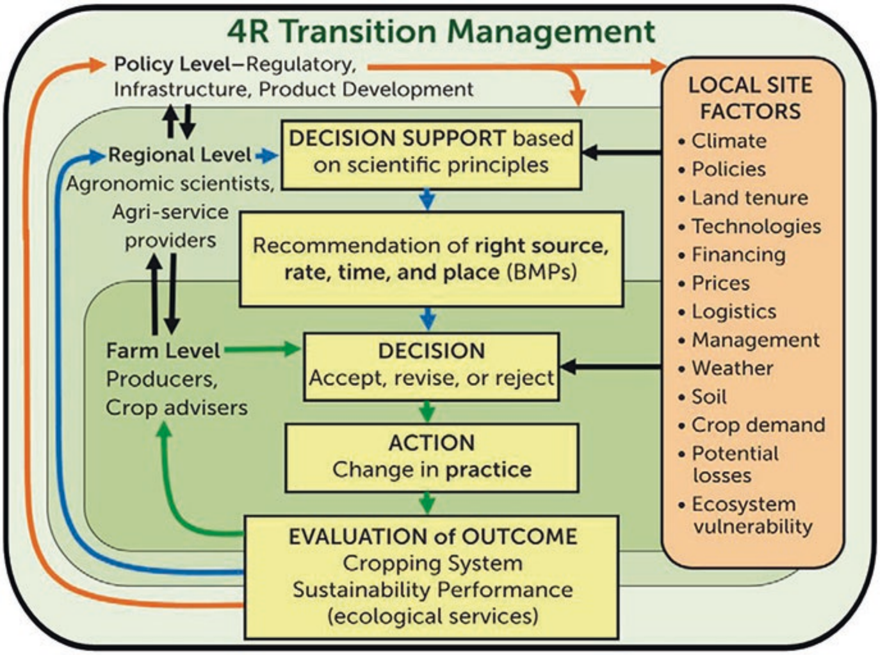

Fig. 5 Evaluation of sustainability performance for 4R nutrient stewardship concept. (Johnston & Bruulsema, 2014)

Agronomic scientists work to give farmers decision-support tools at a more local level. They produce recommendations for the best source, rate, time and location – again, in connection to specific site parameters. Progressive researchers must assess results as well, and if they adhere to the 4R nutrient stewardship model, this assessment of results is based on sustainable performance informed by stakeholders and affects the subsequent amendment of their suggestions. The same is true of policy, which determines the environment in which farmers, advisors and research scientists collaborate and promote research and extension. The ultimate objective is to create an adaptive management process where better management practices result from ongoing assessment (Tables 3 and 4).

4.3 New Strategies of Nutrient Management

This slowing in yield growth rates is likely caused by a decline in the availability of soil nutrients and a reduction in the effectiveness of fertiliser use. Within the next 30 years, yields in all agro-ecologies must rise by 60–70% in order to keep up with population growth (Kumar et al., 2018). Additionally, there will be a significant increase in the demand for nutrients. Over the past 30 years, research has produced

Table 3 Nutrient management practices

	Technology	Description	Potential benefits
		Right rate	
1.	Soil testing	Historically, the most frequently suggested method for determining fertiliser rates is soil testing. In reality, a soil test consists of three parts: Sampling, chemical analysis of the sample and final advice based on the philosophy of the laboratory or advisory service	Making fertiliser rate recommendations Being aware of how to remove nutrients from a field Evaluate the soil's natural capacity to supply nutrients
2.	Nutrient budgets	The balance between crop inputs and outputs can be better understood through nutrient budgets. In essence, they contrast the nutrients added to the soil with those absorbed by crops. A nutrient budget accounts for both the nutrients that are added to a farm and those that are taken away	A precise nutrient budget is a crucial tool for detecting potential issues that may arise from the following: (i) A nutrient surplus (inputs > outputs), which would result in an accumulation of nutrients and an increased risk of loss (ii) A nutrient deficit (outputs > inputs), which would deplete nutrient reserves, increase the risk of deficiencies and result in lower crop yields
3.	Crop scouting	Crop scouting is the practice of carefully evaluating crop performance in order to identify the economic risk posed by nutrient shortage and to assess the possible efficacy of nutrient management strategies. Farmers are typically offered scouting as a paid service as part of integrated nutrient management. Crop problems can now be geo-tagged using handheld computers with GPS and specialised field gear to boost the efficiency of crop scouting	Spotting nutritional deficiencies in crops Quickly taking the necessary corrective action
4.	Variable rate fertiliser applicator	Using a pre-set field map that is created using multiple sorts of information, variable rate fertiliser (VRF) application includes applying varying rates and/or types of fertilisers to uniquely varied soil sections within a field. The goal is to maximise agricultural output and fertiliser inputs	Different rates of fertiliser or manure can be administered to various parts of the field thanks to variable-rate technology Essential for putting precision agriculture into practice
		Right source	
1.	Balanced use of fertiliser	It makes sure fertilisers are applied in the ideal amounts and proportions using the proper techniques, which maintains soil fertility and increases crop output. In contrast to uneven fertiliser, which can cause soil disease and mining, balanced fertilisation promotes soil health	For maintaining soil productivity, balanced fertilisation is essential to improving the applied plant nutrients' ability to be utilised by the plants

(continued)

Table 3 (continued)

	Technology	Description	Potential benefits
		Right placement	
1.	Banding	Any application in which fertiliser is brushed in narrow strips onto or into the soil. Application can be done prior to, during or after seeding (starter), as well as with or near the seed row. Banding may improve crop responsiveness and nutrient efficiency for some nutrients, such as phosphorus and immobile micronutrients, at lower rates	Particularly beneficial when there are low levels of immobile nutrients present, such as phosphate and micronutrients, which may be 'fixed' or immobilised in soils via chemical soil interactions
2.	Broadcasting	Applied to the outside or included. Rapid application technique to quickly cover vast areas. By dispersing nutrients over a larger area of soil, broadcasting may improve nutrient interaction with a larger section of the plant roots	Surface broadcasting is a quick Affordable way for larger application rates when it is necessary to develop low soil-test levels
3.	Cover crop	By utilising extra nutrients from the preceding cash crop, cover crops can stop nutrients from being washed further into the soil profile by percolating water. In production agriculture, grasses and legumes are frequently utilised as cover crops, and the usage of *brassica* species is rising	Assist in the cycle of nutrients Prevent loss of nutrients Improves soil health
		Right time	
1.	Pre-plant incorporation	Pre-plant fertiliser application is the practice of applying fertilisers before seeding or planting. Depending on the nutritional quality of the soil, a pre-plant application's fertiliser dosage will vary	By using this technique, you can ensure that the crop has access to a sufficient supply of nutrients when they are needed by raising the level of soil nutrients to an appropriate level
2.	Controlled-release fertiliser	A granular fertiliser known as a controlled-release fertiliser (CRF) releases nutrients gradually into the soil (i.e. with a controlled release period). Other names for controlled-release fertiliser include controlled-availability, metered-release, delayed-release and slow-acting fertiliser	The usage of CRF is driven by a variety of causes, including more effective fertiliser use CRT guards against chemical harm to crops (fertiliser burn)
3.	Nitrogen stabilisers	Chemicals like NBPT (N-(n-butyl) thiophosphoric triamide), DCD (dicyandiamide) or DMPP are found in nitrogen stabilisers (3,4-dimethylpyrazole phosphate). These substances prevent synthetic nitrogen fertiliser from changing into unstable forms, which causes nitrogen loss	Products that stabilise nitrogen are useful management strategies for reducing fertiliser loss and maximising crop N uptake

Table 4 Research findings on nutrient management practices

	Practice	Findings	References
1.	Soil testing based fertiliser application	On-farm soil fertility testing across different states in Indian SAT showed numerous novel deficits of sulphur (46–96%), boron (56–100%) and zinc (18–85%), in addition to the already recognised shortfalls of phosphorus (21–74%) and nitrogen (11–76%, derived from soil carbon). These findings led to the development of a novel fertiliser management strategy to address the various soil fertility requirements. Nutrient balancing improves nitrogen fertilizer use efficiency in terms of plants uptake from the soil, transport into grains, food production and nutritional quality of grains	Wani et al. (2015)
2.	Nutrient budget	According to a study on nutrient management using the nutrient budget approach, fertilising rubber plantations to promote nutrient usage efficiency is a viable way to increase their sustainability	Brenas et al. (2019)
3.	Variable rate technology	The study on the variable-rate control system for UAV-based granular fertiliser spreader demonstrated that VRT may be utilised to increase labour efficiency and lower production costs in addition to reducing fertiliser use and pollution	Song et al. (2022)
4.	Balanced use of fertiliser	A study on the balanced use of fertiliser has shown that the integration of organic and inorganic sources to provide a balanced supply of nutrients, including micronutrients (Zn, B), was sustainable in terms of crop yield, economic feasibility and maintenance of environmental health. By boosting soil organic C, microbial biomass C and plant accessible nutrient content, this improved recovery efficiency of applied nutrients as well as soil quality	Sarkar et al. (2018)
5.	Banding	The northern Great Plains study on 4R management of phosphorus fertiliser shows that banding P fertiliser in or near the seed row is both environmentally and agronomically advantageous	Grant et al. (2019)
6.	Broadcasting	In a mixed-method study to examine fertiliser sources and application techniques from a nutrient stewardship perspective at the farm level in Punjab, Pakistan's rice-and-wheat growing region, it was discovered that the broadcast method is the most convenient, economical and effective way to apply fertiliser to wheat and rice crops. That is why farmers chose the broadcasting way of applying fertiliser over the other methods, disobeying the suggestions made by scientific research	Ali et al. (2022)
7.	Cover crop	Nutrient cycling is influenced by cover crops, according to research on cover crops for nutrient management. Leaching is likely to cause soil macronutrients like nitrogen (N), phosphorous (P) and potassium (K) to be lost. You can substitute or use less fertiliser from sources other than your own site by planting cover crops (such as inorganic fertilisers and organic fertilisers such as poultry litter and swine sludge)	Farmaha et al. (2022)

(continued)

Table 4 (continued)

	Practice	Findings	References
8.	Controlled-release fertiliser	The study of controlled-release fertiliser (CRF) is essential to the development of sustainable agriculture. It offers a precisely suitable design for nutrient release that is ideal for the physiological and biochemical aspects of plant growth	Vejan et al. (2021)
9.	Nitrogen stabilisers	In a study titled 'impact of nitrogen stabilizer on nitrogen cycling, nitrifying organisms, and winter wheat yield and quality in high rainfall zones of northern Idaho', it was discovered that crop performance was enhanced by the stabilisation of nitrate and the retention of ammonium in the soil	Philpott et al. (2022)

a wide range of specialised technologies and techniques that can be used with various cropping methods. Examples include using new generation fertilisers like supergranules, coated urea, or slow-release fertilisers and customised fertilisers, and precise nutrition management through instruments like the chlorophyll metre and leaf colour charts. Although the importance of the various technologies varies depending on the environment, farmers' choice of NM methods is always influenced by economic rationality and utility. In order to achieve the system- and site-specific farming goals while simultaneously ensuring the long-term conservation of soil and environmental quality, a precise balance of nutrient delivery and removal must be discovered.

4.3.1 New Generation Fertilisers

The development of next-generation fertilisers with slow release and water retention properties has drawn a lot of attention recently because of their crucial roles in the improvement of sustainable agriculture (Benlamlih et al., 2021). Due to inefficiency of soil fertilizers, only 10%–20% of applied nutrients is absorbed and utilized by plants. Fertilisers that are now available must be enhanced in order to increase their bioavailability in soils. Supergranules, coated urea and fertilisers with controlled releases are examples of modern fertilisers. The next generation of long-lasting foliar micronutrient fertilisers is being developed by chemical engineers and researchers in the field of nanomaterials by utilising the advantages of nanotechnology (Fertahi et al., 2020). These techniques might improve the efficiency of P fertilisers while reducing their negative environmental consequences.

4.3.1.1 Speciality Fertilisers

In recent years, a number of fertilisers have become available for use under special situations such as protected cultivation, for high-value crops, for foliar application to fruit trees or for use in fertigation through micro-irrigation (drip irrigation) systems. The main criteria for fertilisers meant for fertigation are that these should be

100% water soluble and are free from any insoluble components, which could clog the nozzles of drip irrigation equipment. A number of such fertilisers have been registered and described in the FCO (Anonymous, 2013).

4.3.1.2 Fortified Fertilisers

SSP fortified with B (boronated SSP) and zincated urea (2% Zn) were the first fortified fertilisers to be developed in India. In recent years complexes such as DAP, 12-32-16, and 10-26-26 have been fortified either with 0.3% B or with 0.5% Zn. Calcium nitrate has been fortified with 0.25% B. Fertilisers fortified with S are also available.

4.3.1.3 Slow-Release/Controlled-Release Fertilisers

Slow-release fertilisers were created due to a desire to conserve nitrogen and regulate the rate at which soluble fertiliser N is released. Controlled-release fertilisers (CRF) and enhanced-efficiency fertilisers (EEF) are acquiring popularity as descriptors for all such fertilisers (EEF). The urea formaldehydes or 'Ureaforms' are the most well-known and longest used of the group. The method for producing ureaform was patented in Germany by BASF in 1924. In the United States, these were patented for use as fertilisers in 1947 and their commercial production began in 1955. Normal ureaform contains 38% nitrogen. The family of ureaforms includes a variety of polymerisation-dependent products. Ureaform is primarily composed of lengthier UF polymers. Methylene ureas (MU), which was developed in the 1960s and later, are polymers with intermediate chain length, whereas methylene diurea (MDU), which was developed in the 1980s, consists of polymers with short chain length.

Eventually, a wide variety of fertilisers with controlled and slow release were created. The isobutylidene diurea (IBDU), which contains 31% N and is 90% water insoluble, deserves special notice among them. Formulations based on IBDU are made in Belgium, Germany and Japan. Crotonylidene diurea, sometimes known as CDU, is another CRF that contains roughly 32% N. It is made in Japan, where the majority of the consumption also occurs.

S-coated urea is one of the most well-known and widely publicised coated fertilisers (SCU). The TVA of the USA created the first S-coated urea in the early 1960s, and a patent was issued for it in 1967 (US Patent 3,295,950). Elemental S was applied to each prill of urea. Bench-scale manufacturing also began in 1961. It was first advertised as 'Gold-N' in the UK. The first commercial production facility was established in the USA after the first large-scale plant for SCU production was established in Canada in the middle of the 1970s. In Japan, S-coated NPK fertilisers have also been created. It is estimated that SCU and a number of other S-coated fertilisers make up roughly 45% of all coated fertiliser manufacturing. Polymer-coated fertilisers are a significant class of CRFs that have changed throughout time.

With the trade name 'Osmocote', these were first made in the USA in 1967. The majority of the goods are polymer-coated NPK products, even though various fertilisers can be coated with polymers. Trenkel (2010) has provided a description of the history and properties of a number of slow- and controlled-release fertilisers, but omits to mention neem.

In India, the properties of neem (*Azadirachta indica*) seed cake or its oil in retarding nitrification and thus conserving applied N were reported in 1971 (Bains et al., 1971). This was later found to be due to the action of tri-terpenes in neem oil. Ordinary urea treated with neem seed cake or neem soil was found to be more efficient than untreated prilled urea. However, it was not until recent years that its commercial potential was tapped by urea manufacturers to produce neem-coated urea (NCU). During 2012–2013, close to 450,000 tonnes of neem-coated urea was produced by a number of urea manufacturers (Chanda & Kuldeep, 2013). Slow-release fertilisers can increase the efficiency of fertiliser N by 10–20% which in any case is substantial (Prasad, 1997).

4.3.1.4 Coated Urea

To regulate the solubility of fertiliser particles in the soil, a number of coatings have been applied. Numerous environmental, financial and yield advantages can be obtained by regulating the rate of nutrient release. The majority of coated fertilisers use urea as their foundation since it has the largest nitrogen content of all commonly used soluble fertilisers. Different resin-based polymers are reacted on the surface of fertiliser granules to create other coated fertilisers (Jadon et al., 2018). Utilising low permeability polyethylene polymers in conjunction with high permeability coatings is another method (Tyagi et al., 2021). Manufacturers use different coating materials and coating techniques. To control the rates at which nutrients are released for specific applications, manufacturers employ a variety of coating materials and coating techniques. They also carefully modify the composition and thickness of fertilizer coating. Specific fertilisers' nutrient release times might range from a few weeks to several months (Fig. 6).

4.3.1.5 Urea Supergranules

To create USG fertiliser, the conventional urea fertiliser is physically altered. Its nature and properties are comparable to those of urea, but its granules are larger, denser and more susceptible to delayed hydrolysis (Table 5). The Urea Supergranule (USG) technology is economical and eco-friendly (Fig. 7). Urea supergranules or urea briquettes are potential materials for smallholder farmers since they can be hand-deep inserted in wetland or irrigated rice fields for fertiliser deep placement (FDP) (Singh 2006).

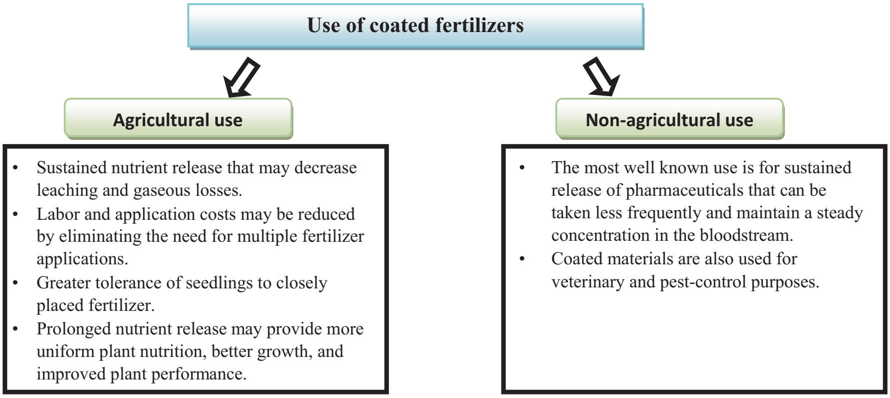

Fig. 6 Use of coated fertilisers

Table 5 To ensure the agronomic effectiveness of deep-placed USG and increase the likelihood of gaining additional yield, the following elements should be taken into account (Sikder et al., 2014)

Soil factors	Use only in soils with a CEC 10 meq 100 g^{-1} and a low water percolation rate
Plant factors	Give attention to kinds of dwarf rice with a short to medium lifespan. Basal deep inserted USG with an appropriate topdressing of N during the panicle start stage might be beneficial for the long duration type.
Management factors	Apply 30–60 kg USG-N ha^{-1} as a base using only the appropriate USG of right weight (1–2 g urea granule). Using the appropriate plant population and modified spacing, place one super granule for every four hills at a soil depth of 7–10 cm. For effective placement of USG by hand or machine, use modified 20 cm × 15 cm or 20 cm × 20 cm spacing

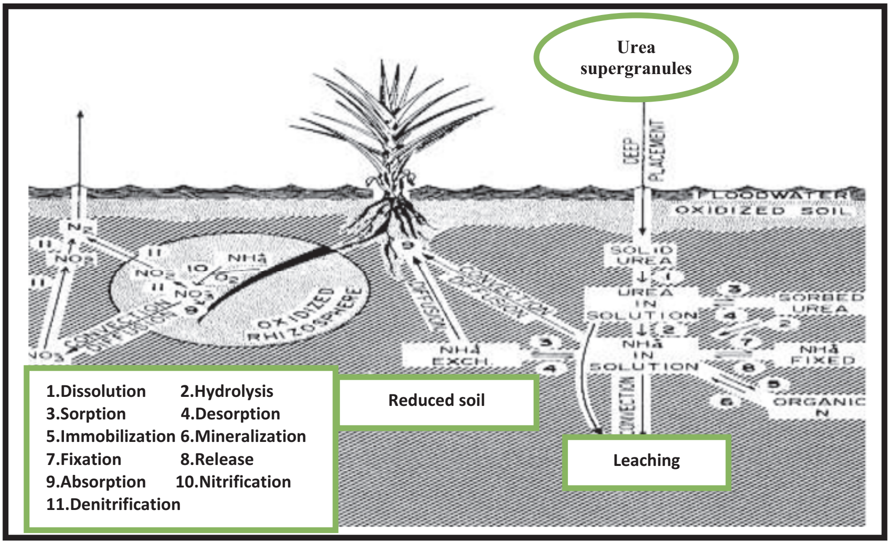

Fig. 7 Overall nitrogen transformation and transport of deep-placed USG N in soil. (Adopted from: Savant & Stangel, 1990)

4.3.1.6 Customised Fertilisers

The idea behind customised fertiliser is to provide plants with a balanced diet. These fertilisers offer the optimum nutritional package for premium quality plant development and yield and are based on reliable scientific research and principles of plant nutrition. They are described as multi-nutrient carriers with the capacity to hold macronutrient and/or micronutrient forms, both from inorganic and organic sources, manufactured through a methodical granulation process, satisfying the crop's nutritional requirements specific to its site, soil, and stage and validated by an accredited fertiliser manufacturing/marketing company's scientific crop model capability (Fig. 8).

It is envisaged that potential manufacturers or marketers will use the software tools, like Decision Support System for the Transfer of Agrotechnology (DSSAT), crop models etc, to identify the best fertiliser grade combinations.

4.3.1.7 Nanotechnology for Nutrient Management

In order to meet the demand for more food from the world's expanding population, nanotechnology has emerged as a breakthrough science (United Nations, 2015). Due to human activities and cultural changes in lifestyle, farmland fertility and productivity have been negatively impacted all over the world. In this aspect, nanotechnology has the ability to meet the future food needs of a growing global population (Fig. 9). By effectively utilising the features of materials at the nanoscale, this technology has improved sustainable agriculture (Ditta & Arshad, 2016).

Nanotechnology has been significant in minimising nutrient losses from the use of conventional fertiliser at the farm level in agricultural crop production. Urban agriculture has become so important to food security and a healthy diet thanks to nanotechnology. Nanoparticles (NPs) are toxic to plants, soil and water (Xiong et al., 2017); however, the end goal of their use in agriculture is to reduce the amount of harmful compounds, such as pesticides and fertilisers, needed in conventional farming (Table 6) (Ditta, 2019; Thakur et al., 2018).

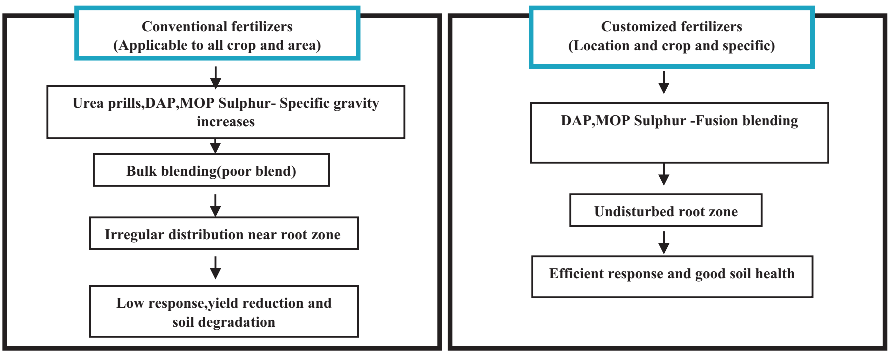

Fig. 8 Diagram showing differences between conventional versus customised fertilisers. (Source: Majumdar & Prakash, 2018)

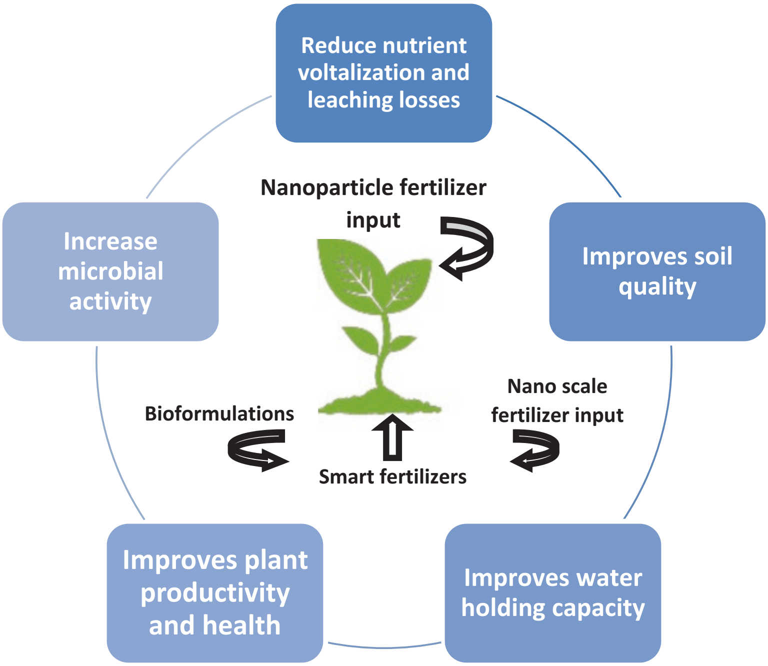

Fig. 9 Potential nanoparticle effect on soil-plant system

Table 6 Examples of potential nanofertiliser designs

Slow release	The nanocapsule slowly releases nutrients over a specified period of time
Quick release	The nanoparticle shell breaks upon contact with a surface (such as striking a leaf)
Specific release	The shell breaks open when it encounters a specific chemical or enzyme
Moisture release	The nanoparticle degrades and releases nutrients in the presence of water
Heat release	The nanoparticle releases nutrients when the temperature exceeds a set point
pH release	The nanoparticle only degrades in specified acid or alkaline conditions
Ultrasound release	The nanoparticle is ruptured by an external ultrasound frequency
Magnetic release	A magnetic nanoparticle ruptures when exposed to a magnetic field

Adapted from Manjunatha et al. (2016)

As an alternative, nanotechnology continues to be at the forefront of improving agriculture and food security by recommending optimum management methods for managing nutrients and soil fertility. The ability to manipulate NPs' properties to achieve specific goals, their effectiveness as a carrier system for delivering nutrients slowly and steadily to specific locations, their low toxicity in comparison to other chemicals and their ease of processing and engineering make them a powerful force for revolutionising agriculture.

4.3.2 Precision Nutrient Management

Precision nutrient management is the science of controlling the geographical and temporal variability in the natural nutrient supply from the soil in order to boost agricultural production systems' productivity, effectiveness and profitability. Understanding the spatial variability of soil is necessary (Jin & Jiang, 2002). Traditionally, a thorough field sample followed by soil testing has been used to determine the geographical and temporal variability of nutrients in soils. This method requires more time and effort. As a result, knowledge of nutrient cycles and the use of precision agriculture techniques to create a nutrient management system that meets the needs of the environment are necessary. At the moment, development of tools such as chlorophyll metres, leaf colour charts, and optical sensors facilitates instant nutrient management decisions (Singh et al., 2020). In order to build a nutrient management system that meets the needs of the plants while also preventing excessive losses from the cycles, knowledge of nutrient cycles and the use of precision agricultural are therefore important (Goff, 2019).

4.3.2.1 Precision Agriculture Technologies Related to Nutrient Management

More technology than ever is accessible for agriculturalists to use (Table 7). The farmer can more readily administer site-specific treatments to specific locations within their fields because many of these technologies are focused on precision agriculture (Goff, 2019). Recent developments demonstrate that geospatial technologies, such as the global positioning system (GPS), geographic information system (GIS), remote sensing and real-time and variable rate applications (VRA), can be used to build need-based fertiliser management in crop fields (Gebbers & Adamchuk, 2010).

If farmers did not accurately record agricultural land from soil tests, yield maps and crop rotations, these technologies would be useless. These are useful tools that give farmers the ability to monitor nutrient intake, identify problem regions and gauge the success of their efforts. Producers can utilise this information to inform their decisions on nutrient management. Producers can now have more exact applications and accurate dosages administered to satisfy plant needs than ever before thanks to data and technologies at their disposal.

4.3.3 Nutrient Expert – an Interactive Decision Tool

In recent years, the International Plant Nutrition Institute (IPNI) has created Nutrient Expert®, a user-friendly, interactive computer-based decision tool for fertiliser recommendations (Pampolino et al., 2012). Whether you have soil testing data or not, it can quickly recommend what nutrients to use in which fields. The tool estimate the potential yield for the farmer's field based on growth conditions, cropping system, nutrient balance, yield, residue management, and fertilizer/manure applied in

Table 7 Precision nutrient management tools

Technology	Description
Optical sensors	To identify the nitrogen stress, optical sensors analyse the visible and near-infrared (NIR) spectral response from plant canopies (Ma et al., 1996). The palisade layer of the leaf's chlorophyll is largely responsible for the reflection of visible light (400–720 nm), while the shape of the mesophyll tissues affects the reflectance of the NIR electromagnetic spectrum (720–1300 nm). The normalised-difference vegetation index (NDVI), which is calculated as (FNIR – FRed)/(FNIR + FRed), where FNIR and FRed are, respectively, the fractions of emitted NIR and red radiation reflected back from the sensed area, provides information about photosynthetic efficiency productivity potential and potential yield.
Global Positioning Satellites (GPS)	The present GPS constellation has 27 slots and is made up of 31 operational satellites in six stationary orbits around the planet (Space Segments, 2018). The GPS receiver can triangulate the user's location if at least three satellites are always in orbit. These days, citizens can use this technology for their own navigational requirements. Global Navigation Satellite System (GLONASS), Compass/BeiDou Navigation Satellite System (CNSS), European Satellite Navigation System (Galileo), and GPS are all current providers (International Committee Members, 2018). With the right software and equipment, these satellite networks can be used. Lightbar guidance systems and yield monitor systems are two agricultural techniques where GPS devices are especially helpful.
Remote sensing	A method that is gaining popularity in the agricultural community is remote sensing. Light reflectance is typically measured by satellites or aircraft. Data on light reflectance can be used to identify parts of a field that might be problematic (McLoud, 2007). Due to their cheaper cost, drones can now be utilised to assist in isolating certain regions within a field. With the aid of this technology, producers may identify possible trouble spots by getting an aerial perspective of a field. Once a region is separated, it can be treated separately from surrounding regions, enabling site-specific treatments.
Chlorophyll meters	Chlorophyll metres are trustworthy substitutes for traditional tissue analysis as methods for evaluating the nitrogen nutritional status of plants. The portable Minolta SPAD502 chlorophyll metre is frequently employed. A rapid, non-destructive hand-held instrument called the SPAD 502 chlorophyll metre (Soil-Plant Analysis Development) was created by Minolta in Osaka, Japan. By using two LEDs (light emitting diodes) that emit red (wavelength = 650 nm) and infrared (wavelength = 940 nm) light while clamping the un-plucked leafy tissue in the metre, it swiftly offers an estimate of the nitrogen status of the leaf as chlorophyll content (Boggs et al., 2003). The range of arbitrary units used to display leaf chlorophyll concentration is 0 to 99.9.
Leaf colour chart	A high-quality plastic strip called a 'leaf colour chart' has numerous shades of green on it, from pale yellowish green to dark green. Beginning 15–20 days after transplanting or sowing until the beginning of blooming, the LCC score of the first completely exposed leaf is measured at intervals of 7–10 days. A predetermined amount of nitrogen fertiliser is supplied whenever the colour of the leaves falls below the critical LCC score.

the previous crop. It also computes the expected N,P and K response in concerned field. Trials conducted with maize and wheat across India validated the effectiveness of 'Nutrient Expert®' based recommendations in increasing crop yields, increasing profits and decreasing greenhouse gas emissions (Sapkota et al., 2014). Almost 90% of smallholder farmers in South Asia do not have access to soil testing, making this a unique tool for implementing site-specific nutrient management on a broad scale. One can download the South Asia version of Nutrient Expert maize and wheat tools from http://software.ipni.net//.

5 Conclusion

A strategy called nutrient management aims to improve production quality while safeguarding the environment for future generations. It depends on the appropriate application of nutrients based on crop needs, conservation, the inclusion of new technology to boost nutrient availability to plants and knowledge sharing between researchers and farmers. Maximising output, preventing on-site deterioration and preventing off-site involvement of applied nutrients are all essential components of proper and sustainable nutrient management. Therefore, it enables policy makers to develop future policies to reduce climate change under various agricultural ecosystems around the world while also saving time and resources.

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Impact on Agricultural Crop Production Under Climate Change Scenario

Saswat K. Kar, Avdhesh Sharma, Suchismita Kar, and Asmit Dey

1 Introduction

Climate changes viz. variations in annual rainfall, global warming, emission of greenhouse gases, decrease of the ozone layer, fluctuations in sea level, heat waves and modification in weeds, pests or microbes had an adverse impact on agriculture and thereby impact crop production and food security worldwide (Wheeler & Von Braun, 2013; Raza et al., 2019). A barrier to the expansion of the farming sector is comprehending how the climate is changing and adapting management strategies to mitigate the barrier to the production of better harvests (Altieri & Nicholls, 2017). Moreover, developed countries are more vulnerable to climate variability than developing states.

Climate change is among the largest environmental issues the world is now facing. The world is getting warmer daily, and the earth is in the grip of global warming daily (Singh & Singh, 2012). Surprisingly, any natural factor is not responsible for this process, but the daily activities of human beings are the leading cause. By 2050, there will be about 10 billion people on the planet, mostly in the regions most

S. K. Kar
Department of Farm Engineering, I.Ag.Sc., BHU, Varanasi, Uttarpradesh, India

ICAR-IISWC, Research Centre, Koraput, Odisha, India

A. Sharma (✉)
Department of Agricultural Economics, NIAS, GNSU, Sasaram, Bihar, India
e-mail: avdhesh.sharma2@bhu.ac.in

S. Kar
Department of Agriculture and Farmers' Empowerment, Odisha, India

A. Dey
Department of Operations Management & Decision Sciences,
Indian Institute of Management, Kashipur, Uttarakhand, India

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impacted by climate change. We have been consuming more fossil fuels, such as coal and oil, which produce CO_2, to power our homes, industries, aeroplanes and cars. We are taking more animal products, which produce methane, one more pollutant. As a result of those gases in the atmosphere trapping part of the sun's energy, the 'Greenhouse Effect' causes the earth to warm up. According to the United Nations (UN), the world is currently 1° warmer than it was in the pre-industrial era (UN, 2022). However, the concern is about the rapid climate change pattern. Furthermore, global warming might become a tragedy in our lives unless we cannot slow it down.

The FCCC, established in 1992, resulting from the UNCED in Rio de Janeiro, laid the groundwork for the eventual stabilization of greenhouse gases in the atmosphere (Freestone, 2016), and in 1994, the convention went into effect. The Kyoto Protocol (1997), which went into effect in 2005, reaffirmed the significance of stabilizing greenhouse gas concentrations in the atmosphere while adhering to the principles of sustainable development (Gupta, 2016). The protocol specifies that developed nations have a responsibility to limit emission levels of six greenhouse gases, namely CO_2, CH_4, N_2O, CFC, HFC and PFC (Nachiappan, 2019). The 'Paris Agreement' was adopted in 2016 by international leaders. The important commitment is to limit rising temperatures to 1.5 or 2° before the year 2100. Global CO_2 levels are still increasing following the accord (Christiansen et al., 2018). So each country sets its targets on how much CO_2 it may emit. The United States left the Paris Agreement by showing that it is increasing their country's financial and economic burden; even Russia and China are accused of not prioritizing their own lofty goals. More coal-fired power stations are being planned for construction in Poland and Turkey. However, some countries are making awareness, which is positive momentum. India is both one of the major producers of greenhouse gases and one of the countries most susceptible to the effects of climate change. The country is already experiencing the consequences of climate change, including water stress, heat waves, droughts, frequent storms, flooding and other negative repercussions on health and livelihoods. India, which has 1.2 billion people and a significant agricultural dependence, would likely see severe effects of ongoing climate change (FAO, 2015). Despite the complexity surrounding predictions for the global climate, India's climate is expected to differ in a number of ways.

Variations in the surface air temperature impact rainfall patterns because of ongoing deforestation, excessive fossil fuel use, air pollution, declining soil fertility and a rise in CO_2 concentration (Wheeler & Von Braun, 2013). Such fluctuations in these parameters over a long period cause either flood or drought. Climate risks like drought are becoming more common throughout ages, which cause a significant danger to humanity's well-being and socioeconomic advancement (Kar et al., 2016, 2018a, b). These abrupt climate changes impact the yield of crops, and their productivity, livestock, dairy and fishery sectors, which adversely influence food security and the global economy (Mishra et al., 2016; Arshad et al., 2017; Hossain et al., 2018; Raza et al., 2019). Also, variation in the temperature and humidity range can increase the insect and pest population, plant disease and uncontrolled spread of weeds in crop fields, which are the other most prominent concern to food security and agricultural productivity (Rosenzweig et al., 2001). Crop production is determined by the relative humidity, which also indirectly impacts disease incidence, pollination, leaf development, photosynthetic rates and plant–water interactions. The production of rice is particularly risky in rainfed locations because of unstable weather, deteriorated soil, water shortages and undeveloped markets. India's agriculture is also at risk due to biodiversity loss, which is impacted by climate change (Kulanthaivelu et al., 2022).

2 Potential Impact of Climate Change on Food Security and Nutritional Availability

The rapid increase in population and a corresponding increase in food demand under this changing climatic scenario is the primary cause of the food crisis, which may lead to global hunger. Climate change directly and indirectly affected the entire food chain, which further threatened food security (Kumar, 2016; Chegere, 2018). Agriculture is the sector that is most at risk from the consequences of climate change (Parry et al., 1999). It immediately impacts crop production and food availability. To achieve food security and self-sufficiency, food production and accessibility should be the primary concern in the global battle against changing climate (Bryant et al., 2000; Smit et al., 2000). Food security is described by FAO (2006) as every person always having physical and economic access to enough, safe and nourishing food to satisfy their dietary needs for an energetic, healthy life. According to FAO (2015), there are four main aspects of food security, i.e. availability, accessibility, utilization, stability, or affordability of food. The changing climatic alternations negatively affect all aspects of food security, reinforcing the other underlying cause of malnutrition that affects the quality of life and environmental health (Kumar, 2016; FAO, 2018).

To sustain food security, there is a need to increase food output and productivity, for that need to adopt diversifying crops and expand the agriculture areas for the higher potential of crop production (Kumar, 2016). However, the current lack of land and water supplies, increasing weather unpredictability brought on by climate change, the rapid rise of the population and the inadequate adoption of climate-smart farming techniques all pose substantial challenges to food security (Parry & Lea, 2009; Tilman et al., 2011; World Bank, 2011; Aulakh & Regmi, 2013; Chegere, 2018). Erratic rainfall results in frequent floods and droughts within the same season; higher temperature and damp conditions increase the chance of insect, pest and disease attacks on crops and decrease food availability, which combined lead to food insecurity (Akudugu et al., 2012). The access to food on the market, its price and productive inputs all have an impact on how easily it may be obtained (FAO, 2015). Food accessibility is negatively influenced by the impact of climate change, which damages the infrastructure, restricts transit on air and sea port terminals and an inefficient transportation system, which may create delays in food transport from producer to consumer (Akudugu et al., 2012). Climate change has an indirect effect on how food is used and produced. Adopting appropriate food processing, storage and usage practices, acquiring and using the appropriate nutrition information to prevent malnutrition all contribute to maintaining adequate food utilization (USAID, 1992; Akudugu et al., 2012). For marginal farmers, the effects of climate change affect household ability and desire to spend on health and education by affecting their income level and stability, which directly affects long-term productivity, development of sustainable livelihoods and food insecurity (FAO, 2015).

Therefore, improving nutrition and ensuring food security for future generations through boosting global food production is a crucial challenge to ending hunger and malnutrition. Additionally, it will try to mitigate the negative consequences of climate change on the environment while accommodating the growing population (Rockstrom et al., 2009; Kumar, 2016). In order to offset the impact of climate change on agricultural and food systems for food security and nutrition, improvements on the ground will have to be made possible through investments, policies and institutions in a variety of fields. Implementing different policies and large-scale investments at the government level should be promoted to encourage the farmer to face natural calamities. The application of crop residues as mulching could enhance crop yield without affecting the environment (Lal, 2004). In order to increase both output and productivity, farmers must be encouraged to use modern agricultural technology, such as farm mechanization, new irrigation infrastructure, efficient post-harvest management procedures and the latest storage techniques.

3 Climate Change Impacts on Agricultural Production

Climate change has a number of detrimental implications on agriculture productivity, water resources, biodiversity at the global level, human health and coastal management (Butler et al., 2007). Climate change results in a decline in agricultural productivity (Arora, 2019; Cline, 2008). The ecological and social systems, which are already under great stress due to fast industrialization, urbanization and economic development, will be further stressed by climate change (Satterthwaite et al., 2010). Rising aerosol emissions from the energy industry and other sources might decrease rainfall, generate more dust and smoke and affect regional and global hydrological processes and crop production (Zhao et al., 2019). The temporal variation in per capita CO_2 emission rate for India and the globe is presented in Fig. 1.

Agricultural activities will be affected by the uncertainty due to monsoonal shifts, which will reduce the lower agricultural productivity (Gornall et al., 2010). Climate change affects agricultural crop production by decreasing yield in many ways. In recent studies, it has been found that the temperature rises to 3° in temperate areas is less harmful than the 2° rise in the temperature of tropical areas for crops which may destroy crop production at the economic level (Mahato, 2014). During the last few years, the erratic rainfall affected Indian agriculture (Kuttippurath et al., 2021; Udayashankara et al., 2016). Because of this disturbance, the farmers are in a

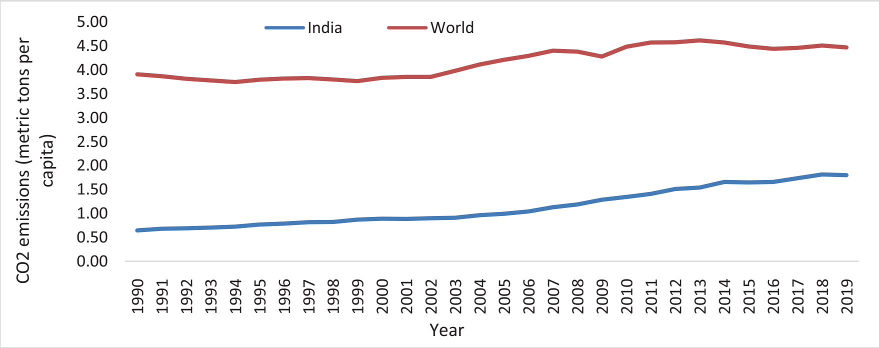

Fig. 1 Temporal variation in per capita CO_2 emission rate for India and the globe. (Source: World Bank, 2020)

dilemma about the timing of crop sowing and harvesting (Mohapatra et al., 2022). The timing and amount of rainfall were also changed (Schär et al., 2016; Pendergrass & Hartmann, 2014), along with rainfall intensity compared to previous years (Calicioglu et al., 2019). Climate change may exacerbate the existing issues in the agriculture system. As a result, the agricultural industry is expected to experience the most severe impact of climate change. Additional financial expenditures will result from upgrading or replacing infrastructures impacted by climate change, such as irrigation systems and infrastructure in the energy and transportation sectors (Maraseni et al., 2012).

4 Potential Effect of Climate Change on Water Resources and Agriculture

Agriculture strongly depends on the hydrological cycle, and climate variability alters the water cycle and its availability, thereby threatening the farming system (Huntington, 2010; Haddeland et al., 2014). A major barrier to agricultural and food production is water shortage and it could be the cause of rising product prices on the global market (Timmer, 2012). Food prices, both locally and globally, can be impacted by even a modest decrease in food production (Kulanthaivelu et al., 2022). The increasing demand for freshwater due to rising urbanization, industrialization and different energy projects, would limit groundwater use for agricultural purposes. It also depletes the water sources, which limits food production more than the per capita requirement of people (Jury & Vaux, 2005; Fereres et al., 2011; Kumar, 2016). Thus, the focus should be placed on the innovation of agronomic practices in accordance with climate change and innovative irrigation methods to save moisture, such as the use of wastewater, use of micro-irrigation systems and careful use of groundwater (Cantero-Martinez et al., 2007; Kirda et al., 2007). Future water shortages may be managed by further limiting post-harvest losses and lowering industry and residential waste (Molden, 2007).

With the inundation of low-lying areas due to sea level rise, the salinity level will also rise in coastal areas, which can indirectly affect crop production (Gopalakrishnan et al., 2019). In order to replenish local water resources, productive agricultural regions in the North rely on spring snowmelt water sources. According to climate predictions, snowmelt will occur earlier, significantly impacting agricultural production due to the unavailability of water during the growing season (Kang et al., 2009). Food Production and Water Supply for Drinking Water and agriculture are inextricably linked because irrigation in India accounts for practically all water use, supporting high agricultural production (Calicioglu et al., 2019). Therefore, the start of the monsoon and its active/break phase is essential to the agriculture industry (Rajeevan et al., 2010).

5 Impact of Climate Change on Crop Disease Incidence

Some pests, such as *Tephritid fruit flies* (which harm fruit and other crops) and *fall* armyworm (*Spodoptera frugiperda*) (which feeds on a growing range of crops, including maize, sorghum and millet), have already spread as a result of the warmer environment. It is also predicted to cause some species, including the desert locust, to alter their migratory paths and geographic distribution (IPPC Secretariat, 2021). Insects would probably widen their geographic range (especially northward). Some pests' abundance will rise due to improved overwintering survival rates and the capacity to produce additional generations (Skendžić *et al.*, 2021). The pathogen, fungus and bacteria's ability to cause disease in plants changes when CO_2, moisture and temperature rise. Farmers may find it difficult to keep insects and pests away from their plants after repeated rainfall events, which leads to more repeated chemical treatments (Ahanger et al., 2013).

6 Climate Change Impact on Post-harvest and Storage Losses of Agricultural Produce

Agriculture will always play a significant role in the production of food and generating income; at the same time, the role of post-harvest practices is also essential for improving income while ensuring food security (FAO, 2013). Numerous factors are responsible for food losses in both pre- and post-harvest systems; among them, the impact of climate variation is one factor (Johnson et al., 2019). Climate change leads to lower potential yield due to pre-harvest losses at the time of crop production and further yield reduction due to post-harvest losses, particularly in the storage condition (Kramer, 1977; Babatola et al., 2008; Kitinoja, 2013; Chegere, 2018;

Johnson et al., 2019). Hence lack of proper pre-harvest and post-harvest systems is another cause of household food insecurity. However, there has been less discussion about post-harvest practices and storage losses in research work (Worldbank, 2011; Chegere, 2018). Food waste and loss are two components of post-harvest loss (Hodges et al., 2011; Aulakh and Regmi, 2013; Chegere, 2018). Additionally, it refers to a reduction in the food's nutritive content, palatability, caloric value, acceptability or any other inherent quality (FAO, 1980; World Bank, 2011). Prior until recently, all studies of how climate change would affect the agricultural sector and the global food supply chain have tended to place more emphasis on agricultural yields and supply than on post-harvest management systems (FAO, 2008). The post-harvest handling practices start from harvesting to consumption, such as harvesting, threshing, husking, drying, primary processing, storage, packaging, transportation, milling, marketing and consumption. A schematic representation of the drivers and effects of climate change on crop production at the consumer level is presented in Fig. 2.

Climatic change has an influence on every stage of the post-harvest system, but the impact of climate variability has the greatest impact on grain storage losses (Johnson et al., 2019). Numerous elements that contribute to storage losses may be divided into two groups: direct losses caused by the actual loss of goods, and indirect losses caused by nutrient and quality loss. Additionally, biotic (insects, pests, rodents and fungus) and abiotic (environmental) variables are to blame for the losses (temperature, humidity and rain) (Abedin et al., 2012; Kumar & Kalita, 2017). Biotic factors cause significant losses during pre-harvest and post-harvest stages due to variations in abiotic factors (Suleiman et al., 2013; Ali et al., 2020). Insect pests and temperature are major factors responsible for the deterioration of quality

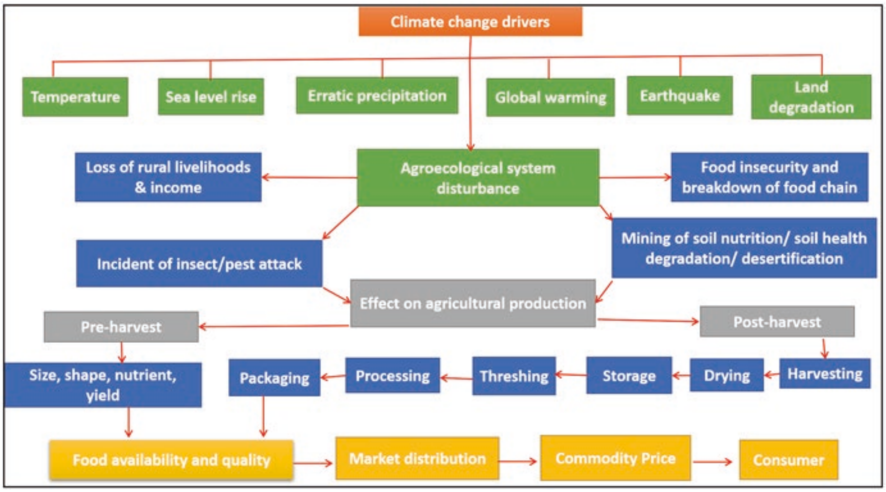

Fig. 2 Schematic representation of the driver and effect of climate change on crop production at the consumer level

of stored grains (Moses et al., 2015). These elements have an impact on food quality either directly or indirectly, which results in post-harvest losses (Kumar& Kalita, 2017). Environmental parameters regulate grain yield at the time of pre-harvest and determine the quality of the commodity during post-harvest storage (Ali et al., 2020).

Alternations of environmental parameters such as the variation in temperature, rainfall and humidity are more reflected during harvesting and storage time as post-harvest losses (Johnson et al., 2019). Variations in moisture, humidity and the optimum temperature will create a suitable atmosphere for toxinogenic fungus to develop and infect the stored items, as well as increase the population of insect pests (Schmidhuber & Tubiello, 2007; Astuti et al., 2013; Suleiman et al., 2013). The possibility of overdrying grains, which results in brittleness and low viability during milling, as well as a decline in product quality and market value, may rise due to the higher temperature. Additionally, increasing temperature during storage has an impact on the nutritional, physiochemical and toxicological properties of grains (Jang et al., 2009). Due to untimely unfavourable damp weather conditions, drying becomes difficult during harvesting, which may cause spoilage or pre-germination and also increase the risk of mycotoxin contamination in grains. It causes higher pre-storage losses, leading to household food insecurity (Chegere, 2018; Johnson et al., 2019).

Typically, grains are kept in storage to provide a year-round supply. The majority of harvested grains are kept in traditional storage facilities, which are inefficient in preventing pre-harvest insect pest infestations and mould growth, and cause increasing contamination and grain losses during post-harvest (Kumar & Kalita, 2017). The extent of disease and insect infestation is influenced by the temperature and humidity of the environment (Qiu, 2009; Moses et al., 2015; Mannaa & Kim, 2017). It is also found that higher humidity and temperature may reduce the effectiveness of the active ingredients of some commercial grain protectants and may also increase chemical and bio-deterioration of stored products which leads to the shorter shelf life of products (Stathers et al., 2013; Chegere, 2018). Insect, pest and disease-associated post-harvest losses of grains and allied products will be more expensive to manage, increasing the risk of global food insecurity and harming farmers' livelihoods (Stathers et al., 2013).

Along with the loss of economic demand (damage) of the produced food, post-harvest losses are also a reason for waste of (include) labour, land, water and non-renewable resources (fertilizer and energy), all of which are utilized in the production, handling and transportation of food product (FAO, 2011; World Bank 2011). Food wastage often occurs at the retail and consumer stage of the supply chain in advanced countries, but in underdeveloped countries, losses occur from the manufacturing to post-harvest stages (CTA, 2012; Johnson et al., 2019).

The use of properly sealed hermetic storage facilities has reduced storage losses by up to 98% and preserved seed viability and quality for a long time (Kumar & Kalita, 2017). The development of an appropriate post-harvest handling system is also necessary for the transportation of food from the time and location of harvest to the consumer. Conduct farmer-level education programmes on the effects of climate change and motivate them to use resilient climate technology through campaigns, workshops, seminars and training. In order to reduce post-harvest losses due to climatic changes, this review suggested that technical advancements and better storage facilities can be quite useful.

7 Climate Change Impact on Food Quality Issues

Variations in environmental parameters can affect the food product's natural microflora, which may provide favourable conditions for the growth of microbes (Janevska et al., 2010). It gradually diminishes the amount and quality of food while also destroying the nutritional content of the products and making the product unsuitable for human consumption. Changes in environmental parameters not only affect crop yield but also reduce the quality of that product while in storage. An increase in temperature decreases the shelf life of insect pests. However, it increases the risk of the rapid growth of insect pests, mould and mycotoxin contamination in stored products, resulting in a decline in quality with the market value of the products (Ali et al., 2020). Climatic alternations cause incredibly high or low temperatures, a rise in CO_2 level concentration, extended drought conditions, reduced groundwater levels and the quality of the produce (De-Pinto et al., 2012). Drought conditions lead to a lack of sufficient soil moisture, which decreases the crop's yield potential and also accelerates the ripening process, which has an impact on how long fruits may be stored after harvest (Henson, 2008). Effect of climatic variables on pre-harvest and post-harvest quality of different crops is presented in Table 1.

The post-harvest quality and storage capability of grains are impacted by prolonged drought and increasing temperatures during the pre-harvest period (Controy et al., 1994). Furthermore, (increasing moisture) build-up moisture in grains during storage reduces protein content and raises free fatty acid concentration, which reduces grain palatability. These factors are all caused by increased rainfall and higher temperatures brought on by climate change during harvest (Moses et al., 2015). High moisture content in the processed product causes rapid growth of insect pests and moulds, which enhances mycotoxin contamination and gradually degrades the product's quality with market value. A higher concentration of CO_2 in the soil reduces the uptake of micronutrients from soil and directly affects the size, shape and nutrient content (Akudugu et al., 2012). Also, the concentration of ozone and CO_2 level in the atmosphere significantly affect the storage life and post-harvest quality of seeds, grains, fruits and vegetables (Ali et al., 2020). The early maturity of the crops without developing the necessary qualities for their post-harvest storage might result in an abundance of yield and inferior quality due to the limited harvest window (Moretti et al., 2010). Crops respond differently to the effects of CO_2 and temperature because during times of stress, soybean plants develop seeds that are higher in protein but lower in oil (Dornbos & Mullen, 1992). Combination stress CO_2 and temperature decreases starch build-up but increases protein content in cereals like barley and wheat, whereas it decreases seed weight but increases seed protein content in *Brassica* species (Savin & Nicolas, 1996; Gan et al., 2004).

Table 1 Effect of climatic variables on pre-harvest and post-harvest quality of different crops

Sl. no.	Climatic variations	Effect on different crops	Reference
Negative impact on crops due to climate change			
1	Increased CO_2 level	Reduces the glucose and raffinose concentration in kidney bean seeds.	Thomas et al. (2009)
		Decrease in concentration of Ca, N, S, Mg, protein, amino acids and increase of gluten composition in wheat cultivars.	Högy and Fangmeier, (2008) and Broberg et al. (2017)
		Common scab, tuber malformation and reduction of sugar contents of potato during postharvest storage.	Högy and Fangmeier (2009)
		During the ripening stage of grapes, there is an increase in dry weight, tartaric acid and sugar levels.	Bindi et al., (2001)
		Reduces the principal nutrients (N, P, Ca, S, Mg, Fe, Zn, Cu) and increases C content in cereals (barley, rice and wheat).	Loladze (2014)
		Decreases protein and increases starch granules in rice which increases chalkiness.	Yang et al. (2007)
2	Increased temperature	It prevents wheat from accumulating too much starch.	Barnabas et al. (2008)
		Reduces the amount of malic acid and the grape's acidity when it is mature.	De Orduna (2010)
		Oleic acid level increase and linoleic acid level decrease with a reduction in the oil of Soya bean seeds.	Thomas et al. (2003)
		Increases the breakage of kernels in rice during grain filling.	Lyman et al. (2013)
		Causes early maturity of cauliflower, celery, lettuce and kiwi fruit, water core in apple.	Hall et al. (1996;) and Wurr et al. (1996)
3	Heat stress	Weight loss of tomato during post-harvest storage.	Gruda (2005), Toivonen and Hodges (2011)
4	Global warming	Changing of taste and texture of apple fruit.	Sugiura et al. (2013) and Ali et al. (2020)

(continued)

Table 1 (continued)

Sl. no.	Climatic variations	Effect on different crops	Reference
5	Increased Ozone concentration	Strawberry ascorbic acid concentration is increased, while the generation of esters is decreased.	Ali et al. (2020)
		Increased levels of lycopene, total carotenoids and lutein in tomatoes. Causes necrosis, and leaf chlorosis and changes sugars and starch composition in tubers, roots, fruit and vegetables.	Moretti et al. (2010)
		Increases in disease susceptibility in soybean.	Eastburn et al. (2010)
		Decreases yield of soybean, wheat and maize.	Porter et al. (2014)
6	Hot climate, high humidity and drought conditions	Aflatoxin production in maize.	Agrimontiet al. (2021)
7	Solar radiation	In mango and citrus fruit, there is less weight, less acid, less juice, more total soluble content and avocados take longer to ripen.	Sites and Reitz (1950) and Woolf et al. (2000)
8	Water stress	Increases dehydration in carrots during postharvest storage. In mangoes, the interior pulp darkening is more severe and the skin is more red, hard and titrable acidity. Reduces flavour in basil.	Shibairo et al. (1998), Pina et al. (2000) and Bekhradi et al. (2015)
9	Rainfall at harvesting stage	It raises the likelihood of fruit rotting, microbial infection and splitting after harvest.	Thompson and Burden (1995)
10	Drought condition	Increased oleic and stearic acid content while reduces the level of fatty acids in peanuts. Reduced total oil content, tocopherols, phenolics and flavonoids contents and increased linolenic acid and oleic acid of maize seeds.	Dwivedi et al. (1996) and Ali et al. (2012)
11	Increased CO_2 level, drought stress and increased temperature	Increased mycotoxigenic mould infestation in stored grain and various edible products.	Magan et al. (2011), Moretti et al. (2019), Medina et al. (2014), and Ali et al. (2020)
12	Drought and increased climatic temperature	Physicochemical damages and growth of insect pests in the stored grains.	Astuti et al. (2013) and Moses et al. (2015)

(continued)

Table 1 (continued)

Sl. no.	Climatic variations	Effect on different crops	Reference
Positive impact on crops due to climate change			
13	Increased CO_2 level	Accelerates the pace of photosynthesis and optimizes the water usage efficiency in C3 crops like wheat and rice.	Porter et al. (2014), FAO (2015)
		Accelerates cassava's photosynthetic rate.	Porter et al. (2014)
		Large starch granules increase in rice. Vitamin E concentration increases in grain, increases the concentration of glucose, fructose and reduces sugars. Browning and acrylamide formation in fried potatoes.	Yang et al. (2007), Zhu et al. (2018), Högy and Fangmeier (2009) and Agrimontiet al. (2021)
		Enhanced antioxidant enzymes activities with an increased shelf life of Button mushroom and Oyster mushroom.	Lin et al. (2017)
		Higher content of proteins in soybean, barley, wheat and *Brassica* species.	Dornbos and Mullen (1992), Savin and Nicolas (1996) and Gan et al. (2004)
14	Increased ozone concentration	Increases firmness, lower disease incidence in Cucumbers. Reduced weight losses, maintain surface colour and soluble solids in carrots. Higher retention of anthocyanins in black mulberry fruit, and maintained the quality of wheat, rice and maize products.	Glowacz et al. (2015), Glowacz and Rees (2016); Sachadyn-Król et al. (2016); de Souza et al. (2018) and Tabakoglu and Karaca (2018)
		Increased cucumber and broccoli shelf life after harvest.	Moretti et al. (2010)
15	UV-C radiation	During postharvest, it boosted the micro- and macronutrients in amaranth and African nightshade, with increased shelf life. Maintained the colour and quality of cucumber fruits. Higher levels of flavonoids and quercetin were found in garlic, which also showed a lower microbial count and retained antioxidant activity. Enhanced storage life in pineapple, maintained surface colour and suppressed browning in oyster and button mushrooms.	Gogo et al. (2017), Imaizumi et al. (2018), Park and Kim (2015), Manzocco et al. (2016), Wang et al. (2017) and Lei et al. (2018)

(continued)

Table 1 (continued)

Sl. no.	Climatic variations	Effect on different crops	Reference
17	UV-B irradiation	Broccoli quality was preserved while being stored.	Lu et al. (2018)
18	Ozonation and drying	Reduced fungal growths in naturally contaminated wheat.	Granella et al. (2018)
19	Drought stress	Tomatoes' shelf life would be extended as a result of weight reduction during the pre-harvest stage and pomegranate taste intensification during storage.	Peña-Estévez et al. (2015), Conesa et al. (2014) and Ali et al. (2020)
20	Increased temperature	A build-up of certain minerals (Ca, Fe and Zn) in soybean seeds and a rise in the amount of flavonoids and antioxidants in strawberry fruits.	Bhat et al. (2017), Wang and Zheng (2001) and Kohler et al. (2019)
Neutral impact on crops due to climate change			
21	Heat stress, salinity and water stress	Quinoa, pearl millet and sorghum are tolerant to heat, salinity and water stresses.	Oudaa and Zohry (2022)

Climate change affects the food quality of stored products, indirectly affecting the market value of post-harvest produce. Maintaining a robust cold supply chain will limit the impact of climate changes by preventing the contamination of edible produce with food poisoning bacteria and by slowing the metabolic activities of the harvested produce. At the same time, UV radiation and O_3 gas can efficiently maintain the food quality and shelf life of food products by destroying harmful pathogens and preserving higher antioxidant capacity (Ali et al., 2020).

8 Economic Loss to Agriculture due to Climate Change

Soon, the global temperature is anticipated to increase by 1.5 °C compared to 1850–1900. However, reaching such a degree of warming might be prevented with rapid and significant reductions in CO_2, methane and other greenhouse gas emissions (WMO, 2022). Rabi crops would be more impacted by the lowest temperature, whereas Kharif crops would be more impacted by rainfall variability. Due to terminal heat stress, wheat is expected to suffer during the Rabi season (Ortiz et al., 2008). For every 1 °C increase in temperature, 4 metric tonnes of wheat are lost. Similarly, the increased level of atmospheric CO_2 will be advantageous for legumes (Goswami, 2017). At the global level, 2–15% less agricultural output will be produced due to climate change by 2050, and it will thus put increased pressure on food prices globally and cause an increase in cultivated area (1–4%) over the same period which will strongly affect the agricultural goods (Delincé et al., 2015).

9 Integrated Application of Remote Sensing Data and GIS Platform for Agricultural Application

9.1 Weather Prediction

Accurate forecasting of climate in agriculture has several potential benefits that allow farmers and other decision-makers to reduce the impacts of unfavourable climatic conditions (Jones et al., 2000). Uncertainty in climate leads to generation of severe economic risks throughout the world as agriculture is involved. Timely forecasting of the adverse weather pattern may reduce the loss and develop coping capacity among farmers. Advanced scientific techniques like air moisture isotope analysis may be used for tracking the hydrological cycle by identifying the source of atmospheric air moisture and understanding the contribution of southwest monsoon and local vapours in rainfall (Krishan et al., 2014). Integrated use of meteorological and satellite data like INSAT, which carries a Very High-Resolution Radiometer (VHRR) to capture visible, infrared and water vapour images, is used for weather surveillance to provide cloud cover, cloud top temperature, sea surface temperature, snow cover, outgoing longwave radiation data along with collection and transmission of other meteorological, hydrological data and warning for upcoming disasters (Kalsi, 2003). The synthesized drought index (SDI)was developed by integrating data from moderate resolution imaging spectro-radiometer (MODIS) and tropical rainfall measuring mission (TRMM) to prepare scenarios of precipitation deficits, soil thermal stress and vegetation growth status to monitor onset, duration, extent and severity of drought (Du et al., 2013).

9.2 Automation in Irrigation System

The automated irrigation system is getting popular over the manual irrigation systems due to its several advantages in terms of efficient water application, high crop yield, energy savings, labour cost and uniform fertilizer application (Yildirim & Demirel, 2011). An automated irrigation system aids in agricultural water consumption optimization in the area having water scarcity and is a cost-effective solution for large fields. It consists of distributed wireless sensor networks of soil moisture and temperature placed in the root zone of the plants or collects canopy temperature data (Evett et al., 2006; Gutiérrez et al., 2013). With the potential to reduce or simplify irrigation management and labour needs while maintaining or boosting yields, an automated irrigation system that monitors stress indicators from the crop itself is a good candidate for adoption (Evett et al., 2000; Evett et al., 2006). Automated irrigation systems could reduce the wastage of irrigation water in the excess application, leaching and run-off losses. Nemali and Iersel (2006) developed an irrigation controller using dielectric moisture sensors coupled with a data logger and solenoid valves that measure volumetric moisture content, and when it drops below the set-point, it automatically irrigates till the water content level is reached. An automated solar power–operated sensor-based irrigation system developed by Uddin et al. (2012) is efficient enough to avoid under or over-irrigation in the field. It consists of sensors installed in the field to monitor the moisture level continuously and send data remotely to the farmer; based on data, the farmer can operate the motor to irrigate the field remotely. A decision support system can precisely manage the quantity of water required to irrigate crops based on real-time soil parameter measurement and climatic variables (Navarro-Hellín et al., 2016).

9.3 Crop Yield Forecasting

Crop yield forecasting helps in mitigating the ill impact of hazards on agriculture and plan accordingly, and also it helps farmers to pre-plan their harvesting time and marketing strategy to fetch a better price. Remote sensing vegetation indices derived from MODIS data integrated with conventional agro-climatic variables are used to improve crop yield forecasting accuracy at regional scales (Kouadio et al., 2014). Using the linear regression method, the crop yield may be estimated and forecasted with an acceptable degree of precision by integrating the majority of the characteristics that affect the crop yield, such as NDVI, soil moisture, surface temperature and rainfall data (Prasad et al., 2006). In case of a lack of high spatial resolution remote sensing data, crop yield estimation can be done by combining this data with the energy balance equation. This novel model's capacity to predict potato production with precision and consistency has been demonstrated (Awad, 2019).

9.4 Crop Disease Detection

Early detection of crop diseases helps adopt suitable measures for preventing further spread of disease and protects the crop from loss. High-resolution remote sensing data can be used to prepare location-specific fungicide application maps during growth stage when fungal infections are expected to occur although it is moderately suitable for detecting crop disease (Franke & Menz, 2007).

10 Conclusion

Mostly agricultural activity is adversely affected by the alterations in climatic conditions. Growth of the plant during the pre-harvest phases is significantly impacted by climate change. Lower protein concentration, decreased micronutrient content and an increase in the synthesis of free acids at the post-harvest stage all have an impact on the quality of stored grains. Using better agricultural practices, adopting climate-smart agriculture technology to develop climate-resilient crops, application of good post-harvest management practices can significantly reduce the negative impact of climate change. There is also a need to increase awareness programs among farmers, extension officers, researchers, NGOs and other stakeholders about the impact of climate-based alternations on pre-harvest and post-harvest storage losses and quality of the stored product, and storage of food product in controlled condition like MAS, CAS and the use of airtight bags to store the grains can be economically effectively adopted by farmers to increase the shelf life of stored products and to reduce storage losses. Training and extension services on the adoption of resilient crop varieties, new harvesting techniques and good storage practices can significantly increase crop production. It can also further improve food availability and help in strengthening food security, poverty alleviation, helping to double the income of smallholder farmers. The nutritional quality of food during storage may alter as a result of climate change, although more thorough research is still needed in this area. In order to reduce the dangers and achieve net-zero goals, we must act immediately.

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Metal(loid) Source and Effects on Peri-Urban Agriculture/Aquaculture Sediments

Preeti Kumari and Pavan Kumar

1 Introduction

In India, peri-urban horticulture is mainly a strategy for achieving food security and economic development. In comparison to rural area, horticultural plants grown in peri-urban areas are generally exposed to a higher level of metal(loid)s. Metal(loid) pollution is a serious menace as the pollutants are ubiquitous having ability to bio-accumulate and bio-magnify in the food chain. Rapid economic development and exogenous input resulted in the introduction of pollutants in soil, water, sediment, as well as biotic organisms. Specifically, the introduction of metal(loid)s is an important concern in sediment, which generally acts as the final sink through receiving atmospheric deposition and/or surface runoff (Zhang et al., 2017). Metal(loid)s in water bodies get deposited in sediments either in soluble, colloid or suspended form, which is liable to be transported to higher trophic levels through the food chain (Araújo et al., 2016; Crémazy et al., 2016; Johari et al., 2020; Giri & Singh, 2015). Metal(loid)s in sediment are regarded as conservative pollutants, though it can release metal(loid)s in water in response to certain natural imbalance (Kumari & Maiti, 2020a, b; Jayaprakash et al., 2015).

Excess amount of metal(loid) deposited in sediments get converted into soil when the river changes its course. The metal(loid)s from sediment may enter either

P. Kumari
Amity Institute of Applied Sciences, Amity University, Ranchi, Jharkhand, India

Department of Environmental Science and Engineering, Indian Institute of Technology (ISM) Dhanbad, Dhanbad, Jharkhand, India

P. Kumar (✉)
Forest Biology and Tree Improvement, College of Horticulture and Forestry, Rani Lakshmi Bai Central Agricultural University, Jhansi, UP, India

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into groundwater through diffusive flux or it may dilute into river water. During the cultivation process, use of river/ground water facilitates the exposure of metal(loid)s into the crops and vegetables grown near to it. These metals may enter into the food chain through dietary intake of crops/vegetables grown in the soil and potentially damage, vital organs such as the kidney and liver, and also cause cardiovascular disease in human (Kumari & Raj, 2024; Giri & Singh, 2015). Inhalation from the atmosphere and dermal exposure are the other methods of metal(loid) exposure in humans (Fig. 1).

Many research articles are available on metal concentration in peri-urban horticulture soils/sediments. Izquierdo and Tuesta (2015) have collected soil samples at a depth of 0–20 cm from a Madrid urban garden in Spain. They have observed the concentration of Cr, Cu, Pb and Zn as 16.93, 37, 98.5 and 139 mg/kg, respectively. Also, they concluded that children playing in the urban garden are exposed to high level of metal(loid) due to accidental ingestion of soil particles while playing. In China, a research was conducted on a vegetable garden by Luo et al., 2011. They have collected soil samples from the depth of 0–15 cm. The vegetable gardens were located near the e-waste processing sites where the process of open incineration and dumping of electronic debris were carried out. They observed the concentration of Cr, Cu, Pb and Zn as 12.3, 324, 95.6 and 122 mg/kg respectively. Also, Laidlaw et al., 2018 have worked on a community garden located in Melbourne, Australia. They collected surface soil samples from the depth of 5 cm. Metal As, Cr, Cu, Pb and Zn as 8, 17, 40, 102 and 218 respectively. Also, they observed high health risk of Pb to the local population.

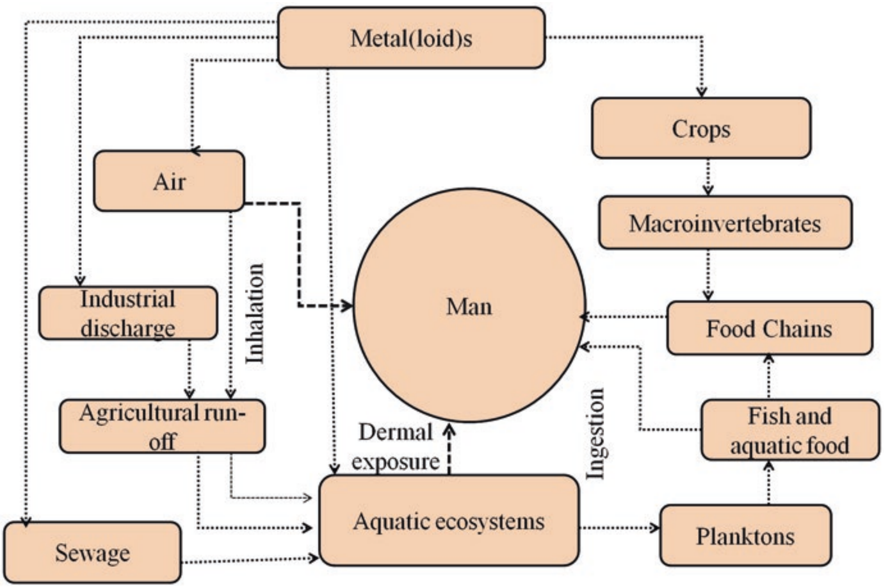

Fig. 1 Human beings are the major metal(loid) exposure population through various process

2 Sources and Effects of Metal (loid)s

Major sources and probable health effects of key metal(loid)s are represented in Table 1.

Metal(loid)s from both natural and anthropogenic sources, including surface runoff, atmospheric deposition, geological weathering, industrial and domestic discharge, agricultural runoff, vehicular emission and more, can be found in any peri-urban horticultural environment (Gupta et al., 2014). Through a number of geochemical processes, horticultural systems give metal(loid) contaminants mobility (Alloway, 2013). Additionally, by depositing pollutants in water and sediment, these horticultural ecosystems may serve as a secondary source (Patel et al., 2018) (Fig. 2).

Following is a discussion of the main sources of metal(loids) and how they affect aquatic species.

Table 1 Natural and anthropogenic sources of metal(loid)s and their possible effects on living beings

Sl. no.	Metal (loid) s	Concentration in sedimentary rocks (in shale)	Natural source	Anthropogenic source	Effects
1	As	13 mg/kg	Volcanic eruption and erosion of As containing rocks	Industrial sewage discharge, smelter operations and mining activities Combustion of fossil fuel for energy production and bricks manufacturing industries Metallurgical process, glass production and medicine preparation Agricultural activities, including irrigation and use of fertilizers Vehicular emission from roads and railways	Adverse effect on the physiological response, ionoregulatory function, growth, reproduction, gene expression, enzyme activities and histopathology

(continued)

Table 1 (continued)

Sl. no.	Metal (loid) s	Concentration in sedimentary rocks (in shale)	Natural source	Anthropogenic source	Effects
2	Cd	0.3 mg/kg	In the form of sulphide ores Found in crude oil and gasoline In lacustrine and oceanic sediment, in oceanic phosphorites, and Mn nodules	Electroplating, chemical sprays and pigments, plastics, batteries, solar cells, alloy and cadmium plating industries Burning of automobile fuel as well as Tyre wear is the form of vehicular emission Sewage sludge and tobacco smoke Phosphate fertilizer based industries	Gene mutation followed by DNA impairment. Abnormal cell growth resulting into cancer of prostate, kidney, liver and stomach Respiratory diseases like pulmonary oedema and even lung cancer in human *Itai Itai* disease Morphological impairment of gills, which further disrupts the plasma ion homeostasis in fish Disrupts homeostasis, ionregulation, endocrinological, histopathological and immunological properties, which affect the growth and reproduction of fish
3	Cr	90 mg/kg	In the shales, river suspended matters and soils	Steel manufacturing, pigment and paint, cement, paper, rubber and textile industries Mining, tanneries, electroplating, dyeing, printing, pharmaceuticals, stainless steel manufacturing, ore reining, chemical and refractory processing, ferrochrome industry, cement manufacturing plant, automobile and leather tanneries and chrome pigments	Impaired respiration and morphological damage of gills Cytotoxic and genotoxic effects on liver, kidney, spleen and gastrointestinal tract Behavioural, cytological, immunological, biochemical and endocrinological deterioration in aquatic organisms Cancer of various organs in human

(continued)

Table 1 (continued)

Sl. no.	Metal (loid) s	Concentration in sedimentary rocks (in shale)	Natural source	Anthropogenic source	Effects
4.	Cu	45 mg/kg	Constituent of minerals in nature; these are, copper pyrites ($CuFeS_2$), Chalcocite (Cu_2S), indigo copper (CuS) and bornite (Cu_5FeS_4)	Smelting, mining, metal plating industries and steel manufacturing plants Sewage sludge, use of fertilizers and algaecides, fungicides and molluscicides Animal manures used in farming	Impairment in ionoregulatory homeostasis, oxidative response, energy metabolism, hepatic activities, immunology, cellular morphology and histology, respiration and neurology, respiration of various organisms Disturbance in gill ionoregulatory function in fishes Stress-causing agents that can potentially alter the biochemical function and cellular morphology Affects energy reserves and level of glycolytic and lipogenic enzymes in some fish species Affect the central nervous system (CNS) in human by restricting the activity of cholinesterase enzymes and disrupting nerve transmission

(continued)

Table 1 (continued)

Sl. no.	Metal (loid) s	Concentration in sedimentary rocks (in shale)	Natural source	Anthropogenic source	Effects
5	Hg	0.4 mg/kg	Occurs in the earth in the form of sulphide ores, such as cinnabar (HgS) Hg forms complex sulphides with metal(loid)s like Zn and Fe	Industrial activities such as mining, coal combustion, chlorine alkali production, waste incineration, thermal power plant, chemical plants, and medicine and electrical industries Organomercuric compound in the form of pesticides and sewage sludge	Mental impairment, limbs abnormalities, retarded growth, excess salivation, dysarthria and lack of organ-coordination Neural disorders as well as brain damage Immunological disorders that may cause huge cell death Renal, cardiovascular, developmental and reproductive abnormalities Affects the development of foetuses, infants, and children through mother and may cause retarded developmental and learning abilities Affects the process of homeostasis in human and causes cardiovascular disorders Decreased fertility rate and the birth of abnormal individuals

(continued)

Table 1 (continued)

Sl. no.	Metal (loid) s	Concentration in sedimentary rocks (in shale)	Natural source	Anthropogenic source	Effects
6	Pb	20 mg/kg	Abundant in atmosphere, lithosphere and hydrosphere mostly in combination with sulphur	Ore smelting, coal burning, and automobile exhaust containing leaded petrol Agricultural runoff from the farming land using lead-containing pesticides Lead smelter, mining activities as well as paint, lead, metal(loid) electroplating, and plastic polymer industries Vehicular traffic (fuel combustion, dust from vehicular components and road dust) and road-making paints	Affects various systems and organs including renal, nervous, growth, reproduction, behaviour and ionic mechanism of fish May alter the haematological parameters and plasma structure in certain fish species Detrimental effect on the process of erythropoiesis, renal function, central nervous system and cardiovascular activities in human May cause the failure of the kidney, liver, heart and muscles. Pb also affects the growth, development and reproduction
7	Zn	95 mg/kg	Forest fire, wind dispersal and volcanic eruption Dead diatoms and live planktons and soft parts of molluscs	Industrial wastes from coal combustion, mining activities, combustion of wastes, batteries plants, electroplating industries and steel manufacturing Application of manure and inorganic fertilizers in the farming sector Sewage discharge and use of cosmetics Corrosion of galvanised product, wearing of vehicle tires, urban runoff, soil erosion, pharmaceutical and pesticides associated wastes	Detrimental effects on morphology, cellular respiration, cardiovascular activities, haematology, reproduction, growth and development in fish Brain, gastrointestinal tract, prostrate, lymphocyte and erythrocyte disorder in fishes Cytotoxicity and DNA damage event in human oral keratinocytes Zn exposure results in stomach cramps, nausea, epigastric pain and vomiting Long-term Zn exposure can affect cholesterol balance, diminish immune system function and even cause infertility in human

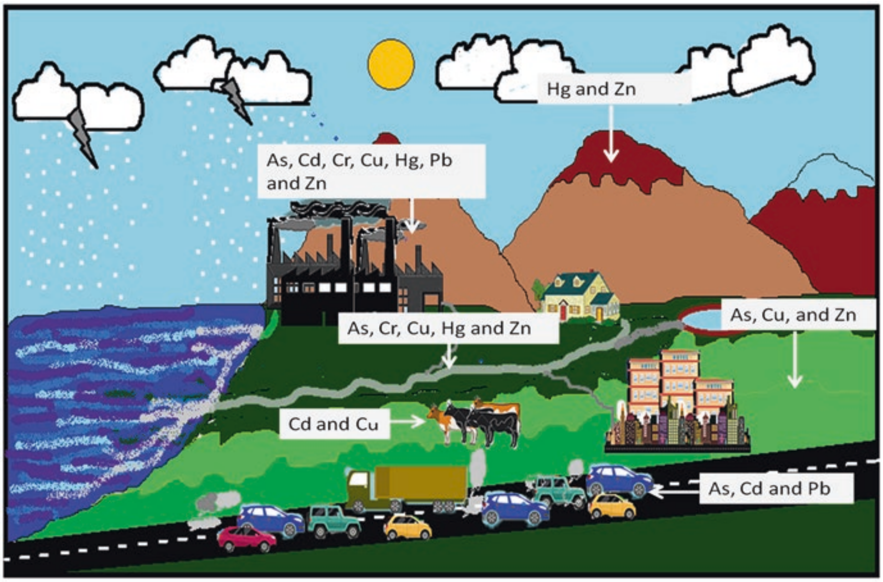

Fig. 2 Major sources of metal(loid) pollution in aquatic ecosystems

2.1 Occurrence, Sources and Effects of Arsenic (As)

Arsenic (As) belonging to the metalloid group is carcinogenic and can produce adverse effects on ecological systems (Bai et al., 2011). It is abundant in earth's crust and biosphere. In the ecosystem, it is present either in trivalent or in pentavalent form. The trivalent form of As is more harmful than pentavalent form. In nature, As is present in more than 300 forms of minerals, the most abundant form of which is sulphides, viz. Arsenopyrites, realgar, cobaltite, Enargite and orpiment (Tabelin et al., 2018).

In sedimentary rocks, the average concentration of As ranges from 5 to 10 mg/kg, whereas in Fe-rich sediments, this concentration is higher and varies between 1 and 2900 mg/kg (Smedley & Kinniburgh, 2002). Moreover, natural activities like volcanic eruption and erosion of As-containing rocks such as of aeolian type are also responsible for elevation of As in the atmosphere (Kumari & Hansdah, 2023; He & Charlet, 2013). Smedley and Kinniburgh (2002) stated that the general concentration of As was higher in groundwater in comparison to surface water because of their close association with rocks as well as the geophysical status underneath the ground favours the As agglomeration. Anthropogenic activities responsible for As concentration in the ecosystem mainly include industrial sewage discharge, smelter operations and mining activities. Combustion of fossil fuel for energy production and brick manufacturing industries also cause problems in the city (He & Charlet, 2013). Also, As extensively used in the metallurgical process, glass production and medicine preparation can contribute to its elevated concentration into the atmosphere (Fishbein, 1981). Moreover, agricultural activities, including irrigation and use of fertilizers, are the human-made activities that also increase the As concentration in the biota (Singh et al., 2016). Fishbein (1981) stated that pesticides contributed about 50% of the total As emission into the ecosystem. Some researcher also blamed vehicular emission from roads and railways for As introduction into the atmosphere. Furthermore, industrial discharge in the form of copper arsenate, arsenic sulphide from As-based pesticides and fertilizer manufacturing industries are the primary source of As pollution in the environment (Ali et al., 2016).

Arsenic can mobilize and transport in the environment through various processes, including precipitation, evaporation, geothermal process and biological activities. Due to the continuous use of fertilizers in agricultural lands, As finds its way into groundwater through the leaching process. In dry climates, As concentration in groundwater increases due to high evaporation rate and extensive use of groundwater. In the saline area, calcite and gypsum act as a sink for As accumulation, which finds its way into the aquatic body through rainfall and irrigation (He & Charlet, 2013). Some arsenic minerals such as arsenopyrites facilitate the leaching process of As rather than precipitation due to the geothermal process. Moreover, certain Fe-reducing bacteria liberating As under reducing conditions can also promote As content in the atmosphere. Besides, the degradation of organic materials in the absence of oxygen also facilitates the release of As in the aquatic body. In fish species, As can produce adverse effects on the physiological response, ionoregulatory function, growth, reproduction, gene expression, enzyme activities and histopathology (Kumar et al., 2019; Kumari et al., 2017). Also, Kumari and Ahsan (2011) reported that As caused glycogenolysis in Indian fish (*Clarias batrachus*).

2.2 Sources and Probable Effects of Accumulation of Cadmium (Cd)

Cadmium (Cd) is one of the rarer earth metals infamous for its bio-accumulative behaviour, persistence (half-life of 10–30 years in humans) and carcinogenic tendency. In nature, Cd exists mainly in the form of sulphide forms in which it follows mostly Zn and Hg and rarely Pb and Cu. In igneous rock, Cd concentration is quite low, whereas, in shale, it is abundant with organic materials. Additionally, Cd is also found in crude oil and gasoline (Goel, 2006). Also, in lacustrine and oceanic sediment, in oceanic phosphorites, and Mn nodules, its level is much higher (Fleischer et al., 1974). However, in sedimentary rocks, Cd content is low in limestone.

Several anthropogenic sources are responsible for Cd accumulation in the ecosystem. About 90% of atmospheric emission of Cd is accounted for following manufacturing industries: (a) electroplating, (b) chemical sprays and pigments, (c) plastics, (d) batteries, (e) solar cells, (f) alloy and cadmium plating and so on. Also, burning of automobile fuel as well as tyre wear is the form of vehicular emission responsible for elevated Cd concentration in the area near to the traffic (Fishbein, 1981). Other sources are smelting and refining of metal(loid) ores as well as burning of coal, plastic and sewage sludge. Sewage sludge often used for filling of lands promotes the leaching process following elevated Cd content in sewage systems. In addition to this, Cd level is also reported for tobacco; hence, smokers are more vulnerable to Cd exposure than that of non-smokers (Goel, 2006).

Cd^{+2}, an ionic form is highly toxic to the biotic world as this may enter into the aquatic environment and can undergo various physical and chemical processes. For instance, it may form a soluble compound or ionic or molecular form that may either find its way into the molecular structure of minerals or accumulate in the biotic or abiotic system through different processes. Similarly, in agricultural land, use of fertilizers results in adsorption of Cd into the soil, which further support the entrance of Cd into the tropical food chain. Mahar et al. (2015) have observed a considerably higher concentration of Cd in the offal of ruminants. Moreover, Cd can potentially be accumulated in the kidney and liver of humans and bind with metallothioneins, metal(loid) binding protein. Being chemically similar to Zn, Cd can be easily absorbed into the animal and plant cells, where it intervenes the Zn-mediated physiological processes and results in gene mutation followed by DNA impairment. This abnormal genetic mutation hinders the cell suicide process (apoptosis) and supports the abnormal cell growth resulting into cancer of prostate, kidney, liver and stomach (Mahar et al., 2015; Tabelin et al., 2018). Also, inhalation of Cd through the air can cause respiratory diseases like pulmonary oedema and even lung cancer in human. Fleischer et al. (1974) stated that at birth, Cd content in human is quite low which increases to an average of 30 mg at the age of 40–50 years, whereas, after 50, Cd content is gradually reduced.

One of the most notable examples of chronic Cd exposure was the first appearance of '*Itai-itai'* disease in Japan in the early decades of the twentieth century. This disease had affected thousands of Japanese population. The leading cause of this disease was the effluent from the mining of Zn and Pb that was discharged into the Jintsu River, which increased the Cd level in the river up to 9 ppm. Irrigation of crops using this contaminated water allowed Cd to enter into the rice, which was the staple food for the local population, hence promoting the daily intake of 100–1000 mg of Cd into their body. This resulted in the *Itai* disease, in which a person suffered from severe pain due to several microfractures in the bones and renal impairments.

According to Kim et al. (2018), the reaction of metal(loid)s in fish species depends on the processes of detoxification, metabolic storage and elimination. The fish body is equipped with a number of physiological defences against metal(loid) poisoning. The most prevalent and widely distributed metal(loid)-binding protein among them is metallothioneins (MT), which contains a lot of cysteine (up to 33% of all residues). Metal(loid) exposure in the gill branchial epithelium causes MT. Due to the abundance of thiol groups in MT, it has the capacity to attach to metal(loid) ions and form complexes, preventing the body from absorbing free Cd ions (Dang et al., 2001). The physiology may be considerably impacted by a high Cd level, which is known to be emitted from phosphate fertilizer, electroplating, chemical, pigment and plastic-based industries (Alloway, 2013; Goel, 2006). Fish have two locations where Cd is taken in from the environment: the gill and the intestine. According to Le Croizier et al. (2018), the order of Cd concentrations is typically: gut > liver > kidney > gill > muscle. According to Dang et al. (2001) and Saibu et al. (2018), gills carry out crucial physiological processes like gaseous exchange, acid-base balance, waste disposal and osmoregulation. Fish plasma ion balance is further disrupted by Cd accumulation in the gills, which affects the morphology of the gills (Dang et al., 2001). Cd enters the digestive system through dietary intake and builds up there. Membrane transporters enable Cd to get absorbed in the intestine. Following the digestive system, the Cd enters the liver and blood circulation before accumulating in the muscular tissue. Cd has a substantial impact on the physiological and metabolic processes in fish species. For example, Cd consumption alters homeostasis, ionregulation, endocrinological, histological and immunological characteristics, which have an impact on fish development and reproduction (Junejo et al., 2019; Le Croizier et al., 2018). Additionally, the biological half-life of Cd in the liver and kidney in some fish species has been shown to be greater than a year, indicating that Cd in fish species may be able to evade elimination systems (Le Croizier et al., 2018).

2.3 Chromium (Cr) as a Key Industrial Pollutant Affecting Living Organisms

Chromium (Cr), in crystalline form, is a steel grey shiny metal found abundantly in the earth's crust as chromite ore ($FeCr_2O_4$). Naturally, the higher concentration of Cr is located in the shales, river suspended matters and soils, whereas, in granite, sandy and carbonate sediments its level is quite low (Alloway, 2013). Most of the Cr content in the atmosphere is the driving mechanism of anthropogenic activities, including mainly the industrial one. Primary industrial sources are (a) steel manufacturing, (b) pigment and paint, (c) cement, (d) paper, (e) rubber and (f) textile industries (Dotaniya et al., 2014).

Moreover, surface runoff from tanneries wastes and domestic sewage contributes to Cr pollution. Some other sources include coal-fired plants, solid waste incinerators and cooling towers (Eisler, 1986). Clausen and Rastogi (1977) collected blood samples of people working in garages and auto repair shops and analysed for metal(loid) content in their blood. Interestingly, they found an elevated concentration of Cr in their blood. They concluded that perhaps welding on old metal plates having chromium-based paints may have resulted in emission of Cr, which may have replaced the Pb present in the petrol/lubricating oil of automobiles. The use of lubricating oils in various automobile applications may have facilitated the dermal exposure of Cr, providing a pathway for Cr to enter into the body of workers.

Being the transition element, Cr exhibits several oxidative states ranging from Cr (−II) to Cr (+VI). Among these Cr (+III) and Cr (+VI) are the most predominant and stable states of Cr. On the contrary, divalent, tetravalent and pentavalent forms of Cr are the unstable forms that are readily converted into Cr (+III), the trivalent form (Dotaniya et al., 2014; Eisler, 1986). The trivalent Cr is less reactive, less membrane permeable, non-corrosive, static and less toxic compound which is dominant under reduced environment. This form of Cr helps in glucose metabolism by binding the insulin hormone to the receptors. Also, Cr (+III) helps in reducing fat, cholesterol and triglyceride level in the body by promoting lipid metabolism (Jobby et al., 2018). On the other hand, Cr (+VI) is highly reactive, corrosive, mobile and toxic compound that can even penetrate the cell membrane due to its high oxidizing potential and then causes gene mutation followed by destructuring of DNA. In soil Cr is mostly found either in an insoluble form ($Cr(OH)_3$) or as Cr (+III), the latter is readily oxidized into Cr (+VI). In the aquatic state, Cr (+VI) is available as $(Cr_2O_7)^{-2}$, $(CrO_4)^{-2}$, $(H_2CrO)^4$ and $(HCrO_4)^-$. The presence of different Cr species depends on various factors mainly include pH, presence of agents (whether oxidizing or reducing), solubility temperature and availability of Cr in the ecosystem.

Elevated concentration of Cr can enter into the food chain and cause harm to the living biota. Cr (+VI) results in retarded growth in plants and causes chlorosis and necrosis diseases in the plant (Jobby et al., 2018). A higher concentration of Cr is often observed in edible fish species, dietary intake of which may increase the carcinogenic risk on human health. Browning and Wise Sr (2017) reported that destructuring of DNA and chromosomal aberration is the driving mechanism of Cr (+VI) mediated lung carcinogenesis, mainly due to the strong influence on the functioning of RAD51, a protein responsible for homologous recombination repair mechanism of DNA present in lung cells. Besides, acute exposure can cause eye and skin irritation and diarrhoea whereas chronic and prolonged exposure can result in haemolysis, pulmonary disorders, deterioration of nerve cells and dysfunction of vital organs such as the kidney and liver (Eisler, 1986). Even a heavy dose of Cr (+VI) can cause death in humans (Jobby et al., 2018).

Even though it is needed in extremely minute levels, chromium is a trace element that is vital for all living things. It is regarded as a vital micronutrient for some species, including humans, and is necessary to numerous biological processes. Chromium, a trace element that is necessary for all living things, is important for fish's physiological and nutritional functions. According to Li et al. (2018), Cr is known to promote growth and development in various fish species, including *Oncorhynchus mykiss*. The main source of Cr is the effluent from industries such as mining, tanneries, electroplating, dyeing, printing, pharmaceuticals, stainless steel production, rubber production, ore reining, chemical and refractory processing, ferrochrome production, cement production, auto and leather tanneries and chrome pigments (Bakshi & Panigrahi, 2018; Mohamed et al., 2020). According to Rowbotham et al. (2000), Cr is found in the environment in the divalent, trivalent and hexavalent oxidation states, with the trivalent and hexavalent states being stable states. Trivalent Cr (Cr-III) is effective in the metabolism of glucose, lipids and proteins because it is less permeable to cellular membranes, non-corrosive and less capable of biomagnifying at the trophic level (Bakshi & Panigrahi, 2018). The structural element of the glucose tolerance factor (GTF), which has the power to enhance the effects of insulin, is Cr (III). Trivalent Cr is less toxic to the aquatic system than hexavalent Cr (Cr-VI), which is more bioavailable and therefore highly toxic to fish

(Li et al., 2018). Additionally, Cr (III) in GTF functions as a cofactor for insulin to transport glucose from the circulation into peripheral tissue. Disrupted respiration and morphological harm to the gills can result from the uptake of dissolved Cr (VI) from the environment through the gill. Cr (VI), which can quickly build in the body's essential organs after passing through the gills, can have cytotoxic and genotoxic effects on the liver, kidney, spleen and gastrointestinal tract. Gills > Liver > Skin > Muscle, according to Bakshi and Panigrahi's (2018) analysis on the pattern of Cr accumulation in fish organs. Reactive oxygen species (ROS) are created within the cell as a result of the metabolic reduction that the Cr (VI) goes through. Due to the disruption of the DNA helix caused by free ROS, the organism may eventually perish (Lunardelli et al., 2018). Fish that have been exposed to Cr (VI) acutely suffer from behavioural, cytological, immunological, biochemical and endocrinological decline. On the other hand, fish may have physiological, haematological, histological and morphological changes as a result of chronic exposure (Bakshi & Panigrahi, 2018). According to Alloway (2013), exposure to Cr causes cancer and birth defects in humans. In contrast, a 1–4 day exposure to less than 2 g of Cr (VI) can cause kidney and liver damage. An oral dose of 2–5 g of Cr (VI) can cause gastrointestinal bleeding, massive water loss, heart obstruction and possibly death (Rowbotham et al., 2000). But according to Costa and Klein (2006), because Cr (VI) is isostructural with sulphate and phosphate at a favourable pH and can spread throughout the body, including the brain, it can induce cancer of many organs in humans.

2.4 Effects and Distribution of Copper (Cu) in Ecosystems

Copper (Cu) is an essential element required for regulating the physiological function of living organisms. It is the vital constituent of enzyme maintaining growth, cardiovascular activity, the flexibility of the lung, performing endocrinological activities and metabolism of Fe (Tabelin et al., 2018). Cu, as a dietary supplement in China, has increased the growth rate and resistance towards disease in animals (Xiong et al., 2010).

In nature, Cu exists in three states: solid forms Cu (0), Cuprous form Cu (+I) and cupric form Cu (+II). Also, Cu is the main constituent of minerals in nature; these are, copper pyrites ($CuFeS_2$), Chalcocite (Cu_2S), indigo copper (CuS) and bornite (Cu_5FeS_4) (Goel, 2006). Human-made processes responsible for Cu in the atmosphere are as follows: (a) smelting, (b) mining, (c) metal plating industries and (d) steel manufacturing plants. Moreover, sewage sludge, use of fertilizers and algaecides, fungicides and molluscicides are also the key sources responsible for Cu emission. Animal manures used in farming and irrigation are the primary input sources of Cu, which has a higher affinity to cause health hazards to humans through accumulation in agricultural lands. In unpolluted river water, the concentration of Cu is 10 μg/L, whereas in polluted water it may exceed up to 60 μg/L. Background Cu content in uncontaminated sediment ranges between 0.8 and 50 mg/kg (Flemming & Trevors, 1989).

Copper is a necessary element for aquatic organisms and humans. It is important for haemoglobin synthesis, haematopoiesis, bone development, metabolic processes, cellular respiration and cyto-biochemistry in living things (Chen et al., 2020). About 12 significant proteins and 30 different types of enzymes that are essential for organism survival use copper as a catalytic co-factor (Monteiro et al., 2009). According to Padrilah et al. (2017), mining waste, agricultural run-off and the use of algaecides and molluscicides are the main sources of Cu. In addition, copper is particularly a poisonous element because, once it enters cells, it cannot be biodegraded (Padrilah et al., 2017). Copper is found in natural water in association with inorganic ions or organic compounds; copper sulphate ($CuSO_4$) is one of these and is extremely hazardous to fish (Carvalho & Fernandes, 2006). Cu is able to connect to proteins within the cell with ease, and nucleic acid disrupts typical cytological processes by causing the transformation of Cu^{2+} and Cu^{1+} and the subsequent production of free radicals (Padrilah et al., 2017). Cu deficiency impairs ionoregulatory homeostasis (Cremazy et al., 2016), oxidative response (Braz-Mota et al., 2018; Carvalho & Fernandes, 2006; Padrilah et al., 2018), energy metabolism (Braz-Mota et al., 2018; Carvalho & Fernandes, 2006), hepatic activities (Monteiro et al., 2009). The most vulnerable organs to stress caused by copper are the gill and kidney. According to Xavier et al. (2019), a high Cu content in the aquatic environment can disrupt gill ionoregulatory function, which has a negative impact on sodium-ion, chloride-ion and occasionally ammonia homeostasis. According to Braz-Mota et al. (2018), elevated Cu is also known to alter some fishes' oxidative reactions. This effect may be caused by the release of reactive oxygen species (ROS) during fish detoxification and repair processes. Cu is also recognized as a stress-inducing substance that has the capacity to change cellular shape and metabolic function (Padrilah et al., 2018; Xavier et al., 2019). Additionally, after exposure to Cu, some fish species, including *Paracheirodon axelrodi*, exhibited changes in their energy metabolism (Braz-Mota et al., 2018). Additionally, according to Carvalho and Fernandes (2006), exposure to copper changes the amount of glycolytic and lipogenic enzymes in various fish species, including *Prochilodus lineatus*, *Ctenopharyngodon idella*, roach, *Rutilus rutilus* and *Larimichthys croceus*. In addition, Cu has a propensity to disrupt nerve transmission and limit the action of cholinesterase enzymes including acetylcholinesterase, butyrylcholinesterase and propionylcholinesterase in the central nervous system (CNS). According to Padrilah et al. (2017), a compromised CNS causes paralysis and possibly death in the organism. Additionally, AnvariFar et al. (2018) observed that increased Cu exposure can result in gill necrosis and damage the chloride cell of the gills in the two fish species *Oreochromis mossambicus* and *Oreochromis niloticus*. According to Grosell et al. (2007), fish mortality from disturbed respiration may also result from elevated Cu concentrations.

2.5 Natural and Anthropogenic Sources and Effects of Mercury (Hg)

Mercury (Hg) is the silvery-white metal(loid) that remains in the liquid state at NTP (Normal Temperature and Pressure). It is extremely volatile element that may be explained by its unique electronic configuration [Xe] $4f^{14}$ $5d^{10}$ $6s^2$, which strongly opposes the removal of electrons from the outer orbit. This is the reason that it behaves like a noble gas and form weak bonds that break even at low temperature. Hg is a rare earth metal that contributes 0.05 mg/kg by mass in average earth's crust. Due to high volatile capacity, Hg can easily escape from its source to the atmosphere and then deposited back into soil and water (Fang et al., 2004; Goel, 2006). Raj et al. (2020) stated that mercury (Hg) could travel a long distance (more than 1000 km) away from their origin of generation. This property of Hg supports its transboundary movement far away from the contaminated sites. Volcanic activities, emission from plants and seafloor, forest fire (Kelly et al., 1996) and geothermal processes are the natural sources of Volatile Hg (Li et al., 2009).

Hg occurs in the earth in the form of sulphide ores, such as cinnabar (HgS). Also, it forms complex sulphides with metal(loid)s like Zn and Fe. Li et al. (2009) have reported that the anthropogenic emission of Hg in India is 149.9 tonne annually. Industrial activities such as mining, coal combustion, chlorine alkali production, waste incineration (Li et al., 2009), thermal power plant, chemical plants, (Hylander & Goodsite, 2006) and medicine and electrical industries (Horvat et al., 2003) are often regarded as anthropogenic sources of Hg emission. Moreover, the introduction of the organomercuric compound in the form of pesticides and sewage sludge are also the key factors for introducing Hg in the ecosystems (Wang et al., 2004).

Hg in nature mainly exists in two species: (a) reactive species: Hg^{2+}, HgX_2, etc. and (b) non-reactive species, like methyl mercury (MeHg) (Alloway, 2013). Hg^{2+} derived from elemental Hg under oxidizing conditions is re-convertible into elemental form. These two forms can be transformed into an organic form, methyl mercury by the interference of certain microbial organisms. Also, monomethyl mercury and Hg^{2+} can be converted into dimethyl mercury by the action of certain bacteria. This monomethyl form of mercury is soluble and bioavailable for accumulation and magnification in the food chain. Whereas the dimethyl form of mercury has a higher volatile affinity; hence, it can be efficiently transmitted from the surface to the atmosphere (Hylander & Goodsite, 2006). The soluble form of Hg is very toxic to human life as it can incorporate into the living organism. Methyl mercury is well known to produce adverse effects as it is teratogenic, mutagenic and carcinogenic to human (Alloway, 2013). Hylander and Goodsite (2006) concluded that Hg is responsible for neurodevelopment abnormalities in about one-third of children belonging to Greenland due to elevated Hg concentration (5.8 μg/L) in their blood. Pregnant woman consuming Hg-contaminated fish can transmit methyl mercury into their unborn child through the placenta. This prenatal exposure of Hg can lead to a disease called congenital Minamata disease, initial symptoms of which are mental impairment, limbs abnormalities, retarded growth, excess salivation, dysarthria and lack of organ-coordination (Goel, 2006). USEPA has also estimated that every year about 630,000 children are born with elevated Hg level in their blood (Jiang et al., 2006).

The First outbreak of Hg poisoning was the Minamata disease in Minamata city in Japan in the middle of the twentieth century. People of Japan were exposed to Hg through the consumption of Hg contaminated seafood and fish. This resulted in the death of hundreds of people, whereas 2217 people were severely affected by neural disorders as well as brain damage (Jiang et al., 2006; Wang et al., 2004). In the late twentieth century, another case of Hg poisoning was reported in Iraq, where approximately 10,000 people died, and 100,000 people suffered from brain damage due to the dietary intake of seed grains treated with fungicides containing methyl mercury (Li et al., 2009).

Power stations, energy-producing facilities, fossil fuel combustion and coal-mediated industries are the main anthropogenic sources of mercury (Okpala et al., 2018). Mercury can be found in the environment in three different chemical forms: elemental, inorganic and organic. Water rarely contains the elemental form of mercury (Hg^0), which is highly volatile and less accessible. Hg^+ and Hg^{+2} compounds, which are typically present in dental amalgams, fungicides, cosmetics, paints and some tattoo colours, are examples of inorganic mercury (Esser, 2016). By either a photochemical reaction or by sulphate-reducing bacteria that live in sediment and the gills and guts of fish, inorganic mercury is transformed into organic forms (such as methylmercury, ethylmercury and phenylmercury) (Okpala et al., 2018). Because it can build up in higher trophic levels through the processes of bioaccumulation and biomagnification, methylmercury (MeHg), one of the organic forms of mercury, is among the most dangerous to living things (Eagles-Smith et al., 2016). Because MeHg is non-soluble and can evade the body's natural elimination mechanisms, the human population is vulnerable to exposure to it through the consumption of aquatic food like fish (Okpala et al., 2018). According to Okpala et al. (2018), exposure to fish Hg can lead to immunological disorders like impaired haematopoietic viability, reduced leucopoiesis, osmoregulatory dysfunction and thymocyte enrichment, which can result in significant cell death. Humans who consume food polluted with Hg run the risk of having serious health problems. Even low levels of Hg exposure are linked to problems in the nervous system, immune system, kidneys, cardiovascular system, development, (Zheng et al., 2019) and reproductive system (Zahir et al., 2005). Through the mother, Hg can have a serious impact on a child's development, including learning and developmental delays (Zheng et al., 2019). Adult exposure to Hg, however, may cause inattentiveness, loss of hearing and vision, increased fatigue and memory loss (Zahir et al., 2005). In addition, a high Hg level might increase plasma creatinine levels and lead to kidney failure (Ursinyova et al., 2019). Additionally, Hg exposure damages human homeostasis and results in cardiovascular diseases (Okpala et al., 2018). Furthermore, Hg ingestion may lead to a lower fertility rate and the birth of abnormal people, according to Zahir et al. (2005).

2.6 Source of Lead (Pb) and Its Effects on Living Biota

Lead (Pb) is a malleable metal with high density (11.34 g/cm^3) but a relatively low (327.46 C) melting point. It is abundant in the atmosphere, lithosphere and hydrosphere, mostly in combination with sulphur. The most common ore of Pb is galena (PbS) occurs mainly with Zn ore on earth. In igneous rocks, the average concentration of Pb is 30 mg/kg, whereas, in sedimentary rocks, the concentration varies from 7 to 150 mg/kg. Having volatility, Pb compounds facilitate the emission of Pb during high-temperature activities such as ore smelting, coal burning and automobile exhaust containing leaded petrol (Alloway, 2013). Agricultural runoff from the farming land using lead-containing pesticides, for instance, lead arsenate can cause an elevated level of Pb in aquatic systems. The industries using Pb for performing various operations such as battery, paint, ceramic, cable insulation, plastics and so on emit a considerable amount of Pb into the atmosphere. Emission from bricks manufacturing industries, which are one of the largest coal-consuming industries, is the major source of atmospheric Pb. Apart from this, vehicular emission despite using unleaded petrol can contribute to Pb emission in the atmosphere. Zheng et al. (2004) collected samples of PM10 airborne particles from seven sampling stations at Shanghai, China. After analysis, they concluded that though the contribution of vehicular emission from automobiles has reduced, but it was still significant at around 20% of total Pb contents. Gioia et al. (2017) also collected aerosol samples from 39 cities in Brazil. They found the significant Pb content in the aerosols despite phasing out of leaded petrol, may be attributed to the use of Pb isotope signature due to a large number of vehicles in the cities. They also identified dust from automotive components and roads as the source of Pb emission in the atmosphere. Goel (2006) had identified cigarettes as a major source of Pb for the person consuming it. He reported that an average cigarette might contain 0.0008 mg of Pb, so a chain smoker is exposed to about 0.0048 mg of Pb per day, out of which, the body absorbs 50% of Pb while the rest is eliminated.

Pb is a highly toxic metal and may enter into a human through three pathways: dermal exposure, dietary intake and nasal exposure. Persons working in Pb smelting plants generally suffer from nervous system disorders and impairment of the kidney and lungs (Tabelin et al., 2018). In infants and children, Pb exposure can lead to retarded mental growth, neurological and physical disorder (Mahar et al., 2015). Even exposure of Pb in a pregnant woman can cause retarded growth and miscarriage of the unborn child. Also, Pb in the human body can mediate the synthesis of enzyme and protein, resulting in the denaturing of these compounds. Inorganic Pb in the blood can disrupt the synthesis of haemoglobin and cause anaemia. However, mild Pb exposure can cause insomnia, restlessness, loss of hunger and gastrointestinal disorders (Goel, 2006).

Since more than 6000 years ago (Adiana et al., 2017), lead has been used to make glass, paint, fuel derivatives, batteries, electronics and cosmetics. Lead is a non-essential, adaptable, subtle and poisonous element (Matouke & Mustapha, 2018). According to Friesl-Hanl et al. (2009), mining operations, paint, lead, metal(loid) electroplating and plastic polymer industries are all potential sources of Pb in the environment (Omar et al., 2019). In addition to this, the main Pb source in aquatic systems is vehicular traffic, which includes fuel burning, road dust and dust from vehicle components (Gioia et al., 2017). Pb in fish is mostly derived from water and fish, like other metal(loid)s. The renal, neurological, growth, reproduction, behaviour and ionic mechanism of fish are among the systems and organs that are affected by Pb toxicity. Additionally, dietary Pb exposure in fish may change the plasma structure and haematological parameters in several fish species (Kim & Kang, 2017). Due to aberrant elongation of tailed nucleoids in fish erythrocytes, Pb compounds have an impact on the micronucleus, chromosomal abnormalities and DNA impairment within the cell (Pham, 2020). Fish consumption is one of the main ways that humans are exposed to Pb. According to Papanikolaou et al. (2005), Pb exposure has a negative impact on the process of erythropoiesis, renal function, central nervous system and cardiovascular functions. Due to the exposure, lead found its way into the bloodstream and was carried to the bones, soft tissues and numerous organs. Only 1% of the absorbed Pb is found in the plasma or serum, whereas 99% of it accumulates in the erythrocytes in the blood. The availability of Ca, Zn and Fe ions affects the absorption of Pb in the blood circulation. Through plasma, the Pb is delivered to the body's critical organs, including the brain, lung, spleen, kidney, bones and teeth. In addition, Pb is transported through the bloodstream to bones and soft tissue, where it can remain for up to 40 days and 30 years, respectively. During the actions of bone metabolism, the accumulated Pb is released into the blood and has harmful effects. According to Kim and Kang (2017), Pb may have a negative impact on the blood system by interfering with the production of haemoglobin and altering the structure of erythrocytes, which results in anaemia and a decreased haematocrit. According to Megasari et al. (2019), exposure to Pb may lower blood levels of haemoglobin, which may ultimately affect neurology and intellectual function. In addition to memory loss, long-term Pb exposure also causes mental disorders, lack of focus, sleeplessness, disorientation and coma in humans (Adiana et al., 2017; Jia et al., 2017; Omar et al., 2019). Additionally, Pb exposure can boost the production of immunological mediators and inflammatory cytokines, which has an impact on the immune system (Yin et al., 2018). The failure of the kidney, liver, heart and muscles may also result from Pb exposure (Adiana et al., 2017; Jia et al., 2017). Pb also has an impact on a species' ability to grow, develop and reproduce (Matouke & Mustapha, 2018). Pb can, like Hg, cross placental barriers, enter the foetal bloodstream and interfere with a child's ability to grow their brain (Tang et al., 2016).

2.7 Abundance and Effects of Zinc (Zn)

Zinc (Zn) is an essential constituent of enzymes that aids in protein metabolism, energy generation and maintaining the structural rigidity of cellular membranes (Hänsch & Mendel, 2009). Zn deficiency can cause retarded growth, loss of reproduction and impediment in immune responses (Alloway, 2013; Tabelin et al., 2018). Moreover, Zn plays a key role in DNA stabilization and genetic expression as Zn is the constituent of associated enzymes such as DNA-polymerases, RNA-polymerases and histone deacetylases. There are several Zn-mediated enzymes present in the chloroplast of the plant cell which plays a vital role in cellular activities (Hänsch & Mendel, 2009). Also, in humans, Zn is essential for the synthesis of luteinizing and follicle-stimulating hormones that help in reproductive metabolisms such as the formation of sperm, development of secondary sexual characters and fertilization of eggs (Tabelin et al., 2018). Naturally, up to 15% of Zn is found in zinc sulphide ores viz. sphalerite or wurzite. Moreover, the average Zn content in igneous rocks is 48–240 mg/kg and 5–140 mg/kg in basalt and granite rocks, respectively. Additionally, in sedimentary rocks, the concentration of Zn for shales and clay, black shales and sandstone are 18–180 mg/kg, 34–1500 mg/kg and 2–41 mg/kg, respectively (Alloway, 2013).

Alloway (2013) reported that about 40% of the Zn emission in 1983 accounted for natural sources, mainly including forest fire, wind dispersal and volcanic eruption. In contrast, the remaining 60% of Zn emission accounted for anthropogenic activities. Anthropogenic sources of Zn are mostly industrial wastes from coal combustion, mining activities, combustion of wastes, batteries plants, electroplating industries and steel manufacturing (Warren, 1981). Less than 1% of the atmospheric Zn is associated with aerosol which can settle down into sediment through wet or dry deposition. Application of manure and inorganic fertilizers in the farming sector are also the major sources of Zn pollution in the sediment. Through surface runoff, these materials may be transported into the riverine body and liberate Zn.

Moreover, sewage discharge and use of cosmetics are the domestic sources of Zn pollution in the aquatic ecosystem. Once accumulating in the aquatic body, Zn can participate in several chemical reactions, including precipitation, dissolution, adsorption and solution complexation and become bioavailable for living organisms (Alloway, 2013). Warren (1981) observed a higher concentration of Zn in the dead diatoms and live planktons. Soft parts of molluscs contain a high level of Zn in comparison to its calcareous part. After the death of these organisms, Zn liberates from them and integrates into sediments.

Zinc is a necessary micronutrient that is important for cell structure, enzymatic activity, lipid, protein, and carbohydrate metabolism, cellular signal recognition, transcriptional regulation, DNA and protein synthesis, normal body growth and reproduction (Kumar et al., 2011; Sanyal et al., 2017; Chen et al., 2018; Wu et al., 2016; Leitemperger et al., 2019; Zheng et al., 2016). According to Abdel-Tawwab et al. (2016), Zn is a ubiquitous element that cannot be biologically depleted or change from one organic complex or oxidative state to another. According to research by McRae et al. (2016), urban runoff, tire wear, soil erosion and wastes related to pharmaceuticals and pesticides are the main sources of zinc in the aquatic environment (Driessnack et al., 2017; Kori-Siakpere & Ubogu, 2008; Kumar et al., 2020). Zinc has negative impacts on fish morphology, cellular respiration, cardiovascular activity, haematology, reproduction, growth and development. According to Plum et al. (2010), Zn exposure in humans causes disorders of the brain, digestive system, prostate, lymphocytes and erythrocytes as well as a Cu deficit. According to Feng et al. (2002), prostate cells that have too much zinc undergo apoptosis. In addition, excess Zn in the human body has been linked to DNA damage and cytotoxicity in human oral keratinocytes as a result of oral ingestion, according to Sharif et al. (2012). Additionally, Zn exposure causes nausea, vomiting, epigastric pain and cramping in the stomach (Plum et al., 2010). According to Zhang et al. (2012), long-term Zn exposure can impair immune system performance, alter cholesterol balance and even result in infertility.

3 Sediment-Based Indices

3.1 Ecological Risk Index (ERI)

In 1980, Hakanson (1980) developed the ecological risk index calculation method aiming to provide a fast and simple quantitative value on potential ecological risk of given pollution characteristics of freshwater ecosystems. Later on, an initial ecological risk assessment framework was provided in 1992 by USEPA for managing the pollution status of industrial sites (Hua et al., 2017). However, in this framework, the decision of managers and stakeholders were ignored. Meanwhile, some other countries around the world were involved in modifying the ecological risk assessment methods. Finally, in 1998, USEPA provided a guideline for assessing the ecological risk, consisting of three phases: problem formulation, risk analysis and risk characterization (Hope, 2006). This guideline was successful in assessing the ecological status of the ecosystems taking into account the suggestion of assessors, managers and stakeholders, to ease taking decisions regarding environmental protection. Now, the ecological risk assessment method has emerged as a fruitful method to assess the probable risk to support an early warning sign, so that suitable measures can be adopted on time. Over the past decades, ecological risk assessment has been used by researchers and policymakers to assess the ecological status of the aquatic bodies. In India, the ecological risk index has been extensively used to monitor the health of rivers (Giri & Singh, 2015; Gupta et al., 2014), lakes (Suresh et al., 2012) and canals.

ERI is calculated using the following equation (Giri & Singh, 2015; Gupta et al., 2014).

$$Er_i = Tr_i Cf_i$$

$$Cf_i = C_i / C_b$$

$$\mathrm{ERI} = \sum Er_i$$

Where Er_i is the potential ecological risk factor of ith metal(loid), Cf_i is the contamination factor for ith element, Tr_i is the toxic response factor of ith element provided by Hakanson (1980), C_i is the concentration of the ith element in sediment, C_b is the background value of earth shale and ERI is the ecological risk index. In Indian lakes and rivers, ERI has been extensively used to rank the sediment into four major categories: (a) low risk ($Er_i < 40$, ERI ≤ 110); (b) moderate risk ($40 \leq Er_i < 80$, $110 <$ ERI ≤ 220); (c) considerable risk ($80 \leq Er_i < 160$, $220 <$ ERI ≤ 440); and (d) higher ecological risk ($Er_i > 160$, ERI > 440).

Several articles are available on literature, identifying the ecological condition of lakes and rivers. Swarnalatha et al. (2013) have worked on the Akkulam Veli Lake in Kerala and assessed the ecological risk through Er_i and ERI. They observed the low ecological risk in the Akkulam Veli Lake sediment. Suresh et al. (2012) assessed the metal(loid) pollution and observed that Vembanad Lake sediment was at low risk with Cr, Cu, Ni, Pb and Zn. Also, the lake sediment was at considerable risk of Cd based on Er_i. However, the overall ecological risk index (ERI) suggested that the Vembanad Lake was at considerable risk due to metal(loid) exposure.

Kumar et al. (2019) studied the ecological risk in a Himalayan river, Beas River sediment and based on Er_i and ERI calculations, they observed that the river sediment was at low ecological risk due to exposure of individual metal(loid). Ganga River is another Himalayan river with the largest catchment area constituted by its tributaries. Gupta et al. (2014) analysed ecological risk in one of the tributaries of the Ganga River, Gomti River sediment. They observed that the river sediment was at low ecological risk due to Cr, Cu, Ni, Pb and Zn. However, Er_i values of Cd suggested that the river was at considerable to higher ecological risk due to Cd. Besides, ERI values of Gomti River suggested the considerable to higher ecological risk due to metal(loid) pollution. Siddiqui et al. (2019) have analysed the ecological risk in seven tributaries of the Ganga River and the average Er_i values suggested that these tributaries were low polluted with Cr, Cu, Pb, Ni and Zn. While the tributaries are at moderate to considerable ecological risk due to Cd exposure. However, the tributaries were at moderate to considerable ecological risk as far as ERI value is concerned. Some studies are also available on ecological risk assessment concerning south Indian rivers. According to Paramasivam et al. (2015), ecological risk analysis of Vaigai River suggested that the river sediment was at low ecological risk from Cr, Cu, Ni, Pb and Zn pollution, but at moderate risk due to Cd exposure. Also, the ERI value of Vaigai River suggested potentially low ecological risk due to metal(loid) exposure. The study on another South Indian, Swarnamukhi River showed the low to moderate ecological risk due to metal(loid) (Cr, Cu, Pb and Zn) exposure. Hence, it is observed that being the highly populated and economically developing regions, urban ecosystems of India is facing a moderate to high ecological risk. But a few literatures are available on the ecological risk assessment of the urban ecosystems, which urgently needed to be addressed.

3.2 Contamination Factor (C_f^i) and Degree of Contamination (C_d)

Contamination factor (C_f^i) is one of the multiple-element contamination indices used to assess the sediment quality of the aquatic ecosystem. It is the simplest and most direct method which compares the metal(loid) concentration with the reference or background value. Due to the lack of regional background value, generally, the average shale values of earth's crust is considered for assessment (Kumar et al., 2017). For the calculation of C_f^i, at least five sediment samples are required. C_f^i is the ratio of metal(loid) concentration in sediment sample and water.

$$C_f^i = \frac{C_m^i}{B_m^i}$$

Where C_m^i is the concentration of the *i*th element in the sediment and B_m^i is the average shale value of earth's crust for the *i*th element. Hakanson (1980) has classified sediment into four types, (a) low contaminated ($C_f^i < 1$), moderate contaminated ($1 \leq C_f^i \leq 3$), considerable contaminated ($3 \leq C_f^i \leq 6$) and very high contaminated ($C_f^i \geq 6$). On the other hand, degree of contamination (C_d) is the sum of the contamination factors for each metal(loid), hence provides a single value for classification of sediment. Generally, $C_d < 6$ is considered as low contamination; $6 \leq C_d < 12$ as moderate contamination; $12 \leq C_d < 24$ as considerable contamination and $C_d > 24$ as very high contamination of sediment.

In India several articles used C_f^i to assess the sediment quality of lakes and rivers. Priju and Narayana (2007) have monitored the metal(loid) concentrations of Vembanad Lake sediment. Based on C_f^i value, it was observed that generally, the study sites were moderate contaminated with Cu, Ni, Co and Zn. However, most of the sites were highly contaminated with Cd. Suresh et al. (2012) have assessed the metal contamination in Veeranam Lake sediment by calculating C_f^i. Based on their calculations, it was observed that the lake was moderately contaminated with Cr, Cu, Ni, Pb and Zn, but considerably contaminated with Cd. The degree of contamination, C_d, 12.23 suggested that the Veeranam Lake was considerable contaminated. Swarnalatha et al. (2013) have worked on metal(loid) contamination in Akkulam-Veli Lake in south India. After calculating C_f^i, they observed that the sites were low contaminated with Ni, moderately contaminated with Cr, Zn, Cu and Co and considerable contaminated with Pb. The C_d value calculated (10.55) suggested that the Akkulam-Veli Lake was moderately contaminated with metal(loid) pollution. Gopal et al. (2017) have also worked on Yercaud Lake, a lake located in south India. Their observations based on C_f^i calculations suggested that the lake was highly contaminated with Cu, considerably contaminated with Cr, Cu, moderately contaminated with Fe, Pb, Zn Ni, and low contaminated with Mn. A study based on C_f^i calculation of Chilka Lake sediment in Odisha, India showed that the lake was low contaminated with Fe, Pb, Cr, Ni, Co, Zn, Cu; moderate contaminated with Mn and very high contaminated with Cd and Hg (Banerjee et al., 2017). Moreover, the C_d value of Chilika Lake sediment ranged between 5.10 and 10.62 in the summer season, suggesting considerable to moderate metal(loid) contamination. Comparatively, the C_d value was quite low (1.19–3.39) in the winter season and suggested the sites were low contaminated. Assessment of 17 lakes in an urban city, Bangalore made the following observations: (a) One lake was low and one another lake was considerable contaminated with Cd; (b) Six lakes were moderately contaminated, while the rest of the site was low contaminated with Co; (c) One lake was considerably contaminated, four lakes were moderately contaminated, while rest of the lakes were low contaminated with Cr; (d) One lake was considerably contaminated, three lakes were moderately contaminated and the rest of the lakes were low contaminated with Cu; (e) All lakes were low contaminated with Mn; (f) Two lakes were highly contaminated, three sites were contaminated, eleven lakes were moderately contaminated and one lake was low contaminated with Ni; (g) One of the lakes was highly contaminated, five lakes was moderately contaminated and rest of the lakes were low contaminated with Pb and (h) One lake was considerably contaminated, four lakes were moderately contaminated and rest of the lakes were low contaminated with Zn (Jumbe & Nandini, 2009). However, the C_d value of 11.03 suggested that the lake was moderately contaminated with metal(loid) pollution.

In addition to lake ecosystems, several research articles on river ecosystems also highlight the metal(loid) pollution based on C_f^i contamination. For instance, Chakravarty and Patgiri (2009) calculated C_f^i from the sediment samples collected from Dikrong River, northeast, India. Their work showed that the river was considerably to very highly contaminated with Cu, as well as moderately contaminated with Pb. However, the C_d value of 11.47 showed moderate contamination with metal(loid) pollution. According to Patel et al. (2018), the sediment of the Swarnamukhi River basin is metal(loid) contaminated with Cu and Pb as far as C_f^i value is concerned. Banerjee et al. (2016) have reported that the River Subarnarekha, traversing through the industrial city Jamshedpur was very highly contaminated with Cd and Pb; considerably contaminated with Ni; considerably to very highly contaminated with Zn; moderately contaminated with Cu and Cr in the summer season. However, the C_f^i value of Subarnarekha River was comparatively lower in the winter season due to low metal(loid) concentration in sediment. Moreover, the C_d value ranged between 5.10 and 10.62, suggesting the low to moderate metal(loid) contamination during the summer season. On the contrary, the C_d value of Subarnarekha River sediment was quite low (1.19–3.39) suggesting that the sites were low contaminated with metal(loid)s. Another important Indian river in Gujarat, Sabarmati River was also being studied by Kumar et al. (2013). Using C_f^i calculations, they classified that the sediment of Sabarmati River was low contaminated with Pb, Ni and Cu, but moderately contaminated with Zn and very highly contaminated with Cr. However, the C_d value ranged between 14.30 and 17.21, suggesting that the river was considerably contaminated with metal(loid)s. Furthermore, metal(loid) assessment and the C_f^i values on Vaigai River of south India showed that the river sediments were moderately contaminated with Cd, Cr, Cu, Ni, Pb and Zn (Paramasivam et al. 2015). While classifying the Vaigai River based on C_d values

(13.90), all the sites may be considered as moderately contaminated. Furthermore, in addition to small Indian rivers, C_f^i calculations are also being used to qualify the sediment quality of major Indian rivers like Ganga, Brahmaputra and Mahanadi. Among these major Indian rivers, the sediment pollution assessment of River Ganga has been extensively studied. Several authors have made different assumptions regarding the categorization of sediment quality of Ganga River and its tributaries. For instance, Siddiqui et al. (2019) have worked on seven tributaries of Ganga River, and observed the moderate to very high contamination of Cd; moderate contamination of Zn, Cu and Ni and moderate to considerable contamination of Cr and Pb. Pandey et al. (2016) assessed the sediment characteristics of Mahanadi River and its tributaries and observed that the average C_f^i value of Pb, Cu, Zn, Cd and Cr value fell under moderate contamination category. Besides, the average C_d value observed was 7.16, suggesting that Mahanadi River was moderately contaminated with metal(loid)s. However, the C_f^i values of Ni, Pb, Zn and Cr suggested the low sediment contamination of Brahmaputra River, whereas Cu suggested moderate contamination of the sediment (Saikia et al., 2016). Also, C_d value (10.60) suggested moderate metal(loid) contamination in the Brahmaputra River.

3.3 Geo-Accumulation Index ($\mathbf{I}_{geo}$)

Geochemical index (I_{geo}) was originally stated by Muller (1981) to determine and define metal contamination in sediments by comparing current concentrations with preindustrial levels, I_{geo} is calculated as follows:

$$I_{geo} = \log_2\left(\frac{C_m^i}{1.5\times B_m^i}\right)$$

The geo-accumulation index is categorized as (a) Class 0: extremely contaminated ($I_{geo} \geq 5$), (b) Class I: strongly to extremely strongly contaminated ($4 \leq I_{geo} \leq 5$), (c) Class II: strongly contaminated ($3 \leq I_{geo} \leq 4$), (d) Class III: moderately to strongly contaminated ($2 \leq I_{geo} \leq 3$), (e) Class IV: moderately contaminated ($1 \leq I_{geo} \leq 2$), (f) Class V: uncontaminated to moderately contaminated ($0 \leq I_{geo} \leq 1$) and (g) Class VI: practically uncontaminated ($I_{geo} \leq 0$).

In addition to C_f^i and C_d, I_{geo} has been extensively used to classify the sediment quality of Indian lakes and rivers ecosystems. Sharma et al. (2017) used I_{geo} value to classify the Kolleru Lake sediment as uncontaminated to moderately contaminated sites with metal(loid)s. Lone et al. (2018) have worked on the assessment on the Anchar Lake sediment and observed that I_{geo} value for Pb, Fe, Co, Cr and Zn showed uncontaminated to moderate contamination. However, I_{geo} value for Cu indicated strongly contaminated sediment. The work of ShibiniMol et al. (2015) suggested that Vembanad Lake sediment was moderately to strongly contaminated with Cd. The study on Chilika Lake showed unpolluted to moderately polluted sediment for

Pb and Co and moderately polluted sediment for Zn when considering I_{geo} values (Barik, 2017). Jeelani and Shah (2006) have studied the metal(loid) contamination in Dal Lake. Based on I_{geo} values, they observed that the Dal Lake sediment was uncontaminated to moderately contaminated with Zn and Cu. Banerjee et al. (2016) have worked on the sediment properties of Subarnarekha River. They found that during winter, the river was moderately contaminated with Cd; and moderately to strongly contaminated with Zn. However, during summer, the Cd contamination may be categorized as Class I to Class II; Pb contamination as moderately to strongly contaminated (Class IV); and Zn contamination as Class III as Class IV. The reported work of surface sediment of Brahmaputra River showed the I_{geo} values below zero for the metal(loids) suggesting that all the sites were practically uncontaminated (Saikia et al., 2016). The average I_{geo} value of Ganga River sediment calculated and used by Pandey et al. (2016) suggested that the river sediment was moderately to strongly contaminated with Cd. Another study on Ganga River sediment performed by Siddiqui et al. (2019) highlighted the Cd pollution level between Class III and Class IV categories. Sediment quality assessment of Swarnamukhi River with the I_{geo} value showed that the river was uncontaminated–moderate contaminated with Cd, Co, Cr, Mn, Ni and Zn. Also, moderate to heavy contamination was observed for Cu and Pb. However, the study on Dikrong River sediment suggested that the river bed was moderately contaminated with Cu.

4 Conclusion

Conclusively, it can be said that peri-urban agriculture systems are vulnerable to various natural and anthropogenic sources of metal(loid)s. Due to their persistency and bioaccumulative behaviour, these metal(loid)s enter into the sediment and cause severe health risks to living organisms, including humans. Their sources may be either natural or anthropogenic. Mainly, the anthropogenic sources are a matter of concern. There are a number of sediment-based indices that are being used by researchers that can easily assess the health of an ecosystem. Various research suggested that metal(loid)s in peri-urban agricultural system may cause morphological and physiological damage to living organisms when these enter into ecological food chain. This study will be useful for the policy-makers to control the metal(loid) exposure from source level.

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Monitoring and Forecasting Land Use and Land Cover Changes in Paddy Cultivation

C. G. Malavipathirana, K. A. Dinusha, K. U. J. Sandamali, and W. D. D. P. Withanage

1 Introduction

The present-day changes in land use and land cover (LULC) primarily result from physical developments and agricultural activities (US Department of Commerce, 2020). The term "land use" refers to human activities associated with a particular site, while "land cover" encompasses the vegetation, water bodies, natural surfaces, and human-made features present on the land (US Geological Survey, 1997). Aerial and satellite images are useful for determining land cover, but they do not provide direct information about land use (US Department of Commerce, 2020). In hierarchical classification, there are two defined levels. LULC areas are classified into nine major categories: urban or built-up land, agricultural land, rangeland, forest, water areas, wetland, bare land, tundra, and perennial snow or ice (US Geological Survey, 1997).

The analysis of land use changes holds significant importance for land surveyors and spatial planners as it provides them with a better understanding of the current landscape through land cover maps (US Department of Commerce, 2020). By examining past changes using land cover maps from different years, authorities can evaluate previous management decisions and anticipate the potential effects of their current decisions before implementing them (US Department of Commerce, 2020). In Asian regions, food security is a pressing issue due to rapid population growth, limited arable lands, plant diseases, environmental changes (such as temperature variations, water shortages, and floods), and climate change (Huang et al., 2014).

C. G. Malavipathirana (✉) · K. A. Dinusha · K. U. J. Sandamali
Department of Spatial Sciences, Faculty of Built Environment and Spatial Sciences, General Sir John Kotelawala Defence University, Sooriyawewa, Sri Lanka

W. D. D. P. Withanage
Survey Department, Colombo, Sri Lanka

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Consequently, developing countries are focused on increasing agricultural production to enhance food supply, employment opportunities, and income. The COVID-19 pandemic has further emphasized the importance of fresh and nutrient-rich foods from small-scale rural producers (Deuja, 2020). Overall, understanding land use changes and their implications for food security is crucial for effective planning, management, and decision-making in agriculture and rural development. It enables authorities to address the challenges associated with food production, sustainability, and resilience in the face of various factors impacting the agricultural landscape.

Rice (*Oryza sativa*) is a staple food crop widely consumed in many Asian countries, including Sri Lanka, where it is a major crop (Dengiz & Formation, 2015). Sri Lanka has historically been renowned for its rice production, and paddy cultivation dominates the agricultural landscape (doa.gov.lk, 2013). Wetland paddy crops are cultivated across all districts in Sri Lanka, with a total estimated land area of approximately 708,000 ha allocated for paddy cultivation (Paddy Statistics, 2019).

However, not all the designated paddy cultivation areas in Sri Lanka are actively farmed due to various factors such as seasonal water shortages and unsettled ground conditions (Paddy Statistics, 2019). Consequently, Sri Lanka has faced challenges in achieving food security and struggles to meet the demand for rice. Therefore, accurate estimation of crop harvests is crucial in addressing these issues. Crop production plays a significant role in a country's food security and economic development. In pursuit of economic benefits, many farmers in Sri Lanka are inclined to convert paddy fields to alternative crops. The conversion of paddy fields to other crops raises concerns about the impact on rice production and food security. It is essential for authorities to monitor and manage these land use changes to ensure sustainable agricultural practices and mitigate any negative consequences for the country's food supply and economic well-being.

Crop monitoring plays a crucial role in decision-making, harvest planning, storage, and commercial purposes for both government agencies and producers. Traditionally, countries have relied on conventional methods such as reports, field visits, and aerial photographs for estimating yields. However, these methods often prove to be unreliable, expensive, and time-consuming. They also have limitations when it comes to monitoring larger regions effectively. To address these challenges, remote sensing techniques, which utilize satellite imagery, have emerged as a valuable tool for crop monitoring. Remote sensing enables the assessment of land cover changes over large areas. With the advancement of spaceborne technology, many research projects now leverage remote sensing for crop monitoring purposes.

Satellite-based remote sensing offers several advantages. It provides a wide coverage area, allowing for comprehensive monitoring of large-scale agricultural regions. The satellite images can be used to analyze vegetation indices, monitor crop health, detect anomalies, and estimate yields. By analyzing the spectral information captured by the satellites, researchers can gather valuable insights about crop conditions and make informed decisions. Remote sensing-based crop monitoring offers a cost-effective and efficient approach, saving time and resources compared to traditional methods. It provides a systematic and objective means of collecting data, enabling timely and accurate information for decision-making processes related to agriculture and crop management. Overall, remote sensing has proven to be a valuable technology for crop monitoring, offering enhanced capabilities to track land cover changes, assess crop health, and support decision-making in agricultural practices.

The objectives of this study are to monitor the land use and land cover (LULC) changes specifically related to paddy cultivation in Sri Lanka using Remote Sensing techniques. The study aims to identify suitable remote sensing methods for monitoring LULC and quantify the changes that have occurred over the past four decades (1980–2020) in the Sooriyawewa Divisional Secretariat Division (DSD). Additionally, the study seeks to examine the underlying factors contributing to these LULC changes in the paddy fields of the Sooriyawewa DSD.

By conducting this analysis, the study aims to provide insights into the historical changes that have taken place in the study area and to understand the current land use dynamics occurring in the region. The temporal nature of the problem highlights the significance of this research, as it addresses the need for up-to-date information on land use changes related to paddy cultivation. The findings of this project are expected to be valuable for relevant authorities and policymakers involved in decision-making processes related to land use planning and policy development.

By utilizing remote sensing techniques, the study can offer a comprehensive assessment of the LULC changes in the paddy fields of Sooriyawewa over the specified time period. This information can contribute to a better understanding of the patterns, trends, and drivers of land use changes, enabling informed decision-making for sustainable land management, agricultural practices, and policy interventions in the study area.

2 Background of the Problem Description

Rice cultivation holds significant importance in Sri Lanka, and several regions in the country are known for their substantial contribution to rice production. According to Paddy Statistics (2019), the main areas for rice cultivation in Sri Lanka include Ampara, Kurunegala, Polonnaruwa, Matara, Hambantota, Batticaloa, and Anuradhapura. The specific study area for this research is the Sooriyawewa Divisional Secretariat Division (DSD) located in the Hambantota district of Sri Lanka. The Hambantota district is recognized as the fifth-largest rice-producing region in the country, according to Paddy Statistics (2019). This implies that rice cultivation plays a significant role in the agricultural landscape and economy of the Hambantota district.

In the Sooriyawewa region, paddy and Other Field Crops (OFC) are the predominant crops cultivated (Perming, 2013). Paddy cultivation faces various challenges and threats that can impact its productivity. Some of these challenges include uncertainties in rainfall patterns, flood situations, droughts, price fluctuations, and the prevalence of pests and diseases. These factors pose significant obstacles to successful rice cultivation in the area.

The paddy cultivation calendar in Sooriyawewa follows two main seasons: Yala and Maha (Paddy Statistics, 2019). The Yala season spans from April to August, while the Maha season occurs from September to March of the following year. Each season has specific sowing and harvesting periods defined within these time frames. Among the two seasons, the Maha season holds greater significance for paddy cultivation in Sooriyawewa. It is during this season that a substantial portion of paddy cultivation takes place, contributing significantly to the agricultural activities and economy of the region. The identification of these cultivation seasons and an understanding of the challenges faced by rice farmers in Sooriyawewa are crucial for effective planning, resource allocation, and implementing appropriate agricultural practices. By addressing these challenges and promoting sustainable agricultural practices, it is possible to enhance rice production and ensure the stability of the paddy cultivation sector in Sooriyawewa.

In recent years, there has been a noticeable trend of converting paddy fields into alternative crops in Sri Lanka. A web journal by Hirimburegama et al. (2004a, b) highlights an example where approximately 2500 ha of paddy area were converted to banana cultivation within the past six years. The shift toward alternative crops like bananas is driven by their higher economic profitability, lower water requirements, reduced input materials, and labor involvement compared to rice cultivation. As a result, farmers cultivating bananas can achieve higher net profits compared to those engaged in rice cultivation.

However, this shift in land use from paddy fields to alternative crops raises concerns about the future of rice, which is a staple crop in Sri Lanka. If rice production is unable to meet the demands of the growing population, the country may have to rely on importing rice from other nations, which could burden the economy. Land use changes have a significant impact on human lifestyles, and the Hambantota district, which has experienced rapid development since 2010 (Mariyathas et al., 2016), requires careful land management due to the scarcity of land resources. Continuing this trend of converting paddy fields to alternative crops, particularly in the Sooriyawewa area, may lead to increased demand for land. This situation can result in social, economic, and environmental issues among the local community residing in the area. Thus, it becomes crucial to carefully consider and manage land use changes, taking into account the long-term sustainability and the potential consequences on various aspects of the community and the environment.

In the current context, Sri Lanka relies on traditional methods for crop monitoring, which are associated with several limitations. These traditional methods are often time-consuming, subjective, expensive, and have limited coverage. Additionally, field observations conducted through traditional methods may lead to large errors, and the overall efficiency and accuracy of these methods can be compromised (Huang et al., 2013). In contrast, Remote Sensing has emerged as a promising approach for crop monitoring globally. It offers significant advantages in terms of evaluating natural resources, management, and monitoring crop conditions. Remote Sensing allows for the assessment of crop health, identification of land use changes, and estimation of crop yields in a more efficient and accurate manner.

This research aims to leverage Remote Sensing techniques to identify changes in paddy land use in Sri Lanka. By utilizing Remote Sensing technology, the study can overcome the limitations associated with traditional methods and provide a more comprehensive and accurate assessment of paddy land use changes. This approach has the potential to enhance the efficiency and accuracy of crop monitoring, leading to improved decision-making in agricultural management and resource allocation.

By adopting Remote Sensing techniques, this research contributes to the advancement of crop monitoring practices in Sri Lanka, promoting more effective and reliable methods for evaluating agricultural landscapes and supporting sustainable agricultural development.

3 Research Methodology

3.1 Study Area

The target area for this study is the Sooriyawewa Divisional Secretariat Division (DSD), located in the Hambantota district of the Southern Province in Sri Lanka. Sooriyawewa DSD shares borders with the Sewanagala, Hambantota, Lunugamwehera, and Embilipitiya DSDs. The geographical coordinates of Sooriyawewa DSD range from approximately latitude 6° 11′ 40″ to 6° 24′ 20″ North and longitude 80° 55′ 00″ to 81° 05′ 00″ East (Fig. 1). Sooriyawewa DSD is characterized as the driest DSD in the Hambantota district (Perming, 2013).

The Hambantota district holds the fifth position in rice production within Sri Lanka, highlighting its significance in agricultural activities (Paddy Statistics, 2019). Paddy cultivation is the primary occupation of the inhabitants in this region. In addition to paddy, other field crops (OFC) such as bananas are also extensively cultivated in Sooriyawewa (Perming, 2013).

Sooriyawewa possesses certain distinct characteristics that make it an interesting area for analysis. Firstly, the terrain in this region is predominantly flat, lacking significant geological barriers that could impede analytical processes. Furthermore, being situated in the dry zone, Sooriyawewa is less susceptible to environmental hazards like floods and landslides. The area experiences an average annual temperature of 27.5 °C and receives an average precipitation of approximately 1148 mm, as recorded by the Census and Statistical Department. Secondly, although Sooriyawewa has traditionally been referred to as a rural area, it is currently undergoing transformation. Development projects have been implemented in the vicinity, leading to an increase in the population over the years, as reported by the Department of Census and Statistics (Perming, 2013).

These unique characteristics of Sooriyawewa, including its flat topography, dry zone location, and changing rural landscape, offer valuable insights for the analysis of land use changes and crop cultivation patterns in the area. By considering these factors, the study can provide a comprehensive understanding of the dynamics and challenges associated with agricultural practices in Sooriyawewa.

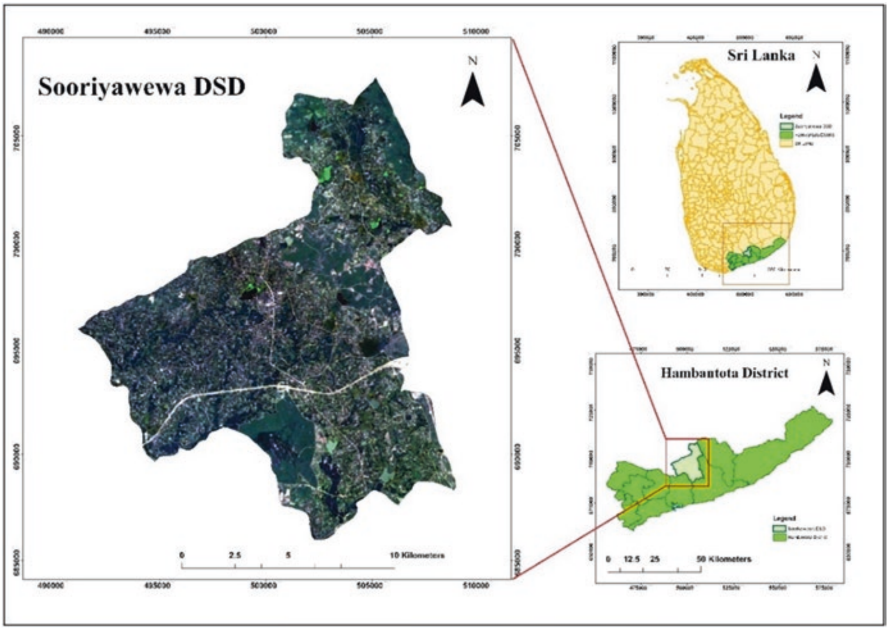

Fig. 1 Study area

3.2 Data Collection

In conducting this study, a combination of primary and secondary data was utilized. The researchers collected primary data by engaging with experts in paddy cultivation, including farmers and agrarian officers, to gain insights into the causes of land use and land cover (LULC) changes in the study area.

Additionally, secondary data sources were also utilized. These may include existing literature, reports, statistical data, satellite imagery, and other relevant sources of information. By combining primary and secondary data sources, the study aims to gather a comprehensive and well-rounded understanding of the causes for LULC changes in the study area, ensuring a robust analysis and reliable conclusions.

3.2.1 Contacting Expertise

The main purpose of contacting expertise to identify the current paddy monitoring systems in this area and what are the underlying causes for LULC changes over the paddy cultivation in Sooriyawewa according to their experiences. But questionnaire survey or a meet with the farmers was not performed due to the COVID-19 pandemic condition. As a result, the interview took place over the phone.

3.2.2 Landsat Images

For this investigation, Landsat images from different years were selected to capture the evolution stages of the study area. Landsat 2, 5, and 8 images were utilized to cover a broader temporal range and ensure consistency in the analysis. To minimize the influence of seasonal fluctuations, images were collected with similar acquisition dates, focusing on the Maha season that occurs from September to March the following year. Specifically, satellite images were downloaded for the period from January to March of each year.

Table 1 above provides an overview of the Landsat images utilized in the study, indicating the respective years and the corresponding acquisition dates of the images. Figure 2 illustrates the raw images that were used in the experiment.

3.3 Experimental Materials

3.3.1 Arc GIS 10.5 Software

Geographic Information Systems (GIS) play a crucial role in managing and analyzing spatial data, including land use and land cover information. In this study, the GIS software used for the land use and land cover categorization and analysis is ArcMap 10.5 licensed software.

3.3.2 Quantum GIS (QGIS) 2.18 Software

Quantum GIS (QGIS) is indeed a powerful and widely used free and open-source Geographic Information System (GIS). It provides extensive support for various geospatial data formats, including both vector and raster formats, making it a versatile tool for geospatial analysis. MOLUSCE (Modules for Land Use Change Evaluation) is one such plugin for QGIS that specifically focuses on land use change

Table 1 Landsat images used

Satellite series	Year	Date acquired
LANDSAT_3	1980	1980-02-06
LANDSAT_5	1988	1988-03-02
	1992	1992-01-25
	1997	1997-02-23
	2000	2000-01-23
	2005	2005-03-17
	2010	2010-01-26
LANDSAT_8	2014	2014-01-21
	2019	2019-01-03

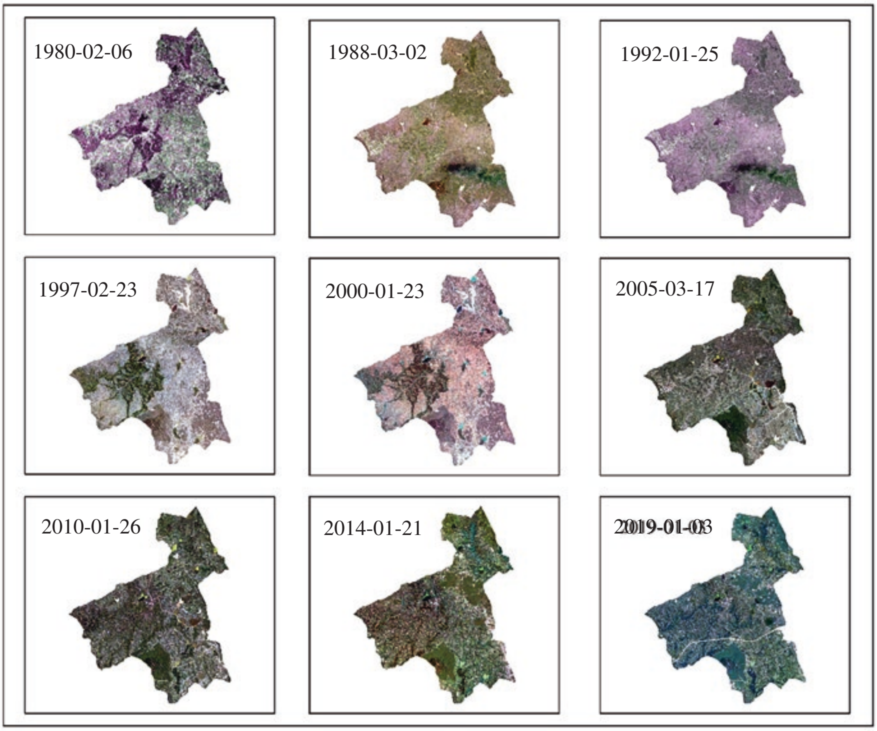

Fig. 2 Landsat images of different years that were used in the study

analysis, modeling, and simulation. MOLUSCE plugin in QGIS 2.18 software was utilized for the prediction of land use and land cover changes. This plugin likely facilitated the modeling and simulation of various scenarios to evaluate potential future land use changes in the Sooriyawewa area.

3.3.3 Google Earth

Google Earth software was utilized to detect land cover changes in different years and assess the accuracy of the procedure.

3.4 Experimental Workflow

Experimental workflows can vary significantly based on the field and nature of the study. They often involve adherence to specific methodologies and ethical considerations. Adjustments and modifications might be necessary based on the unique requirements of each experiment (Fig. 3).

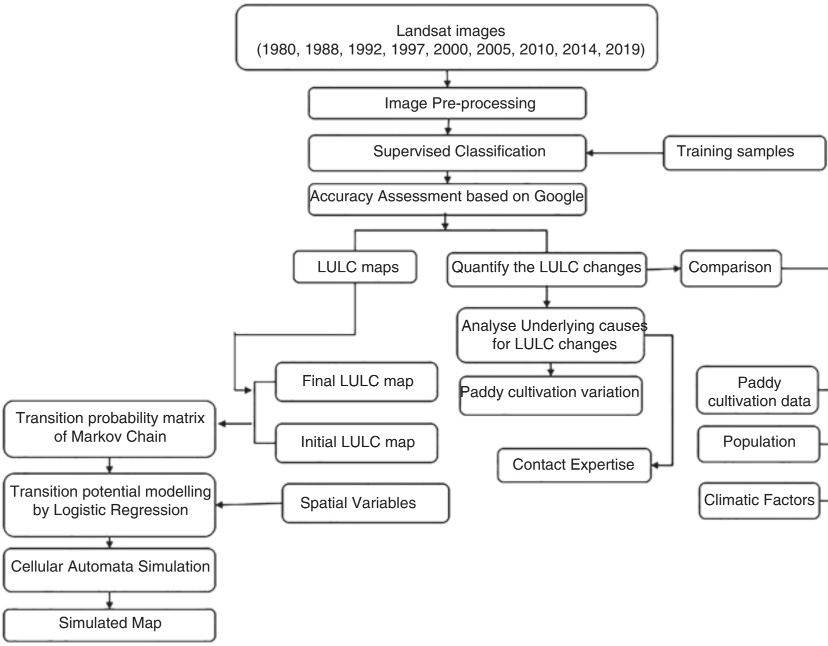

Fig. 3 Experimental workflow

3.5 Image Processing

3.5.1 LULC Classification Scenario

According to Kafy et al. (2021), image classification is indeed a crucial step in analyzing land use and land cover changes. It involves grouping image pixels into different classes based on their spectral characteristics to create a thematic representation of the landscape. There are several techniques available for image classification, including supervised, unsupervised, and object-based classification. In supervised classification, training samples or signatures representing different land cover classes are used to train a classification algorithm. These training samples are polygons or regions of interest that are labeled with the corresponding land cover class. Supervised classification is particularly effective when working with larger study areas as it tends to deliver more accurate results compared to unsupervised and object-based classification methods. By using supervised classification, the study aimed to accurately categorize the image pixels into specific land use and land cover classes, facilitating the analysis of LULC changes over time in the study area.

Specific training samples were chosen in the experiment to find variances in paddy cropping. These training samples included paddy area, other agricultural area, forest area, water area, built-up area, and bare land area and were identified and selected using Google Earth for each of these land cover classes (Table 2).

Table 2 LULC types applied in this study

Value no	LULC type	Description
1	Paddy area	Areas where paddy is grown.
2	Other crops area	Cultivated farmlands and homestead vegetation.
3	Forest area	Including forest, densely planted parks or areas, and/or densely densified tall trees are all examples of densely planted areas.
4	Water area	Rivers, reservoirs, canals, streams, and other active hydrological features are all included in this category.
5	Built-up area	Sites for residential, commercial, and industrial use, as well as transportation networks (including roads and highways) and other urban features are also considered.
6	Bare land area	Fallow soil, sand, and empty soil are all examples of vacant lands.

3.5.2 LULC Prediction Scenarios

The MOLUSCE plugin, integrated within the open-source QGIS 2.18 software, was employed to simulate future land use and land cover (LULC) modifications using the Cellular Automata (CA) model. This plugin offers the functionality to analyze and model LULC changes effectively within the QGIS environment. With MOLUSCE, it is possible to calculate the total transformed area at the land cover class level, estimate change probabilities, simulate changes using cellular automata, and validate the model (A. A. Kafy et al., 2021).

In the prediction phase of this study, two types of variables were employed: dependent variables and independent variables. The dependent variable represented the historical change pattern of the land use and land cover (LULC) maps between 2014 and 2019. On the other hand, the independent variables included factors such as distance to roads, distance from water bodies, built-up area, elevation, and slope. The distances were calculated using feature vector data and the Euclidean distance algorithm in ArcGIS. Digital Elevation Model (DEM) data were utilized to compute elevation and slope values.

Both the dependent and independent variables were used as input parameters in the model to assess conversion matrices and change probabilities in the initial modeling phase. Subsequently, an Artificial Neural Network (ANN) model was employed to estimate the likelihood of LULC change transitions. Transition potential images were generated to identify areas suitable for land cover conversion. The LULC map of 2019 served as the base map, while the conversion matrices and conditional probability images from 2014 to 2019 were used as input to simulate the LULC maps for the years 2024 and 2029 (Kafy et al., 2021).

4 Results and Discussion

4.1 Supervised Classification Results Analysis

The study utilized Landsat images to estimate the past patterns of land use and land cover (LULC) variations from 1980 to 2019. The Maximum Likelihood classification method was employed to classify the images, and the results are presented in Table 3. The Maximum Likelihood classification achieved an overall classification accuracy of more than 80% for each year.

To produce an error matrix, the accuracy of the categorized imageries was determined by producing 60 reference points. After that, User Accuracy (UA) and Producer Accuracy (PA) were computed.

Landsat data obtained in 1980, 1988, 1992, 1997, 2000, 2005, 2010, 2014, and 2019 was processed and created nine classification maps for the six LULC categories found in the research region (Fig. 4).

4.1.1 Paddy Area Changes

The major purpose of this study was to identify changes in paddy regions. Table 4 displays the evolution of paddy fields during the previous four decades.

Table 3 Summary of user accuracy and producer accuracy

		LULC type					
Year		Paddy	Other crops	Forests	Water	Built-up areas	Bare lands
1980	UA%	83	82	100	100	100	89
	PA%	100	90	90	100	90	80
1988	UA%	100	91	83	100	90	100
	PA%	90	91	100	90	90	100
1992	UA%	83	90	82	100	100	100
	PA%	100	90	90	100	80	90
1997	UA%	100	91	83	100	90	100
	PA%	90	91	100	90	90	100
2000	UA%	82	100	90	91	100	90
	PA%	90	91	90	100	90	90
2005	UA%	90	83	90	100	82	100
	PA%	90	91	90	90	90	90
2010	UA%	90	82	90	100	91	100
	PA%	95	90	82	100	91	89
2014	UA%	82	90	82	100	100	100
	PA%	90	90	90	100	90	90
2019	UA%	83	90	88	100	91	90
	PA%	100	90	80	90	100	90

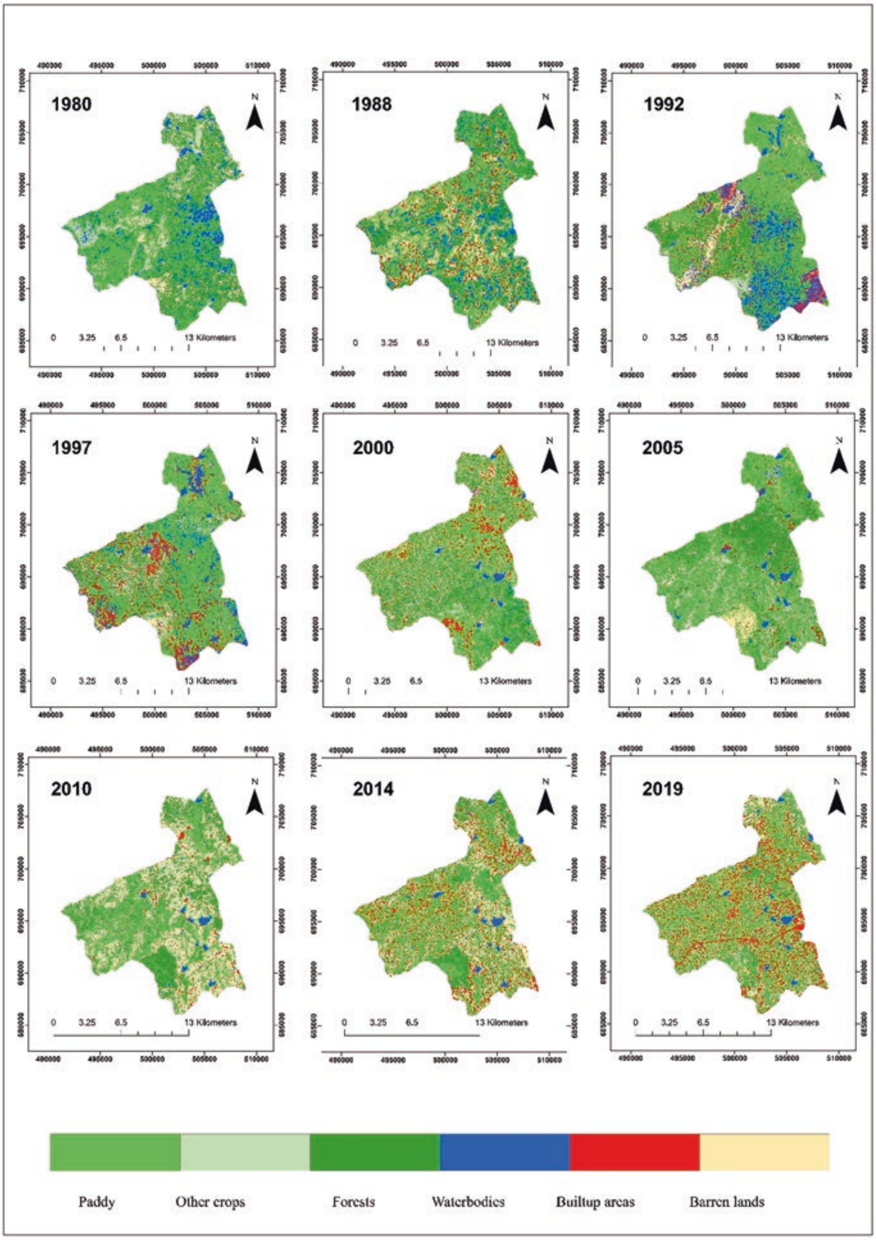

Fig. 4 Supervised classification results

Table 4 Changes in paddy areas (in square kilometers)

Year	1980	1988	1992	1997	2000	2005	2010	2014	2019
Paddy area	74.536	72.836	71.626	70.814	68.431	62.391	58.719	48.493	45.765

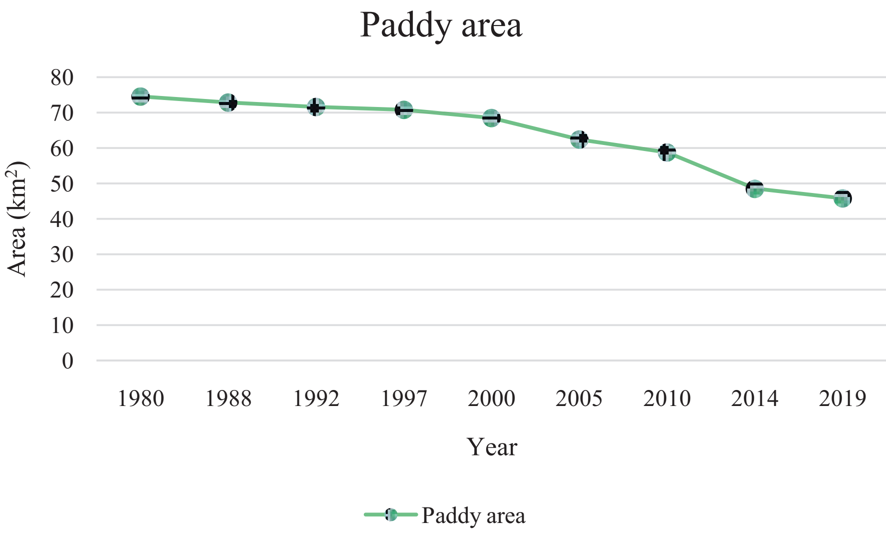

Fig. 5 Paddy area changes (1980–2019)

Since 1980, paddy areas have been dropping, but there has been a major reduction since 2000 (Fig. 5).

4.1.2 Other Crops Area Changes

This region grows a range of crops, including bananas, pomegranates, and papayas, among others (Table 5).

Figure 6 represents the other agricultural regions that have strayed in recent years. Other agricultural areas have grown significantly since 1992.

4.1.3 Forest Area Changes

Due to increased urban development, the research region has a low forest cover (Table 6).

The reduction of extremely green areas has been reported in all directions of the research zone. However, there was a significant drop in 2005 (Fig. 7).

Table 5 Changes in other crop areas (in square kilometers)

Year	1980	1988	1992	1997	2000	2005	2010	2014	2019
Other crops	21.747	22.234	22.655	30.834	33.894	37.808	43.585	42.458	40.453

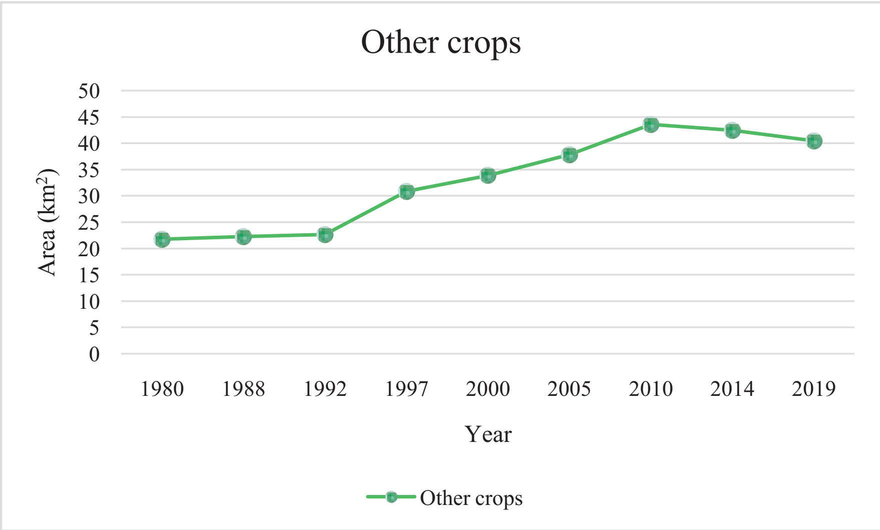

Fig. 6 Other crop area changes (1980–2019)

Table 6 Changes in forest areas (in square kilometers)

Year	1980	1988	1992	1997	2000	2005	2010	2014	2019
Forests area	49.129	48.985	47.758	43.726	44.268	45.302	35.500	39.819	38.083

4.1.4 Waterbody Area Changes

Water sources have been the lifeblood of human culture in a variety of ways since prehistoric times. Water is the most significant concern affecting the global tourism industry. Instead of conserving water resources, people are encroaching on them, producing pollution as a result of haphazard construction plans and unplanned urban growth (Table 7).

The past four decades' deteriorating phenomenon had a direct impact on this region's agriculture, particularly rice production. Rapid, unrestrained urban expansion destroyed the natural balance, rendering the region unfit for life and agriculture (Fig. 8).

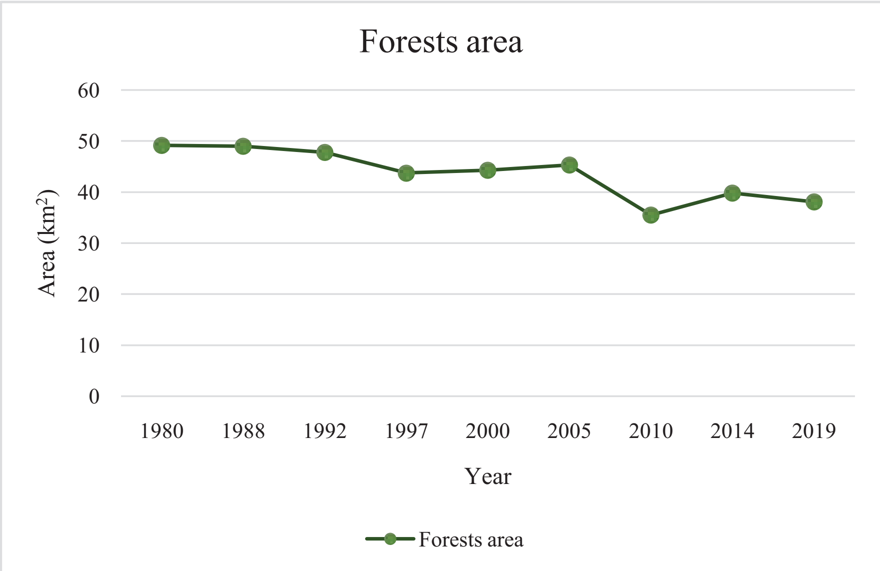

Fig. 7 Forest area changes (1980–2019)

Table 7 Changes in waterbody areas (in square kilometers)

Year	1980	1988	1992	1997	2000	2005	2010	2014	2019
Water area	8.9149	8.7945	8.2998	8.188	7.1334	4.9158	3.5496	3.7377	3.7062

4.1.5 Built Up Area Changes

Since 2010, the government has focused on the Hambantota region, launching various development initiatives in the Hambantota district. Mattala International Airport, Sooriyawewa International Cricket Stadium, and the Southern Expressway are the main projects. As a result, administrative, commercial, recreational, infrastructural, telecommunications, and transportation amenities are expanding in this area. For a variety of reasons, urbanization is accelerating. Natural growth includes rural–urban migration, higher career opportunities, enhanced quality of life, and natural growth. Despite the fact that significant urban growth is underway in the area in all directions.

All of these features make this study site more enticing to residents than to non-residents. In addition, the spread of these services is transforming the region into a hotspot for urban expansion by attracting an increasing number of corporate and administrative operations. These areas were formerly disregarded by rural residents, but today, people are lured to them in quest of better work opportunities and a higher quality of life (Table 8).

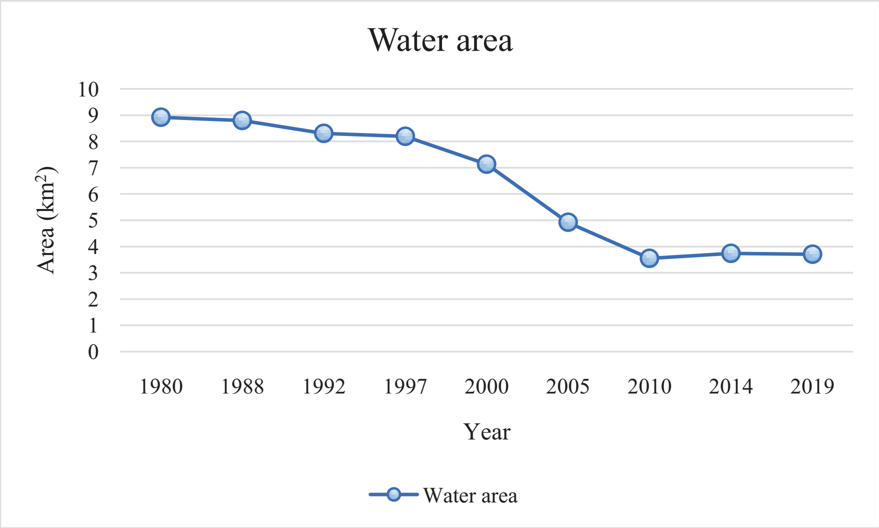

Fig. 8 Waterbody area changes (1980–2019)

Table 8 Changes in built-up areas (in square kilometers)

Year	1980	1988	1992	1997	2000	2005	2010	2014	2019
Built-up areas	11.883	12.822	14.056	15.239	17.156	17.472	24.112	26.287	34.11

Figure 9 represents built-up area variation from 1980 to 2019. As a general overview, built-up areas accumulate in this time gap. From 2010, there is a huge increment of the built-up areas.

4.1.6 Bare Land Area Changes

The visual and ecological aspects of bare lands, which are largely undeveloped urban areas and open spaces, provide residents with environmental, social, and economic benefits. The changes in bare lands during the classification were influenced by significant rural–urban migration and a lack of emphasis on maintaining open spaces (Table 9).

The extent of bare land changed between 1980 and 2019, as seen in Fig. 10.

The statistics table of LULC change in the Sooriyawewa DS Division is shown in Table 10.

Figure 11 depicts a schematic diagram of each LULC from 1980 to 2019, with the diagrams displaying the rise and decline in each LULC.

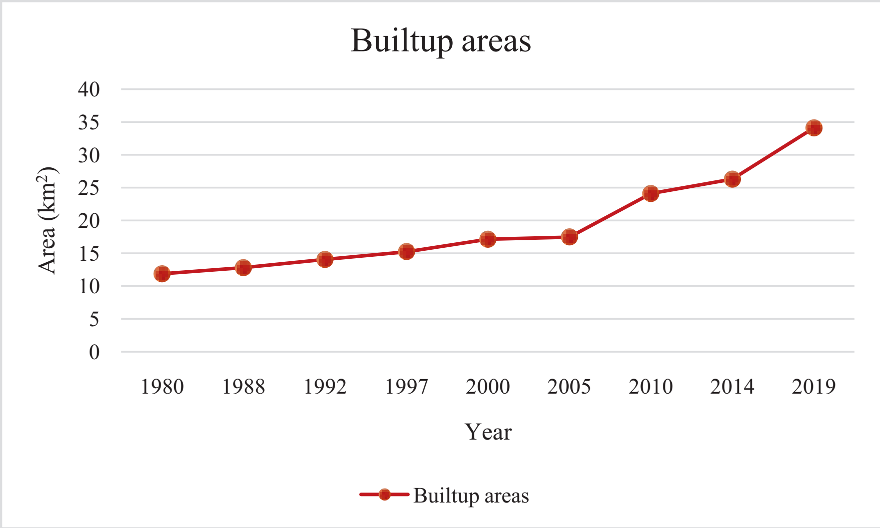

Fig. 9 Built-up area changes (1980–2019)

Table 9 Changes in bare land areas (in square kilometers)

Year	1980	1988	1992	1997	2000	2005	2010	2014	2019
Bare lands	19.517	20.056	21.239	16.832	14.751	17.747	20.169	24.840	23.518

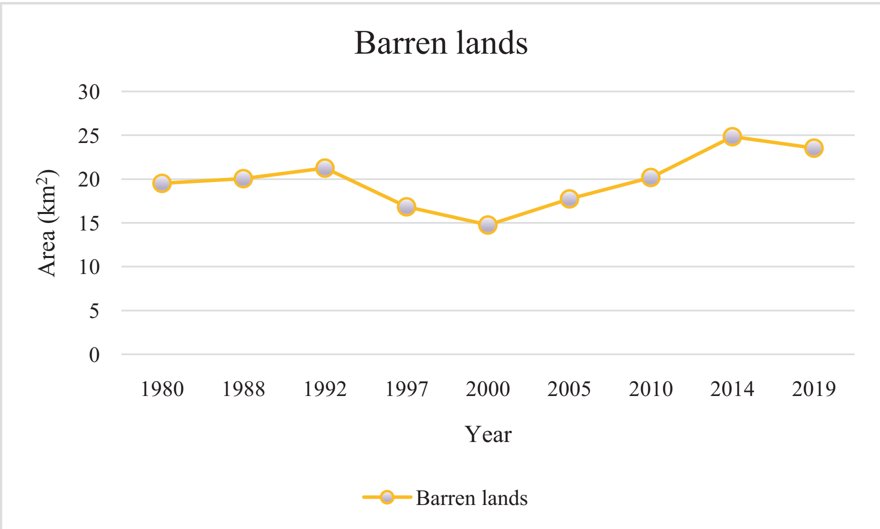

Fig. 10 Bare lands area changes (1980–2019)

Table 10 Maximum likelihood classification results (in square kilometers)

LULC type	Paddy	Other crops	Forests	Water	Built-up areas	Barren lands
1980	74.536	21.7477	49.1294	8.9149	11.883	19.4266
1988	72.836	22.2341	48.9856	8.7945	12.8222	19.9652
1992	71.6265	22.6557	47.7603	8.2998	14.0562	21.2391
1997	70.8147	30.8349	43.7265	8.188	15.2397	16.8338
2000	68.4315	33.894	44.2684	7.1334	17.1566	14.7537
2005	62.3916	37.8081	45.3024	4.9158	17.4726	17.7471
2010	58.7196	43.5852	35.5005	3.5496	24.1128	20.1699
2014	48.4938	42.4584	39.8196	3.7377	26.2872	24.8409
2019	45.7659	40.4532	38.0835	3.7062	34.11	23.5188

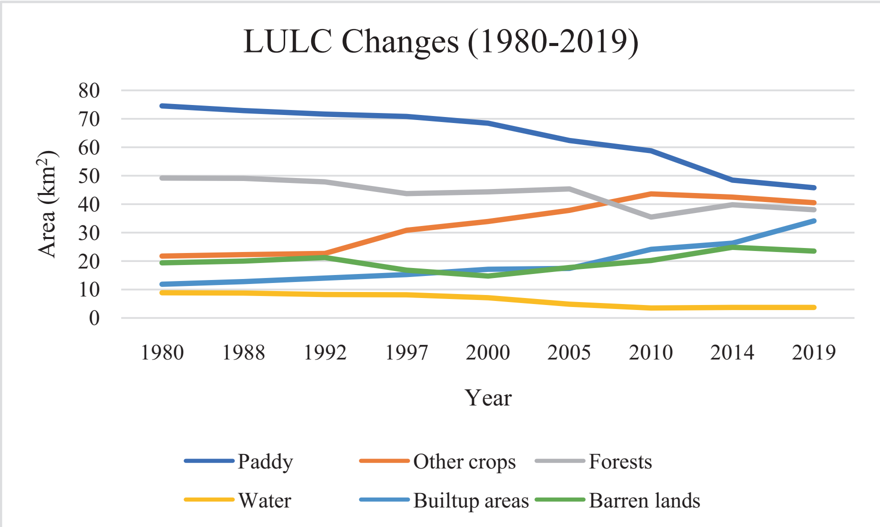

Fig. 11 Changes in LULC from 1980 to 2019

4.2 *Future LULC Prediction Analysis*

Future LULC projection aids in the development of an effective framework for sustainable urban planning. The CA model was used in this work to forecast future LULC changes between 2024 and 2029 (Fig. 12).

Figure 13 depicts the expected LULC map for Sooriyawewa, which shows that the built-up area will rise significantly in 2024 and 2029 by 20.34% and 21.37%, respectively. Waterbodies will be reduced by 1.79% in 2024 and by 1.67% in 2029 (Table 11).

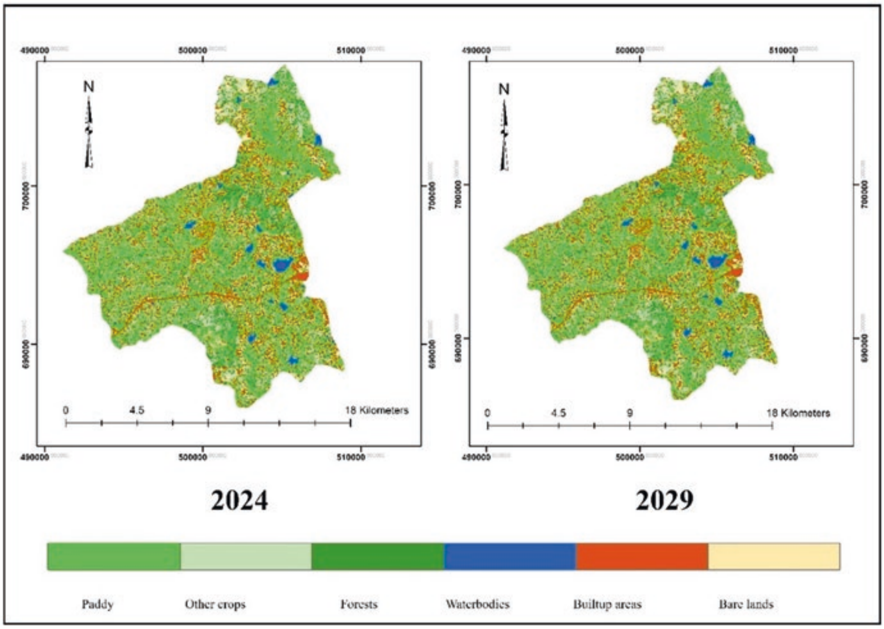

Fig. 12 LULC predictions of study area in 2024 and 2029

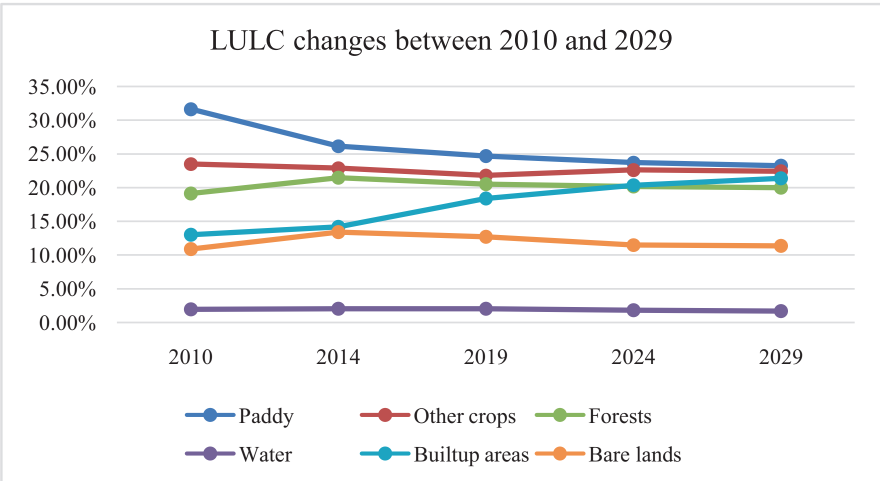

Fig. 13 LULC changes of study area between 2010 and 2029 (with predicted values)

Table 11 Predicted LULC results in 2024 and 2029

LULC type	Area (km^2)					
	2010	2014	2019*	2019**	2024	2029
Paddy	58.7196	48.4938	45.7659	44.802	43.9495	43.0962
Other crops	43.5852	42.4584	40.4532	41.3279	41.9519	41.6054
Forests	35.5005	39.8196	38.0835	37.9509	37.395	37.0899
Water	3.5496	3.7377	3.7062	3.7224	3.3183	3.1023
Built-up areas	24.1128	26.2872	34.11	34.2761	37.7541	39.6702
Bare lands	20.1699	24.8409	23.5188	23.5583	21.2688	21.0736
Total	185.6376	185.6376	185.6376	185.6376	185.6376	185.6376

*Classified result **Simulated result

4.3 Causes for the LULC Changes

To determine the causes of the LULC variations in the research area, relevant literature was studied and experts in paddy farming, including farmers and agricultural officers, were interviewed.

4.3.1 Water Shortages

In Sri Lanka, certain regions experience occasional water shortages due to variations in water distribution across different geographical areas and seasons. The Dry Zone, in particular, faces challenges during the months of June, July, and August, as rainfall is limited while evaporation rates remain high. However, climate change has disrupted traditional weather patterns, leading to unpredictability in rainfall patterns, which has further exacerbated the problem of water scarcity in these regions. As the world's population rises, anomalies will become more prevalent as a result of present climate change combined with growing food demand.

As a developing country, Sri Lanka already suffers with agriculture management, and the management of these components will undoubtedly have a significant impact in the future. The Sri Lankan government is aware of these problems and has devised ways to address them. The policies emphasize the need of water conservation. The task, however, may not be straightforward to complete. Farmers in Sooriyawewa, Sri Lanka, have expressed concerns about the unauthorized use of water despite significant investments in rehabilitating irrigation systems. Studies indicate that Sri Lanka is experiencing a general trend of decreasing precipitation rather than an increase. This decline has been attributed to factors such as deforestation over the past decade, which has disrupted the regulation of the hydrological cycle by forests. Changes in monsoon patterns have also been discussed as contributing to the water scarcity issue. Additionally, the use of irrigation and chemical inputs in agriculture, as highlighted by Droogers in 2004, raises concerns about the potential negative impacts such as biodiversity loss, soil salinity, and erosion.

4.3.2 Alternative Crop Cultivations

According to a study conducted in Hambantota, banana, watermelon, papaw, pomegranate, and passion fruit are the most commonly grown alternative crops in Sooriyawewa DSD. Farmers in the region have opted to cultivate bananas in paddy areas due to the potential economic benefits (Kumarage & Arunakumara, 2019).

Chena cultivation, which involves forest firing or "Nikini Paaluwa," begins in October in the Hambantota district, coinciding with the Maha rains. Farmers typically initiate the practice in August during the dry season. The increase in alternative crops can be attributed to various factors, including water scarcity, economic considerations, damage caused by animals, and a lack of government support in the form of fertilizer and seed subsidies.

Farmers also highlight marketing as a significant challenge, which is influenced by political actions and market demand. They mention that timing the harvest of bananas is crucial to align with periods of peak market prices. In Sri Lanka, the fruit season typically runs from April to June, resulting in market competition and lower prices for bananas. Consequently, when banana production is low, market prices tend to rise. In contrast, paddy has a minimum price set, but this is not always the case.

Paddy production involves high initial costs, requiring substantial investments from farmers. The paddy industry is susceptible to risks such as floods, droughts, pest and disease outbreaks, and price fluctuations. If farmers experience crop losses, they face significant financial challenges. Therefore, cultivating alternative crops is considered a viable solution for both individual and commercial farmers in the Sooriyawewa area.

4.3.3 Construction Activities Near Sooriyawewa

From 2005 to 2015, the Government of Sri Lanka had a primary focus on enhancing infrastructure and initiating various development projects in the Hambantota district. This period witnessed the initiation of several significant projects that had an impact on the land use and land cover (LULC) in Sooriyawewa DSD. Notable projects included the Hambantota International Port, the Mahinda Rajapaksa International Airport in Mattala, the Mahinda Rajapaksa International Cricket Stadium in Sooriyawewa, the Southern Expressway, and the Magam Ruhunupura International Convention Centre. The construction activities associated with these projects played a significant role in driving LULC changes in the Sooriyawewa DSD.

These infrastructure development initiatives brought about changes in land use patterns, resulting in the conversion of natural or agricultural areas into built-up areas. The expansion of transportation networks and the establishment of commercial and recreational facilities in the region influenced the spatial distribution of land cover types in Sooriyawewa DSD during the specified period (Figs. 14 and 15).

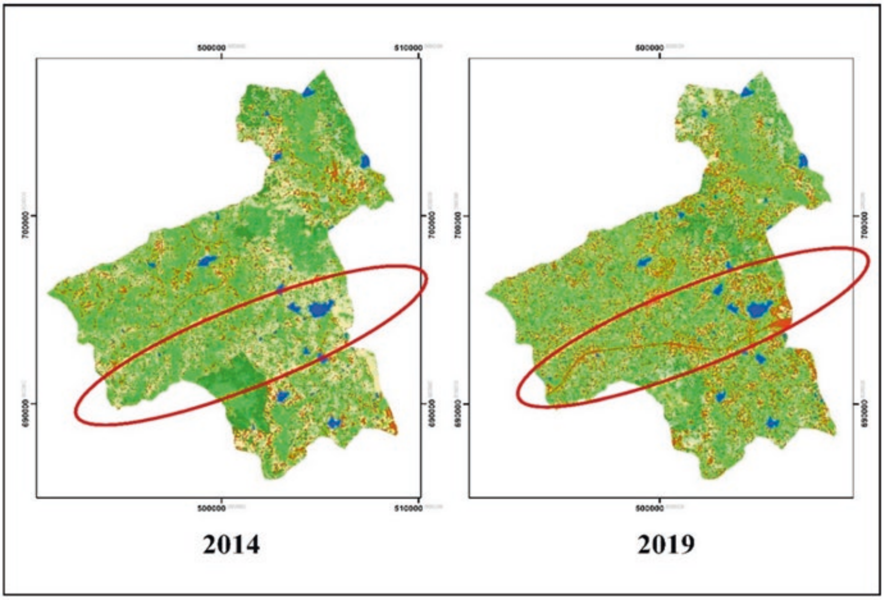

Fig. 14 In 2014, LULC map not having the Southern Expressway, but in 2019, LULC map depicts Southern Expressway

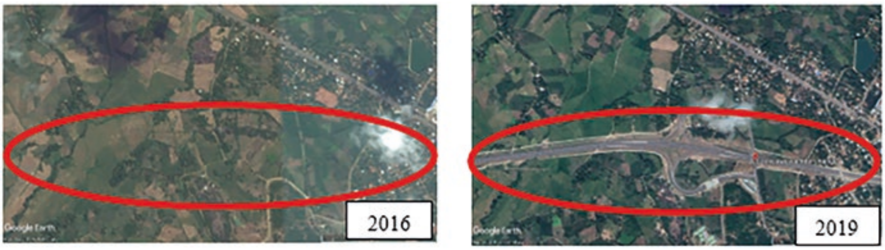

Fig. 15 2016 and 2019 Google Earth images. (Source: Google Earth)

4.3.4 Pests and Diseases, Fertilizer Problems

It is critical to reduce and avoid natural dangers such as pests and illnesses during paddy production. Bananas, unlike paddy, were shown to be more susceptible to disease throughout the interviews. The crop was supposed to be easier to cultivate if the farmer was able to keep the banana from becoming afflicted with illnesses. Currently, the government is taking steps to encourage the production and usage of organic fertilizer in agriculture. They expect to boost crop yields, improve soil fertility, and cut chemical fertilizer imports. However, due to a lack of chemical fertilizers, farmers are having a difficult time cultivating.

5 Conclusion

This study employed Landsat satellite images to monitor and predict the changes in land use and land cover (LULC) in Sooriyawewa DSD, Sri Lanka. The focus of the research was primarily on analyzing the changes in paddy cultivation from 1980 to 2019. However, the study also observed notable changes in other land cover categories such as waterbodies, built-up areas, and other crops. The primary objective of the research was to analyze the changes in the extent of paddy cultivation over the specified period. However, the analysis of LULC changes revealed significant transformations in other land cover types as well. Between 1980 and 2019, there was a noticeable decrease of −15.50% in the paddy cultivation area. On the other hand, there was a significant increase in built-up areas by 11.97% and in the cultivation of other crops by 10.08%.

These findings indicate that there have been substantial shifts in land use patterns in Sooriyawewa DSD over the past few decades. The decrease in paddy cultivation may be attributed to various factors, while the expansion of built-up areas and the cultivation of alternative crops reflect changes in socio-economic activities and development in the region. The analysis of LULC changes provides valuable insights into the evolving landscape of Sooriyawewa DSD and can assist in understanding the drivers and implications of these transformations. The predicted result for 2024 and 2029 revealed paddy area percentage as 23.67% and 23.22% from the total land cover.

Traditional methods of crop monitoring often face challenges such as being time-consuming, subjective, expensive, limited in scope, prone to errors during field observations, and less efficient and accurate. However, the emergence of Remote Sensing technology has revolutionized crop monitoring by providing efficient and accurate methods for evaluating natural resources and managing agricultural activities (Unal, 2020). Sri Lanka still uses conventional methods for crop monitoring (e.g., reports and field visits). Many countries in the world use space-born data collection for paddy cultivation monitoring. However, in Sri Lankan context, there are not any space-born data collection in paddy cultivation. Overall, Remote Sensing technology has become a widely recognized and effective approach for crop monitoring, offering numerous benefits over traditional methods. Its ability to provide timely and accurate information about crop health and productivity has made it an indispensable tool in modern agriculture. Thus, this study identified what are the reviewed system for monitoring the LULC changes and applicable Remote Sensing techniques, then quantify the LULC changes over paddy cultivation during the past four decades (1980–2020) and finally examined the underlying causes for LULC changes over the paddy.

The most common alternative crops in Sooriyawewa DSD are banana, watermelon, papaw, pomegranate, and passion fruit, while a study conducted in Hambantota in 2015–2016 discovered that farmers choose to plant banana in paddy regions for economic advantage (Kumarage and Arunakumara, 2019). According to farmers and agrarian officials, the main reasons for the increase in other crops are water shortages, economic factors, animal damage, and, most critically, a lack of government help, which includes fertilizer and seed subsidies. According to research conducted in recent years, there is a trend in Hambantota to convert rice fields into alternate crops, specifically banana farms. (Hirimburegama, Dias and Hirimburegama). Given that this scenario is going to continue, Sri Lanka may face food security challenges as a result of being unable to fulfill demand. If there is insufficient rice to feed the growing population, it may have to be imported from other nations, which will harm the country's economy. As a result, there will be a red alert for Sri Lanka's primary crop. Because the Hambantota district has experienced fast development since 2010, land management for proper agriculture is critical. If the government pays attention to this and takes necessary action, the crisis can be mitigated. This situation can be minimized by providing necessary facilities to the farmers for cultivation (e.g., improve the loan conditions for the farmers, giving fertilizers and pesticides), improving their living standards, educating them about paddy cultivation, giving them a fair price for the harvest, and preparing farmers for extreme weather events such as droughts. Farmers should be taught how to create their own manure. Using sustainable and natural materials will be less expensive and safer.

The conversion of paddy fields and natural resources into built-up areas in Sooriyawewa has significant environmental impacts, including the reduction of ecosystem services, loss of agricultural land, increased heatwaves, and potential health-related issues. To address these negative consequences, it is crucial to implement a sustainable land use management plan in Sooriyawewa that focuses on anticipating and monitoring microscale changes in various directions and imposing restrictions on the conversion of natural resources to built-up areas.

The methods and findings of this study hold great value for concerned authorities, policymakers, government officials, and urban planners. By adopting a micro-level directional approach in Local Area Planning (LAP), these stakeholders can utilize the study's insights to develop strategies for making Sooriyawewa a livable city. These strategies may include initiatives such as plantation programs, conservation of waterbodies, and planned urban infrastructure development. By implementing a planned, inclusive, and environmentally sustainable approach, Sooriyawewa can ensure a balance between urbanization and the preservation of natural resources.

It is crucial for the relevant authorities to recognize the temporal nature of this problem and understand the necessity of undertaking projects that address these issues. The findings and recommendations from this study can serve as a valuable resource for decision-making processes, aiding in the development of effective policies and measures to promote sustainable development and mitigate the adverse impacts of land use change in Sooriyawewa.

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A Bioinformatics Insight on Agriculture

Bharti Vyas, Sunil Kumar, and Mymoona Akhter

1 Introduction

Bioinformatics has come out as a new branch of science that has multifaceted use of in silico database and algorithms to analyze gene, proteins, and macromolecule (DNA/RNA) and whole genome. Huge numbers of sequence and structural data are produced via advances in proteomics, next-generation sequencing technology, and large-scale molecular biology initiatives. It is extremely difficult to analyze this biologically data. In 1970, "Paulien Hogeweg," a Dutch system biologist, coined the word "bioinformatics" to describe the application of information technology to the study of genetics. Bioinformatics is an interdisciplinary branch of science area that comes out as a tool to facilitate biological discoveries and appropriate knowledge for biological records organize, distribution, and management more than a decade ago. But soon it manifested itself fundamentally in giving tools for statistics analysis, modeling, and interpretation. Additionally, because of in silico method, it was able to examine and comprehend the function and structure of both larger molecular collections obtained from commonly called omics experimental techniques and individual bio-molecules (Berg, 2009; Batley & Edwards, 2016).

B. Vyas
School of Interdisciplinary Science and Technology, Jamia Hamdard, New Delhi, Delhi, India

S. Kumar
ICAR-Indian Institute of Farming System Research, Modipuram Meerut, Uttar Pradesh, India

M. Akhter (✉)
Department of Pharmaceutical Chemistry, School of Pharmaceutical Education and Research, Jamia Hamdard, New Delhi, Delhi, India
e-mail: makhtar@jamiahamdard.ac.in

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2 A Conceptual Approach of Bioinformatics

The cell, organism, and evolution are three possible abstractions for the science of bioinformatics. Deoxyribonucleic acid (DNA), ribonucleic acid (RNA), and protein carry the information archives found in every organism, or the building blocks of a living cell. Inside the cell, these DNA and RNA (in the case of some viruses) create genetic material that contains the information necessary for inheritance (Batley & Edwards, 2016; Esposito et al., 2016). The four fundamental nitrogen bases, which make up the genetic material (DNA or RNA), are arranged in the following ways to create the genome's instructions:

A cell's DNA contains millions of genes, and the transmission of genetic information through genes encodes proteins that, in turn, control how the cell functions. "The central dogma of molecular biology" refers to the mechanism that underlies the transformation of DNA sequence into protein sequence. It was first put forth by Francis Crick in 1958 and consisted of two main phases, as indicated in (Fig. 1). Transcription is the first process, during which the data included in each cell's DNA is transformed into a messenger RNA (mRNA). The second process is translation, in which the base sequence of the mature mRNA is "read" and changed into amino acid sequences that create a particular protein. Three-letter words (triplets) called codons are used to decipher the information contained in a nucleotide in the mRNA sequence. The central dogma of genetics is, in essence, that DNA is translated into RNA and then transcribed into proteins (Esposito et al., 2016). The main focus of genetic biology is on specific genes, messenger RNA (mRNA) transcripts, noncoding RNAs, and proteins. Contrarily, bioinformatics focuses on the entirety of an organism's DNA, RNA, and protein sequences (i.e., proteome), collectively known as its "genome," "transcriptome," and "proteome," respectively (Henikoff, 2002). Massive amounts of biological data are produced as an outcome of the significant progression genetic science and genomic technologies, creating both immense opportunities and enormous obstacles (Imran et al., 2018).

Applying databases and algorithms to cellular and molecular biology is a key component of the *in-silico* method to molecular sequence data. Functional genomics is a term that has been used to describe this approach. This exemplifies the core characteristics of bioinformatics: biological problems can be handled at several points, including single gene and proteins, cellular pathways and networks, or even entire genomic responses. Our objectives are to comprehend how to research collections of several genetic metrical like gene or proteins as well as individual gene and proteins.

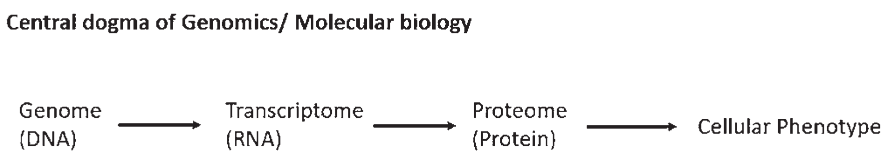

Fig. 1 Central dogma of genomics

3 Sections of Bioinformatics

There are three nearly related sections of bioinformatics; genomics, transcript omics, and proteomics, founded as a result of the characterization of these categories of factors and the corresponding advancement of analytical techniques.

3.1 Genomics

Genetics plays a crucial role in modern biological studies, which reveal mechanisms that underlie difficulties associated with macromolecule function, structure, biochemical or disease processes, and evolution. It involves comprehensive analysis of nucleic acids through molecular biology techniques before the facts are ready for handing out by a computer. A living organism's genome sequence is used to try to explain it in this branch of study (its constituent genetic material) (Kumar, 2018).

Many bacterial genomes have previously been fully sequenced and made available to the public. The first bacteria to be sequenced was Haemophilus influenzae in 1995. The first eukaryotic organism, the unicellular genetic model *Saccharomyces cerevisiae*, was sequenced after the genomes of bacteria. The nematode *Caenorhabditis elegans*, the first multicellular organism, was added to the list in December 1998 and is today regarded as a model organism to teach us about the special roles played by more complex organisms. The potential for using all of this data to better understand how life works can be explored with the aid of genomics, which is essentially identical to bioinformatics (Ghosh & Mallick, 2008).

Plant genomics has made significant strides with the completion of the genome sequences of tomato (Solanum lycopersicum), rice (Oryza sativa sp. Japonica Nipponbare), Arabidopsis thaliana, and rice. The genomes of these model crop species were the focus of extensive sequencing efforts before moving on to other non-model species. When communicating functional knowledge to closely-related species, model animals serve as a platform. However, the size of sequenced genomes (plant) ranges from tiny 63.6 Mb (Genlisea aurea) to exceptionally big 22.18 Gb (Pinus taeda), which is almost seven times larger than the human genome, and almost 82% of its genome is occupied by duplicated sections as opposed to just 25% in human. Most of the current assembly techniques, for some reason, are unable to handle the complexity; as a result, it is necessary to either prepare huge sequencing insert libraries, use mate-paired reads, sequence DNA samples from homozygous lines, or a combination of these. More than 30 plant species have purportedly had their entire genomes sequenced, and updated genome data is now accessible in databases. The availability of whole genome sequences and a deluge of sequence data, however, have made bioinformatics function increasingly important. To organize and evaluate, these massive volumes of data without the aid of *in-silico* tools are nearly impossible (Gajula et al., 2016).

3.2 Transcriptomics

The entire collection of RNA molecules in a single biological cell, a population of biological cells, or an organism is known as the transcriptome. Transcriptomics is the study of the transcriptome. Using methods like sequential analysis of gene expression (SAGE) or DNA microarrays, which can sample tens of thousands of different mRNAs at once, this study aids in illustrating the level of gene expression. Gene expression can change according to illness conditions or a number of intrinsic and extrinsic cues. The development of novel sequencing technologies and other in silico tools has made it possible to evaluate gene expression in uncharacterized plants or identify novel genes (Gajula et al., 2016).

3.3 Proteomics

The proteome, which is made up of all the proteins present in a cell at any one time, is the second by-product of genome expression. In proteomics, the amino acid sequence of a protein is analyzed, together with its 3D structure and relationship to the protein's function. Uses of in silico techniques in the field of proteomics included the analysis of amino acid sequences, detection of polymorphism, post-translational modifications, and splice variants, as well as the discovery of protein binding partners. The main technologies in the field of proteomics include mass spectrometry, protein microarrays, and two-dimensional gel electrophoresis. In silico tools are essential for understanding and extracting information from the data produced by these many devices.

Bioinformatics tools are significant in predicting protein structure and sequence while establishing a relation between the genome and the proteome. This application is critical for biotechnology research, particularly in understanding the importance of physicochemical properties of proteins in cells. With the improvement of precise protein structure prediction algorithms, it will be possible to translate entire genome DNA sequence data into physicochemical properties of protein: Such progress can be responsible for a critical relation between an organism's genetics and its expressed phenotype. In contrast to predictions, plant protein sequences are more complex, indicating plenty of potential for further study. In-silico methods to structure and integrate omics data require modeling both the proteome and its interactions. Several successful studies on protein structure prediction, modeling, and simulation have been published, which aid in understanding protein functional mechanisms and protein interactions (Gajula et al., 2016).

3.4 Metabolomics

The study of metabolic compounds and polymers on a large scale (typically throughput) is called metabolomics. In the context of Metabolomics, biochemical analysis is used to identify and characterize a wide variety of metabolites. The significance lies in the quantitative identification of metabolites that serve as a direct indicator of the desired phenotype (Gajula et al., 2016). In silico tools are required at every stage of the process, from screening to data storage, because metabolites ultimately represent the dynamics of a cell.

4 Research Area of Bioinformatics

Bioinformatics is categorized into two areas of study: the progress of databases and tools and their use in the generation of biological information to better understand biological data. Bioinformatics can be employed in a variety of fields, including

4.1 Analyzing Gene Sequences and Identifying Gene

The sequence analysis of a biomolecule (nucleic acid and protein) is based on understanding the different features that give it its unique function. The first step is to retrieve corresponding molecule sequences from public databases. As a result of refinement, various tools enable highly accurate prediction of their features, such as their function, structure, evolutionary history, or homologies. Sequence analysis includes alignment of sequences, the search for sequence databases, the assembly of genomes, the discovery of patterns and motifs, promoter discovery, reconstruction of evolutionary relationships, and comparison. These analyses are valuable for identifying terminator, promoter, or untranslated regions involved in expression regulation, an open reading frame (ORF), exons, introns, recognizing a transit peptide, and identifying specific variable regions to be used as diagnostic signatures. A number of tools have been developed for this purpose; some of the most important tools are listed below (enlisted in Table 1 with function).

In addition, DNA sequences and encrypted information do not directly reflect how genetic information creates traits and behaviors (phenotypes). It is possible to deduce this with area of biological study, comparative genomics in which genome sequences of diverse species of organism from microorganisms to humans are related to know their evolutionary mechanisms. In comparative genomics, synteny regions are defined as the conserved order of genes on chromosomes that descend from a common ancestor in related species (Kumar et al., 2016; Turner, 1999).

Table 1 Tools for primary sequence analysis tools description BLAST

Tools	Description
BLAST	The tool is used for searching DNA or protein sequences based on their identities
THMMER	This tool is used to search the homologous protein sequences
Clustal Omega	This tool is used to predict multiple sequence alignments
ProtParam	Protein physico-chemical properties are predicted using this tool
JIGSAW	This tool can predict splicing sites from selected DNA sequences, and find genes
ORF Finder	This tool can be used to find Open Reading Frames (ORFs) for putative genes
PPP	Gene promoter sequences upstream of prokaryotic genes can be predicted with this tool
Genscan	A sequence's intron-exon position can be predicted using this web server
Softberry Tools	A number of tools are available that allow the annotation of organism genomes, as well as prediction of the physicochemical properties of proteins

4.2 Sequence Databases

A crucial task of dry lab (bioinformatics) is to interpret the massive amounts of sequence and structural data generated by NGS (genome sequencing), large-scale molecular biology, and proteomic analyses. Biological sequence databases contain data about genetic material which are identified by unique keys. It is important for both future use and primary use (sequence analyses). Increasingly high-throughput sequencing techniques are allowing us to sequence entire genomes that is producing a large volume of data every day. Globally, numerous databases have been created as a result of the storage of data. In accordance with the information they contain, databases may be classified as primary, secondary, or composite databases. In a primary database, data is obtained through experiments such as XRD, yeast-two hybrid assays, affinity chromatography, NMR approaches relating to structure or sequence. Databases such as, UniProt, Swiss-PROT, PIR DDBJ, GenBank, Protein Databank (PDB), and EMBL are examples of primary databases. In the secondary database, data is included that has been derived from analysis of data stored in a primary database, such as active sites, conserved sequences referred to by a protein family, or conserved secondary motifs referred to by a protein molecule. Examples of secondary databases include CATH, eMOTIF, SCOP, and PROSITE. Data derived from different primary sources constitute a composite database. There are several types of composite databases available, including NRDB (non-redundant database), which contains data from PDB, GenBank (CDS translations), PIR, SWISS-PROT, and PRF. INSD (International Nucleotide Sequence Database) is another example of a composite database, which is a collection of nucleic acid sequences from DDBJ, GenBank, and EMBL. In addition to UniProt (universal protein sequence database), other databases including PIRPSD, Swiss-Prot, and TrEMBL provide sequence data (Turner, 1999; Degrave et al., 2002; Edwards & Batley, 2004). The names of the relevant databases along with their functions are given in the table below (Table 2).

Table 2 List of important web servers

Web server	Description
Nucleotide databases	
DNA Data Bank of Japan (DDBJ)	An international nucleotide sequence database (INSD); it is one of the most significant nucleotide sequence databases
European Molecular Biology Laboratory (EMBL)	Repository of DNA and RNA sequences that is complementary to GenBank and DDBJ
GenBank	It is a nucleotide sequence resource
Protein databases	
Uniprot	It holds huge data about the biological function of protein, which is resulting from the research literature
Protein Data Bank	This server contains structures of large biological molecules (nucleic acids, proteins)
Prosite and InterPro	It provides information on conserved domains, active sites, and families of proteins
Pfam	There are a number of protein families contained within it
SWISS-PROT	In this database, protein sequences are curated and annotated at a high level
Genome databases	
Ensemble plants	This resource integrates genome-scale information on an increasing various of plant species that have been sequenced
Phytozome	It provides comparative data and analysis on plant genomes and gene families
PIR	PIR is used to proteomic and genomic research
Miscellaneous databases	
TAIR	This database of molecular genetic data is maintained for the Arabidopsis thaliana plant model
KEGG	This database combines genomic and higher order functional data to provide systematic analysis of gene functions
Rfam	This database provides the information about structured RNA elements and non-coding RNA families

4.3 Phylogenetic Analyses

Analyses of phylogenetic relationships are procedures for reconstructing the evolution of a group of related molecules or organisms, predicting certain properties of molecules of unknown functions, tracking gene flow, and determining genetic relationships. This could be represented by a genealogical tree. In phylogeny, living organisms are grouped. The use of phylogenetic comparative analyses is extensively employed to address the problem of statistical independence among species. Three major approaches are used to build a phylogenetic tree: the distance method, the parsimony method, and the likelihood method. These three methods are not perfect; every method has a particular weakness and strength (Emmersen et al., 2007). Like, the distance-based trees method easyto build up tree but not specific. Limitation of the maximum parsimony and maximum likelihood methods is more specific but it takes more time to run. The most straightforward are the distance-matrix approaches,

Table 3 List of proteomics web server and package

Tools	Description
ExPASy	It is a proteomics server that is used for knowledge and analysis in depth of the protein
CATH (Class Architecture Topology/fold Homology/ superfamily	This database delivers evidence on the evolutionary association of protein domains.
SCOP (Structural classification of Proteins)	This database provides information on classification of protein structural domains based on amino acid sequences and similarities of their structure
Swiss-Pdb Viewer	It allows to analyze several proteins at the same time
I-TASSER	A web-based server is used to generate the 3D structure of proteins using the fold recognition method (in this method, find a similar template from Protein Data Bank)

such as Neighbor Joining (NJ) and Unweighted Pair Group Method with Arithmetic Mean (UPGMA).

4.4 Analysis of the Physicochemical Properties of Proteins

Biologically active proteins begin as amino acid chains and eventually fold up to form a 3D structure. The correct folding of a protein into the accurate topology is essential to the operation of the protein in its biological role. Therefore, 3D protein structure prediction is crucial for understanding the function of specific protein. So many techniques are available to find out the 3D structure like NMR spectroscopy and X-ray crystallography (Table 3). The limitations of such methods are that they are complicated, time-consuming, and costly, and they are often hampered by the inability to obtain good crystals and poor heterologous expression. As a result, very few structures obtained through X-ray crystallography and NMR spectroscopy are submitted to PDB. Alternatively, the 3D structure of a protein might be predicted using a variety of bioinformatics method, and as a result, this has emerged as a significant key area in the study of bioinformatics (Field et al., 2005; Fraser et al., 2009).

5 The Applications of Bioinformatics in Agriculture

The need to develop a sustainable agricultural production system and to ensure food security is becoming increasingly important as a result of population growth, the degradation of the environment, and the effects of climate change. Its ultimate goal is to facilitate the innovation of biological visions and to provide a wide perception on which to draw unifying biological concepts. As part of the "genomic revolution," bioinformatics was concerned with creating and maintaining a database that would store biological information, such as nucleotide and amino acid sequences. The field of bioinformatics is currently gaining significance in the life sciences, particularly in the fields of molecular biology and plant genetics. In evolutionary biology, molecules of different organisms are examined to determine whether they share a common evolutionary history. The potential benefits of this process include the discovery of previously unknown relationships between life forms. A bioinformatics approach can be used to track this data, allowing evolutionary biologists to gain new visions into the causes and cures of certain diseases. The examination of plant genomics involves understanding the genetic and molecular basis of all biological processes that are related to a particular species. It is crucial to understand plants as biological resources so that new cultivars of essential crops can be developed with improved quality, reduced economic inputs, and reduced environmental impact. Knowledge of this area is also essential for the development of new diagnostic tools for plants. The primary traits of interest in this study are those associated with pathogen and abiotic stress resistance, quality traits for plants, and reproductive traits determining yield. Plant genetic resources can be gathered and stored to produce crops that are more drought, stronger, disease, and pest resistant, and to raise the caliber of animals so that they are disease resistant and more productive. A good programmer might be envisioned as a highly effective software/tool for plantae improvement(Fraser et al., 2009; Hermosa et al., 2006).

5.1 Crops

Plant genomes remained conserved during evolution and did not provide much information. The advent of bioinformatics tools made it possible to extract information from the genomes of specific plantae. Two species of food plants have had their genomes completely mapped, for example, Arabidopsis thaliana (water cress) and Oryza sativa. Water cress is a small plant that grows on rocks. A small genome size drew researchers' interest, and they studied its developmental processes. It has five chromosomes on which 100Mbp of DNA is distributed and reproduces in 5 weeks. The study of its genes and their expression provides information about the physicochemical properties of plant proteins. Understanding the genome of *A. thaliana* has many applications, but the primary one is the ability to increase the yield of plants.

5.2 Renewable Energy

Plant-based biomass can be used as a source of energy by converting it into biofuels such as ethanol, which could be used to power vehicles and planes. Various biomass-based crops such as maize (corn), switch grass, and lignocellulosic plants like bagasse and straw are used to produce biofuel. The detection of sequence variants in biomass-based crop species would allow us to maximize biomass production and resistance. It has recently been revealed that the genome of eucalyptus grand is one of the major resources for biomass components, and all of the genetic material involved in the conversion of sugars into biomass components have already been deciphered. Consequently, in silico gives invaluable insight into the mechanisms and pathways responsible for this conversion, in order to improve the production of biomass components in eucalyptus and other relevant plants in the future. In other words, genetic material and bioinformatics combined with breeding would likely increase the ability of breeding crop species to be used as biofuel feedstocks and consequently increase the use of renewable energy in modern society (Fraser et al., 2009; Hermosa et al., 2006; Kumor, 2009; Luscombe et al., 2001; Jayaram & Dhingra, 2010).

5.3 Insect Resistance

The precisely needed genes can be inserted into many plants to develop insect resistance. *Bacillus thuringiensis* is a type of bacteria that naturally exists in soil and is used to improve soil fertility and protect plants from pests. It produces a protein that causes immature insects (larvae) to release poisons that damage their guts and cause them to starve and become infected (Kumar et al., 2016). After sequencing its genome, scientists used its genes by introducing them into plants to increase their resistance to insects. For instance, potatoes, corn, and cotton have been genetically modified to withstand pests. In addition to reducing the need for insecticides, the effective deployment of Bt genes develops the capacity for plant genomes to resist insect breakout. Thus, its cost-effectiveness increases the nutritional value of plants and might be useful for human wellbeing (Fig. 2).

5.4 Improve Nutritional Quality

In order to improve rice's levels of iron, vitamin A, and other micronutrients, scientists recently succeeded in inserting gene into the grain. Like golden rice, which can combat vitamin A deficits, was created with the aid of bioinformatics technology. This research may significantly reduce the incidence of blindness and anemia brought on by iron and vitamin A deficiency, respectively (Paine et al., 2005). A tomato plant with fruit that hangs on the vine for longer as a result of scientists inserting a gene from yeast into the plant.

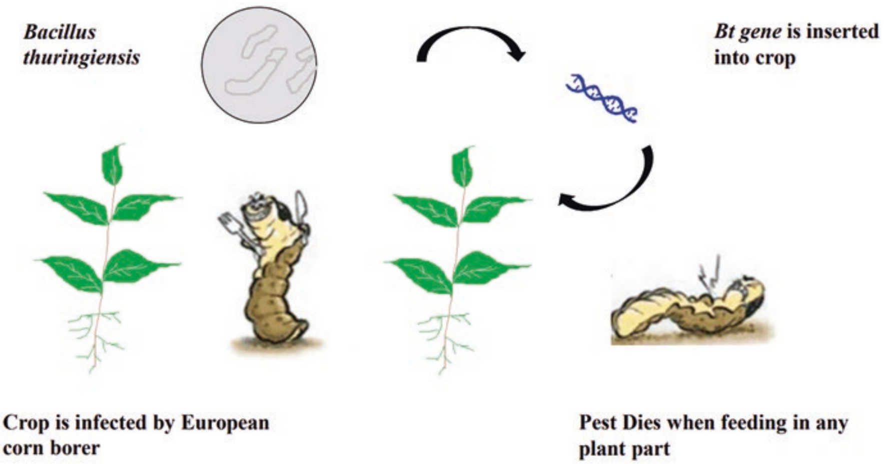

Fig. 2 This flow diagram demonstrates how corn develops resistance to corn borer infection through the insertion of a gene from the bacterium Bacillus thuringiensis

5.5 Grow in Poorer Soils and Drought Resistantce

The development of cereal types that can tolerate soil alkalinity, free aluminum, and iron toxicity better has advanced. By enabling agriculture to flourish in locations with weaker soils, these varieties expand the available land for food production worldwide. Research is being done to create crop varieties that can tolerate low water circumstances (Wang et al., 2004). Huge amounts of data are gathered as a result of such thorough research, making it challenging for one scientist to analyze. Greater aid is provided by bioinformatics in resolving such issues.

5.6 Plant Breeding

Phytogenomics is concerned with understanding the genetic basis for all life processes within plantae. This comprehension is essential to enabling the effective misuse of plantae as biological resources in the creation of novel crop with enhanced value and lower financial and ecological expenses (Fig. 3). It is now possible to picture omics data as a crucial tool for improving plants. Understanding how plants react towards interact with external and internal stimuli is made possible by the capacity to evaluate gene expression. Future breeding choice management systems may use these data as a key tool (Lindeberg et al., 2005).

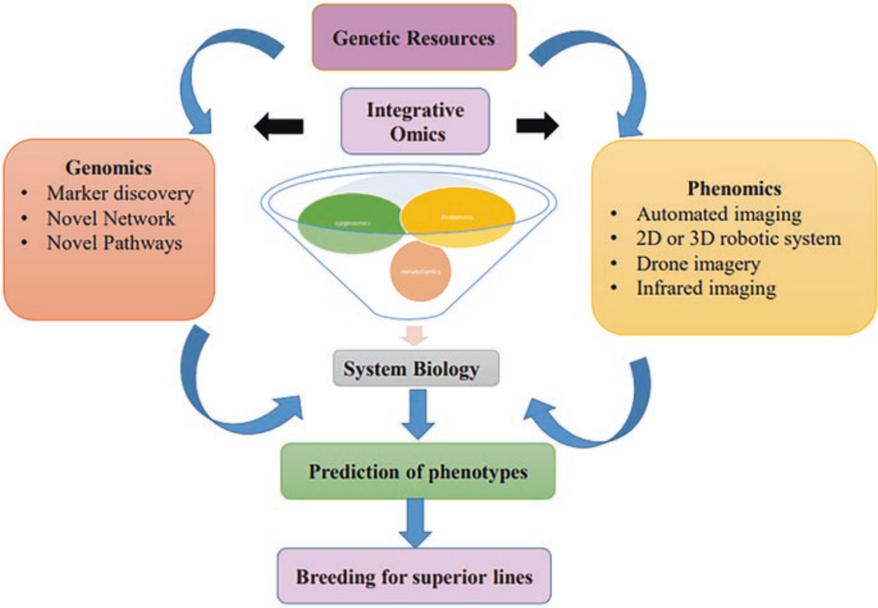

Fig. 3 Schematic flowchart of integrated omics in genetics and breeding for crop improvement

5.7 Agriculturally Important Microorganism

A meta-genomics and transcriptomics approach used in bioinformatics enables the identification of microbes and pathogens and their effects on plants to be determined. This allows us to develop pathogen-resistant cultivars and find the microorganisms that are valuable for the host.

5.8 Bioinformatics in Plant Disease Management

The core focus of plant bioinformatics is thought to be pathogen characteristics. The mapping of many organisms' whole genomes in just over a decade was made possible because of advancements in bioinformatics. Due to current efforts to identify the activities of genes and proteins, the ability to comprehend the underlying causes of pathology has improved and we are now able to discover new treatments for them. The need for data and analysis in the biological sciences will also probably be a major driver of many future advancements in bioinformatics (Boyle, 2004; Fraser et al., 2009). This field has various applications in plant disease management, including the examination of pathogenicity factors and host–pathogen interactions; all these factors help in designing the best management techniques.

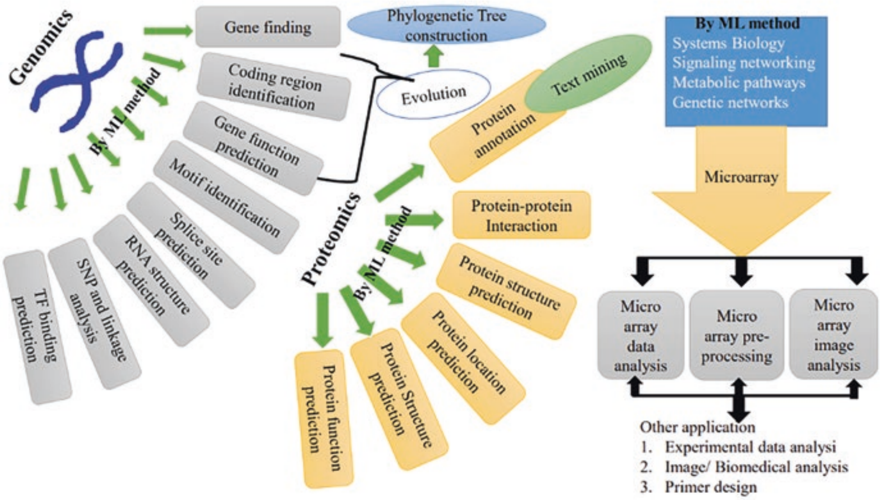

Fig. 4 A systematic diagram of all biology topics using ML methods

6 The Bioinformatics Machine Learning Era

The exponential increase in the volume of biological data available raises two issue; first is the effective management and storage of the data, and the extraction of information that might be used. And second is a more challenging task in computational biology that required the new and advance development of tool and techniques to transforming all these heterogeneous data into biological information about the underlying mechanism. These tools/techniques help us to simplify the description of data into testable models by using machine learning (Fig. 4). The study of artificial intelligence (AI) falls under the field of computer science and machine learning is part of AI. Machine learning is a technique of computer science that is used for the development of algorithms to find out hidden/deep information of biological data. When trained on huge datasets, these systems are capable of making rather complicated predictions due to their multi-layered approach to understanding patterns in the input data. Six separate biological domains: systems biology, microarrays, genomics, proteomics, evolution, and text mining have seen the most use of machine learning (Larranaga et al., 2006).

7 Conclusion

Today, bioinformatics plays an increasingly important role in agricultural development, agro-based industries, and the efficient use of by-products from agriculture, and better environmental management. A rapid advance in genomics has led to the sequencing of model plants and plant pathogen genomes, which has created a number of opportunities for genetic improvement of crop plants. Several useful traits have been discovered for crop improvement due to the high degree of synteny between diverse plant species, the commonality between traits, and the availability of information regarding expression and function. Researchers have sequenced the genomes of several important plant species and are identifying the "chromosome" and "variation" factors in their sequences. An application of this method has been made for the identification of crop improvement traits. The use of comparative genomics and bioinformatics could contribute to the improvement of maize, rice, and other crops such as rye, barley, wheat yields, and sugarcane. Plant genomes have been represented with high resolution using bioinformatics tools.

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Part II
Advanced Technology in Agriculture for Climate Smart Farming

Tech-Driven Agriculture: Adapting to Climate Challenges

Aishwarya and Pavan Kumar

Agriculture plays a vital role in sustaining global food security, but it also faces significant challenges posed by climate change. As climate variability and extreme weather events become more frequent and unpredictable, the need for climate-smart farming practices becomes increasingly urgent. This abstract presents an overview of advanced technologies in agriculture aimed at enhancing climate resilience, improving productivity, and reducing environmental impacts.

The adoption of precision agriculture techniques, enabled by cutting-edge technologies like Internet of Things (IoT) devices, drones, and remote sensing, allows farmers to collect real-time data on soil moisture, temperature, and nutrient levels. These data-driven insights empower farmers to make informed decisions and optimize resource usage, leading to more efficient and sustainable farming practices. Another critical aspect of climate-smart farming is the implementation of smart irrigation systems. These systems employ sensor-based technologies to precisely manage water usage, reducing water waste and conserving this precious resource. By tailoring irrigation schedules to match crop water requirements, farmers can mitigate the impact of droughts and water scarcity, while maintaining crop productivity.

In addition to precision agriculture and smart irrigation, advanced breeding techniques like CRISPR-Cas9 and genetic engineering offer the potential to develop climate-resilient crop varieties. These genetically modified crops can possess traits that enhance tolerance to extreme temperatures, pests, and diseases, ensuring more stable yields under adverse climate conditions. Furthermore, data analytics and

Aishwarya (✉)
Department of Agronomy, Institute of Agricultural Sciences, Banaras Hindu University, Varanasi, UP, India

P. Kumar
Forest Biology and Tree Improvement, College of Horticulture and Forestry, Rani Lakshmi Bai Central Agricultural University, Jhansi, India

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artificial intelligence are revolutionizing agriculture by providing predictive models for pest outbreaks, disease detection, and yield forecasting. These predictive insights enable farmers to proactively respond to potential threats, minimizing losses and optimizing production. Climate-smart farming also embraces sustainable practices like agroforestry, cover cropping, and crop rotation. These techniques contribute to biodiversity conservation, soil health improvement, and carbon sequestration, thereby mitigating greenhouse gas emissions and enhancing the overall sustainability of agriculture. As technology continues to evolve, it is crucial to ensure that these advanced agricultural solutions are accessible to all farmers, regardless of their scale of operation or geographical location.

Policy support and investments in research and development are essential to promote the widespread adoption of climate-smart farming technologies. In conclusion, the integration of advanced technology in agriculture is a game-changer for climate-smart farming. By harnessing data, automation, and genetic innovations, farmers can build resilient, sustainable, and productive agricultural systems, effectively combating the challenges imposed by climate change and securing the future of global food production.

This Part explored the applications and benefits of advance technology in agriculture, focusing on its role in climate-smart farming. It examines the ways in which advance technologies can enhance adaptive strategies and promote resilient agricultural systems in the face of climate change. Advance technology involves the use of remote sensing tools, such as satellites, drones, and ground-based sensors, to gather data on various environmental and agricultural parameters. These data can be used to monitor climate conditions, crop health, soil moisture levels, and other crucial factors that influence agricultural production. By employing remote sensing techniques, farmers can make informed decisions based on real-time information, thereby optimizing resource management and improving overall efficiency.

The Part is segregated into 10 chapters. Chapter 11 discusses the *Adaptation and mitigation strategies under climate change scenario*. This chapter provides a comprehensive view on the concept of such strategies and approaches in different sectors. A decisive component of adaptation and mitigation is the enactment of strategies that are appropriate, economically and socially viable, and effective for stakeholders. Chapter 12 is devoted to a *Precision Farming: A step towards sustainable, climate-smart agriculture*. Chapter explored the climate-smart agriculture offers solutions for both adaptation and mitigation of the impacts of climate change. Chapter 13 presents *Geospatial technology for climate change: Influence of ENSO and IOD*. Chapter 14 discusses *Simulation modelling for climate smart agriculture* in the various dimensions of the climate-smart agriculture, their positive effects on the agriculture sector and environment and their role in improving food security under climate change scenarios. Chapter 15 discusses *Strategic intervention for climate-smart agri*culture because the chapter comprehensively documents existing rice agroecological typologies. This book chapter is relevant not only to food system actors but also to researchers, and social activists. Chapter 16 discusses *Climate policies for climate-smart approach*. Agricultural damage due to natural disasters triggered by climatic change is a big loss for small-scale farmers. Therefore, policy initiatives to respond to such situations are necessary and agricultural insurance schemes are appropriate to these conditions. Chapter 17 is devoted to *Land use change and agro-climatic interactions*. Chapter 18 examines the *Drone technology in perspective of data capturing.* This chapter explores the evolution and current state of drone technology in the context of data capturing applications. By utilizing unmanned aerial vehicles (UAVs), data acquisition processes have been revolutionized, presenting new opportunities and challenges across sectors. Chapter 19 discusses *Renovating conservation agriculture: Management and future prospects*.

Adaptation and Mitigation Strategies Under Climate Change Scenario

Shubhi Patel, Anwesha Dey, Abhiraj Chaturvedi, Avdhesh Sharma, and Rakesh Singh

1 Introduction

Climate change has been observed throughout the world with an average increase in human-induced global surface temperature in 2010–2019 relative to 1850–1900, which is 1.07 [0.8–1.3] °C (IPCC, 2021). The rise in temperature across the world has resulted in an increase of extreme events and adverse effects on all the important dimensions of society like agriculture, human lives, and the economy. The occurrence of extreme environmental events, specifically heat waves, floods, dry spells, cold waves, and drought, has jeopardized both the man-made and regular biological systems. These fluctuations in weather parameters lead to uncertainty in crop yield, food security, and thus income received by farmers.

In India, there has been a temperature rise of 0.45 and 0.63 °C in kharif and rabi, respectively, while rainfall has declined on an average by 33 mm in rabi and 26 mm in kharif (Economic Survey, 2017–2018). The economy of Asia is one of the most vulnerable economies to climate change where agriculture is the most severely affected sector (Dellink et al., 2017). These variations in crop yield also affect the economy and thus the income of the farmers. India has suffered economic losses of 79.5 billion dollars during the last 20 years due to natural disasters (UN, 2018).

S. Patel
Department of Agricultural Economics, Narain College, Dr. Bhim Rao Ambedkar University, Shikohabad, UP, India

A. Dey · A. Sharma · R. Singh
Department of Agricultural Economics, Institute of Agricultural Sciences, Banaras Hindu University, Varanasi, UP, India

A. Chaturvedi (✉)
Institute of Environment and Sustainable Development, Banaras Hindu University, Varanasi, UP, India

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During rabi season, per unit rise in temperature causes a 4.1% loss in revenue, and per unit loss in rainfall causes a 5.5% loss in revenue (Economic Survey, 2017–2018).

The agricultural system's vulnerability to these climatic changes depends upon the adaptive capacity. As adaptive capacity is "the ability of a system to adjust to climate change (including climate variability and extremes) to moderate potential damage, to take advantage of opportunities, or cope with the consequences" (IPCC, 2001). Knowledge of changing climate encourages the need to work out to adjust responses in agriculture (IPCC, 2007; Addisu et al., 2016). A pre-requisite for appropriate identification and implementation of adaptation is prior knowledge and also the awareness about climate change (Jodha et al., 2012; Maddison, 2006).

India is a land of small and marginal farmers with average land holding 1.08 ha and 86% of the farmers being small and marginal (Agriculture Census 2015–2016). These small landholders are more vulnerable to climate change because they have a low capacity to adapt. Local elements, including socioeconomic, agroclimatic, and climatic impacts, influence the adaptation techniques used at the farm level. Thus, the knowledge and strategies are subject to regional variation. A key barrier to adopting and increasing climate resilience is a lack of understanding about the true causes of climate change and how to develop adaptation measures. Emphasizing the intricacy between adaptation, mitigation, and climate change impact, it becomes imperative to understand the nexus between them. Thus, this chapter was designed to understand adaptation and mitigation, what are the options available, how adaptation and mitigation have been practiced till now, and what the way forward is.

2 Adaptation: Understanding the Intricacies

The ability of socio-economic frameworks to function properly will face new obstacles as a result of adaptation, which takes into account how climate change will be experienced in relation to the frequency and magnitude of effects, as well as the imperceptibility of causal links in everyday events. It thus consequently emphasizes the need to understand adaptation options and work out suitable solutions. Adaptation according to biologists refers to the occurrence of new traits in an organism as a result of natural selection (Heams et al., 2015). Smit et al. (2000) defined adaptation as, "adjustments in a system's behavior and characteristics that enhance its ability to cope with external stress." Conceptually adaptation to climate change also signifies the occurrence of new traits/characteristics. But these traits or here, we can denote, practices are not the result of natural selection but human effort.

Consequently, climate change adaptation may be intentional, the consequence of carefully thought-out actions, or occasionally, explicitly organized into structures. There have been several definitions of adaptation in climate change. A few of them have been tabulated in Table 1.

We can therefore see that adaptation to climate change can be defined in many different ways, all revolving around the central idea of adapting to new environment. Climate change as we all know has caused losses of biodiversity, habitats,

Table 1 Adaptation definitions

IPCC (2021)	Adaptation in human systems is the process of adjustment to actual or expected climate and its effects, in order to moderate harm or exploit beneficial opportunities. In natural systems, the process of adjustment to actual climate and its effects; human intervention may facilitate adjustment to expected climate and its effects.
IPCC (2014)	Adaptation is an action against climate adjustment, whether it be to existing or anticipated conditions. In human systems, adaptation aims to reduce or prevent harm or reap the benefits of favorable prospects. Human intervention may help certain natural systems adapt to predicted warming and its impacts.
IPCC (2007)	Adjustment in natural or human systems in response to actual or expected climate stimuli or their effects, which moderates harm or exploits beneficial opportunities.
IPCC (2001)	Adjustment in ecological, social, or economic systems in response to actual or expected climatic stimuli and their effects or impacts. This term refers to changes in processes, practices, or structures to moderate or offset potential damages or to take advantage of opportunities associated with changes in climate. It involves adjustments to reduce the vulnerability of communities, regions, or activities to climatic change and variability.
IPCC (2001)	Adjustment in ecological, social, or economic systems in response to actual or expected climatic stimuli and their effects or impacts
Smit (1993)	Involves adjustments to enhance the viability of social and economic activities and to reduce their vulnerability to climate, including its current variability and extreme events as well as longer-term climate change.
Füssel & Klein (2002)	All changes in a system, compared to a reference case, reduce the adverse effects of climate change.

crop production, health, etc. This has put pressure on food security, nutritional security, and the well-being of individuals as well as trade and prices. The only way to cope with these inevitable events is to adjust to these occurrences and work a way out to insulate the stakeholders from the losses. This requires well-planned strategies and a framework that fits into the upcoming projected scenario. According to the steps taken under the adaption, it has numerous types Out of these, there are three main types according to IPCC:

(1) Anticipatory adaptation—Anticipatory adaptation refers to the adaptation process when efforts are made before the visible impacts occurring due to climate change. It is also referred to as proactive adaptation process.
(2) This process follows a process of adapting to another area based on previous climate change impacts in the surrounding area.
(3) Autonomous adaptation—Autonomous adaptation is an unconscious adaptation to climatic stimuli caused by ecological changes in natural systems or market or welfare changes in human systems, which is also called spontaneous adaptation. It is an empirical adaptation method to climate change that is based on current technology and knowledge systems.
(4) Planned adaptation—The adaptation focused on mobilizing resources, institutions, and policies is known as planned adaptation. It is a dynamic process that

grows over time and helps us act against changing circumstances to maintain or achieve a desired state.

2.1 Adaptation and Vulnerability

It goes without saying that developing appropriate adaptation and mitigation strategies requires a direct analysis of local adaptability and vulnerability. Vulnerability assessment is an important tool in impact assessment studies. The concept of vulnerability is very helpful for multidimensional issues assessment. Various indicators are used as proxies for vulnerability assessment. Vulnerability is specific in context, place, space, individual, dynamic, and so on. According to the AR4 framework, IPCC vulnerability is defined as a combination of exposure, sensitivity, and adaptive capacity, while AR5 deals with exposure as a precondition of vulnerability, and vulnerability is represented as a function of adaptive capacity and also sensitivity (Hahn et al., 2009; IPCC, 2007, 2014; Oppenheimer et al., 2014). The adaptation capacity presents a negative relationship with vulnerability. That is, in any system where there is a high concentration of adaptive capacity, there will be low vulnerability and vice versa. Vulnerability assessment is a relative concept that allows for a relative assessment of places, groups, and nations. Instead of being an "ending point," it serves as a "beginning point." The main purpose of vulnerability analysis is to highlight areas vulnerable to problems and to identify viable and practical adaptation strategies for communities.

2.2 Mitigation

Mitigation and adaptation, although used together, are conceptually very different. Where adaptation means adjusting to the existing situation, mitigation refers to the minimization of the harmful effects/losses. According to UNFCC, Efforts to reduce emissions and enhance sinks are referred to as "mitigation." Mitigation refers to the reduction in the factors causing climate change. Greenhouse gas emissions have been proven to be the main cause of the global increase in mercury. As reported by IPCC AR6, the global net anthropogenic GHG emissions have increased over the century (Fig. 1).

Therefore, when mitigation strategies are developed, they are based on reducing carbon emissions into the atmosphere. The objective of mitigation as stated by IPCC, 2014 is to "stabilize greenhouse gas levels in a timeframe sufficient to allow ecosystems to adapt naturally to climate change, ensure that food production is not threatened, and to enable economic development to proceed in a sustainable manner" (IPCC, 2014). On March 21, 1994, the United Nations Framework Convention on Climate Change (UNFCC) was established, which currently has members from 197 countries. The convention was established to stabilize greenhouse gas

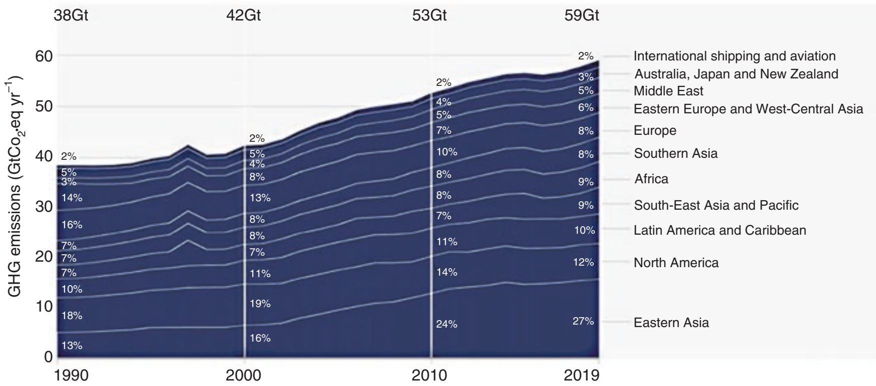

Fig. 1 Region-wise global net anthropogenic greenhouse gas emission for 1900–2019. (Source: IPCC, 2022b)

emissions at levels that discourage human intervention in the climate, as climate change is an anthropogenic phenomenon. The treaty works to set low-emissions targets, coordinate financing for climate change in developing countries, and monitor national efforts towards the set targets. In 1997, the Kyoto Protocol entered into force. The Protocol operationalized the UNFCC by requiring developed countries and economies to limit and reduce their greenhouse gas (GHG) emissions in accordance with agreed individual targets. In 2012, the Doha Amendment to the Kyoto Protocol was passed, updating the commitment targets. Primarily, it proposed reducing greenhouse gas emissions by at least 18% below 1990 levels. In 2004, the landmark event known as the “Paris Agreement” occurred. This is a legally binding international agreement on climate change that aims to keep global warming below 2 °C compared to pre-industrial levels. At COP21, it was agreed that tougher and more ambitious climate change measures are of utmost importance to achieve the goals of the Paris Agreement. The Marrakech Partnership was launched at COP22. It emphasized strong cooperation for better and immediate climate action between governments and other stakeholders.

These agendas and conventions have worked to the benefit of the low-emission goal. But what is noteworthy is that the limits should not come in the path of growth of developing countries. The AR6 report (IPCC 2022b) has stated that the unit expenses of a few low-cost innovations have fallen persistently starting around 2010. This was possible due to innovation policy packages that help to reduce costs and uphold global adoption through customized strategies and far-reaching approaches.

3 Adaptation and Mitigation Strategies—An Insight to Their Importance

It has been established that under no adaptation situation, the risk to livelihoods, economy, bio-diversity, etc. is high. The reports given by IPCC in 2022, that is, AR6, show that a rise in temperature is inevitable. And, the climate risk under no adaptation is high (Fig. 2).

With time the adaptation options have increased that has shown positive signs of resilience build-up. But, what is more, concerning is the adaptation gaps (IPCC, 2022a). In general, it can be said that mitigation, adaptation, and risk management reduce climate risk (Fig. 3). In the near term, due to time lack, adaptation is dominant followed by risk management when compared to mitigation. While in the long term, mitigation strategies have a greater role to play in reducing carbon emissions.

Only when mitigation, adaptation, and risk management are used in concert, the danger of climate change risk can be mitigated. Losses and damages are substantially larger if interventions are not handled properly and in a planned manner, but losses and damages are relatively modest if interventions are done in accordance with the scenarios. In near-future scenarios, adaptation procedures are highly effective in reducing climate change risk; but in the long run, when risk is far higher than these scenarios predict, the importance of mitigation strategies will rise.

When it comes to adaptation strategies, it is important that adaptation strategy is not only just a strategy but a framework encompassing several aspects (Fig. 4). A good adaptation strategy is an amalgamation of exploring the existing climate risk management, identification of the key drivers of impact, assessing the effectiveness, and then developing climate resilience. As mentioned in the figure, framing of adaptation policy requires focusing upon three major areas, that is, increasing awareness among individuals, reducing vulnerability, and increasing the adaptive capacity (Schipper, 2007). The major focus areas are low emission through several options like climate resilient production, products, and services for climate management including efficient use of resources through enhanced productivity and also biodiversity conservation, etc. Climate change is not a local problem, but a global one, so any action taken for better adaptation must emphasize global cooperation. Integration of local organizations and local people serves as collateral of effective adaptation hence demanding localized solutions too (Agrawal et al., 2008; Naess, 2013). Proper identification of the problem is the pre-requisite for developing an effective plan, but challenges like low rates of adoption and diversity of the people involved emphasize that 'one policy for all' is difficult.

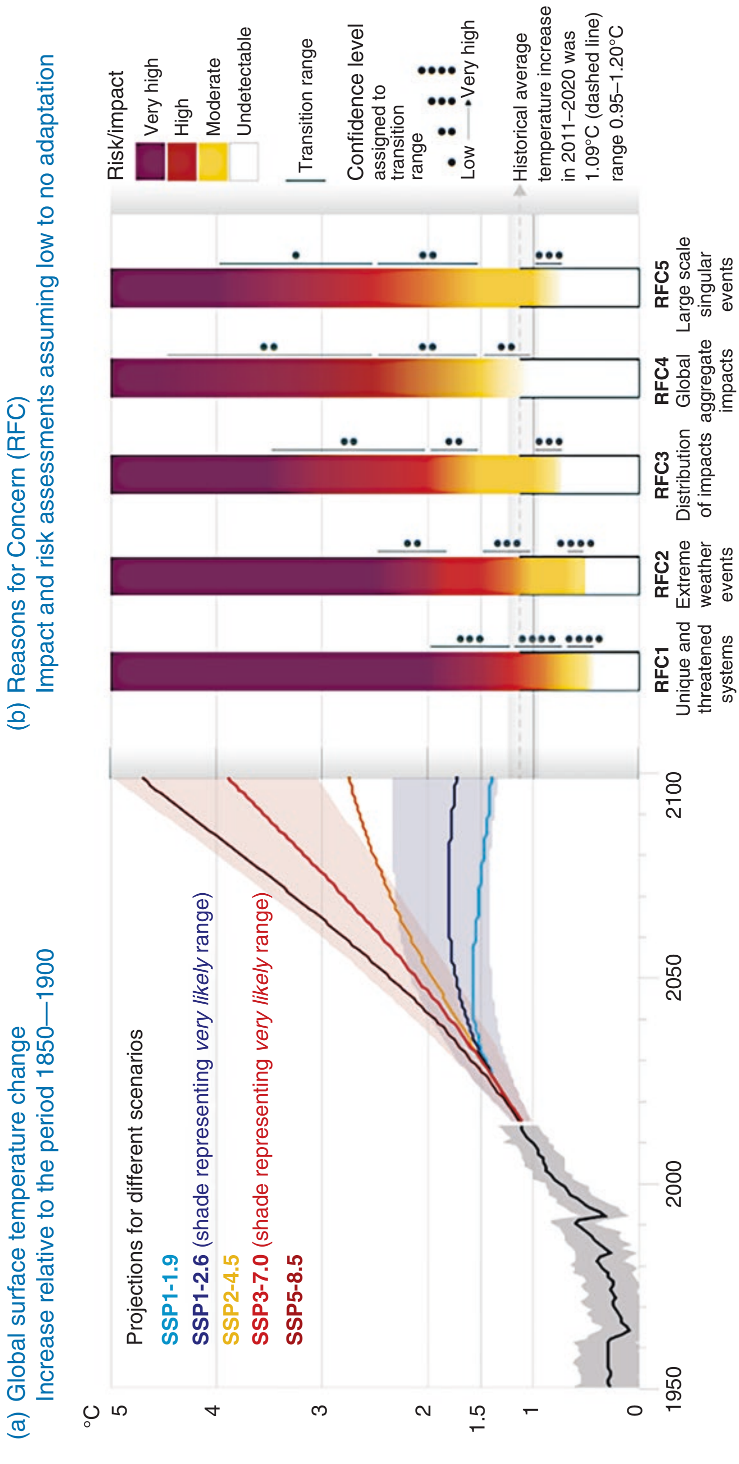

Fig. 2 Importance of adaptation (**a**) Global surface temperature change increase in comparison to 1850–1900. (**b**) Reasons for concern impact and risk assessments assuming low to no adaptation. (Source: IPCC 2022a)

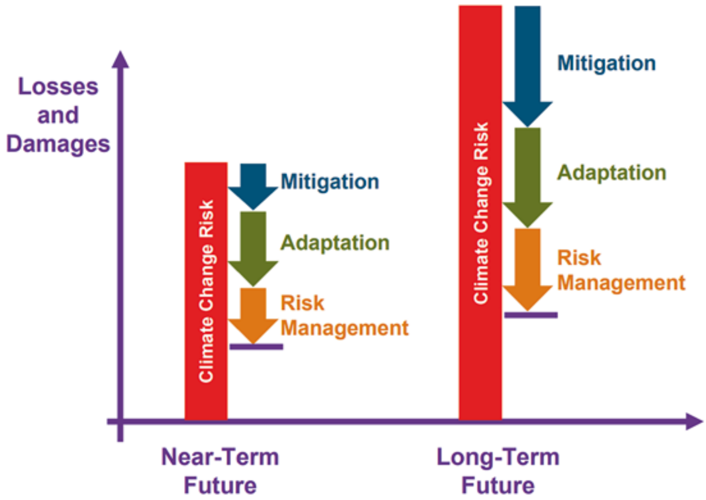

Fig. 3 Relationship between adaptation, mitigation, and risk management system in different scenarios. (Source: NASA- Applied Remote Sensing Training Program)

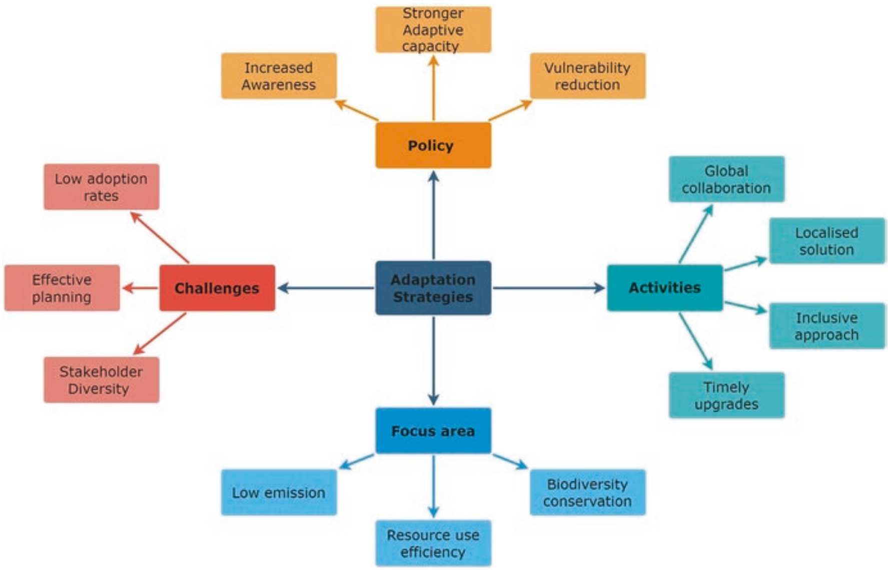

Fig. 4 Summarization of key elements of adaptation strategies

3.1 Mitigation Strategies

Mitigation strategies can be broadly divided into three major classes: conventional methods, negative technologies, and radiative forcing geoengineering technologies (Fawzy et al., 2020). The conventional methods involve the use of carbon emission–reducing technologies. This includes the use of renewable energy such as solar energy, wind energy, hydroelectric power, ocean energy, geothermal energy, and biofuels. The other option is increasing energy efficiency through improving combustion in thermal power plants, waste heat recovery, better working efficiency, etc. And also, the use of environmentally friendly fuels like bio-ethanol, hydrogen gas, natural gas, and the use of nuclear power. The negative technologies, on the other hand, include decarbonization technologies that reduce carbon and sequester it too. Two of the most important technologies are bioenergy carbon capture and storage (BECCS) and afforestation and reforestation (IPCC, 2018). Others include direct atmospheric carbon capture and storage, wetland construction and restoration, biochar, enhanced weathering, ocean fertilization and increased alkalinity, soil carbon sequestration, and mineral carbonization (Fawzy et al., 2020). Efforts are being made to modify the radiative energy budget at the surface of the atmosphere, in part to combat global warming.

3.2 Adaptation Strategies

3.2.1 Agriculture

The impacts of climate change—erratic and premature rainfall, rising temperatures, droughts, floods and changes in daily temperature rhythms–directly impact agriculture by jeopardizing food security. The extreme events and alterations in optimum temperature & rainfall requirements cause changes in crop yield, phenology, product quality, and nutritional value. Adaptation in agriculture has two dimensions, first the policy framing by the institutional end, and second the adoption of the practices by the stakeholders. The development of a suitable adaptation strategy is based on the avoidance of the damage caused by these weather parameter alterations. The suggested strategies can be divided into various sub-sections that focus on different aspects of agriculture (Smith & Skinner, 2002; Stehr & Storch, 2005). Studies have suggested the development of biotechnologically and genetically modified resistant varieties. It will enhance resistance to drought, flooding as well as heat stress and other relevant climatic conditions. For preparedness, easy accessibility and availability of early warning systems provide short-term and long-term weather predictions and seasonal forecasts. The rise in temperature not only requires resistant varieties but also suitable crop management practices. It is suggested that moisture-conserving tillage methods, water management innovations, stubble mulching, and the following should be brought into practice (Rosenberg, 1992; Smith & Skinner, 2002). The other practices like providing irrigation at critical stages, a combination of high-yielding varieties with critical irrigation, and strategic nutrient management are also suggested (Kadiyala et al., 2021; Shanabhoga et al., 2020). Farmers have adopted shifting cropping patterns, mixed cropping, agroforestry, and diversified livestock holdings as their strategies. Apart from the use of the conventional methods, other options like rewarding early adopters, assessing of risk involved, and informing about mitigation targets, can also be considered (Howden et al., 2007). Encouragement of crop insurance, diversification of household income, income stabilization program, change of cropping scheme, diversification of crops, and variety are a few other adaptation strategies. Raising farmers' awareness of climate change and adaptation is also a necessary and important strategy. Because the degree of adoption is influenced by the level of awareness.

3.2.2 Marines Systems

More than 70% of the Earth's surface is covered by oceanic systems, which have the power to influence climate and weather patterns from the region to the global scale. The oceans are important for maintaining the temperature balance on Earth. Marine heatwaves, ocean acidification, sea level rise, and frequent occurrences of severe tropical cyclones are all manifestations of climate change. The following factors, which can be interpreted in the following aspects, significantly contribute to damage to marine system flora, fauna, biodiversity, and ecology at different levels.

A. Ocean Heat Waves—Due to increased concentrations of greenhouse gasses, higher temperatures were trapped in the atmosphere and terrestrial temperatures also increased. In the process of temperature equilibration, excess heat is absorbed by the oceans due to the high-temperature gradient between the ocean and the land, resulting in ocean heat waves (Patočka, 2020). Ocean heat waves play a major role in causing significant local-scale effects due to high humidity concentration, along with temperature extremes over oceanic regions. It puts a strain on tropical and subtropical marine ecosystems, their functionality, localized biodiversity systems, island economies, and shipping sectors. Globally, an increase in more than 50% in days of MHW has been observed in the last century (Sen Gupta et al., 2020). Moreover, in the future, MHW days will occur more frequently, according to futuristic scenarios. Marine protected areas are treated as an adaptation policy by different governments for protecting and growing marine ecosystems away from human activities, but not very appropriate. In order to limit the occurrence of MHW, it is necessary to treat the entire planet as a unified system and try to take certain methods for reducing temperature as a holistic phenomenon. There is a need for more research in the field of adaptation and mitigation-based MHW.

3.2.3 Ocean Acidification

There is no denying the crucial role of the ocean in the carbon cycle. They are responsible for 30% of the environment's CO_2 absorption (Sabine et al., 2004). Due to climate change, the CO_2 input in oceans has also significantly increased and also responsible for changing the chemistry of ocean water (Billé et al., 2013). Some part of this CO_2 is dissolved in carbonate, but another part of CO_2 is replicated in the form of acidification in the form of carbonic acid. Adapt the changes in ocean chemistry and mitigate them. CO_2 reduction is useful as an important tool, but it can't be possible to reduce CO_2 with immediate effect. Therefore, there is a need to develop and implement such measures, which can provide enough time that the efforts currently being made by global organizations such as IPCC to reduce CO_2 concentration can be successful.

Sea Level Rise—Sea level rise is a big threat to coastal and island regions of the world (Miller et al., 2018). There is a possibility in RCP2.6 of a 0.3 to 0.6-meter hike in sea level at the end of the century. Human settlement, tourism sector, and biodiversity sector which are affiliated with sea level are under pressure. If the adaptation process is not undertaken, then the losses from sea level rise are much higher than taking action for adaptation. IPCC is the body that suggests various strategic frameworks for adapting the sea level rise in the current and futuristic conditions.

All of these discussions highlight the main problems of the marine system. All these problems are prominently correlated with global temperature rise. But this global phenomenon can't be mitigated in a day so there is a need for more time, which can be possible with the development of some measures that are helpful to buy some time for the current system.

3.2.4 Urban Area

The urban area inhabits a population that is diverse, that is, high standard of living as well as a low standard of living, and is a major contributor to global warming. There are pieces of evidence of flooding in cities due to overpopulation and defects in city planning, for example, cities like Mumbai and Kolkata flood during rainfall. To re-plan the city structure is technically difficult, but adaptation and mitigation can be used to reduce the impacts. Thus, for planning in urban areas, the spread of the risk and insulating the people through infrastructure development, awareness, and preparedness come to light. In the short run, reducing water use, water harvesting, insurance, early warnings, and drain management are some of the adjustments. While in the long run, investment in climate resilience and the inclusion of resistant infrastructure to strengthen flood, storm, and coastal defences (Nicholas, 2007). Apart from that, the use of street plantations, city parks, green roofs, and urban plantations is a great way to reduce the environmental impact of rapidly increasing vehicle emissions, as cities account for a large share of CO_2. Community led projects, transformative changes in socio-institutional structures, participatory approach, leadership, law enforcement, resource mobilization, micro-finance, mobilization of NGOs to provide support (Gaffin et al., 2012; Hurlimann & March, 2012; Pelling, 2011).

3.2.5 Tourism

Climate and tourism are directly related entities, that is, highly climate-sensitive sectors. Tourists travel to destinations based on the climate, that is there is nature-based tourism, winter tourism, health tourism, and sports tourism. For example, during summer areas with snow and cold temperature are preferred, and for the experience of the sun, the tropics are preferred. The most important tourism that is based on climate reports is snow tourism specifically ski tourism. To measure the climate factors that have the greatest impact on the quality of the tourism experience, include the Tourism Climate Index, Beach Comfort Index, Physiologically Equivalent Temperature Index, and Modified Tourism Climate Index (Fang et al., 2018). For effective adaptation strategies, it is important to assess causality and the interdependence of economies. Countries where tourism plays a dominant role in their economies are more vulnerable to the adverse impacts of climate change (Scott et al., 2019). Using weather forecasts, developing resilient infrastructure and, most importantly, raising personal awareness are part of the strategy. Events like the 2013 floods in Uttarakhand and the 2018 floods in Kerala have devastated tourist attraction points and claimed lives and livelihoods. It is worth noting that there is considerable potential in extensive research on the impact of climate change on tourism, especially in India.

3.2.6 Other Avenues

To comprehend the adaptation strategies is a never-ending task. As this is a dynamic domain, where the strategies change, upgrade, or get replaced or obsolete. It depends upon the location, population, timeframe, and vulnerability. Still apart from planning for agriculture, marine, tourism, there are domains like awareness and migration that are also playing pivotal roles in adaptation. Another dimension related to human movement is migration. As migration is an option to adapt against the negative impacts of climate change, a new term "Climate migrant" has emerged which refers to people migrating from their homes due to climate change impacts. Labors from flood-affected and drought-affected regions migrate from their natives in search of livelihood opportunities and income generation. It has been observed that in India the weather extremes have increased rural-urban migration majorly among agricultural labors, while a reduction is evident in rural-rural and international migration (Sedova & Kalkuhl, 2020). The reason is that climate, agricultural yields and migration are interlinked and there is a negative relation between agricultural yields and out-migration of agricultural laborers in India (Viswanathan, 2015). The strategies adopted at farm level are driven by local factors such as climate impacts, socio-economic, and agro-climatic factors. Thus, the knowledge and strategies are subject to regional variation. The lack of knowledge about the real cause of climate change and how to develop adaptation strategies is a major constraint in adoption. Knowledge, perception, and own experience of individuals and society are pivotal in determining the course of mitigation and adaptation actions. The awareness will encourage the farmers to adopt various adaptation strategies. This will ensure the income stability of the affected community.

4 Way Forward and Challenges

Adaptation constraints limit the variety and effectiveness of options for actors to secure existing goals or to alter natural systems in ways that preserve productivity and function (IPCC AR5). The constraints faced are categorized into different classes. Physical constraints refer to the issues related to soil, migration of people, infrastructure, etc. While a biological constraint, as it says, refers to the lower adaptive capacity of humans due to biological reasons. The macroeconomic issues and low-income lead to economic constraints. The social and cultural constraints are caused due to the level of awareness among individuals, perception as well as gender. Successful implementation of policies, mobilization of resources and reduction in imbalances remove the government and institutional constraints. Despite these constraints, adaptation has increased over the years, and the strategies have been made sounder and more effective. But it is not merely the constraints, there is also evidence of the existence of an adaptation gap (IPCC, 2022a). Which is the difference between actually implemented adaptation and a goal that was predetermined by the society. This gap is found in the form of unequal distribution of adaptation across regions and majorly among low-income groups. Another challenge that exists is maladaptation. It refers to activities that may increase the risk of climate change adversities, reduced welfare, higher vulnerability, etc. This has a more adverse impact on the vulnerable sections of society. It can be sidestepped by multi-sectoral, enduring, and inclusive planning. When it comes to mitigation, the biggest challenge is that the low-emission goals should not hamper the developmental progress of developing nations (Bowen et al., 2014). The provision of mitigation requires finance to switch to cleaner energy sources. The developing nations, especially those that are at lower levels of the economic scale, need mitigation finance as an incentive (Perkins, 2008). Mitigation and adaptation both can be integrated for climate change resilience. Here, mitigation helps to respond at global levels while adaptation is useful at local levels.

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Precision Farming to Achieve Sustainable and Climate Smart Agriculture

Rizatus Shofiyati, Muhammad Iqbal Habibie, Destika Cahyana, and Zuziana Susanti

1 Introduction

Climate change is one of the most pressing issues of our time, and its impacts are being felt in many areas of our lives, especially agriculture. In countries like Indonesia, where agriculture plays a significant role in the economy, the impacts of climate change are particularly pronounced. Prolonged droughts, severe flooding, or a start of the rainy season that differ from the norm can significantly impact cropping planning and agricultural production (Fig. 1).

FAO (2021) reported that climate-smart agriculture (CSA) offers promising solutions for both adaptation and mitigation of the impacts of climate change. By implementing CSA models and practices that utilize and develop current technologies, sustainable land management practices can be enhanced. In particular, the utilization of space-based data integrated with field-based measurements, such as remote sensing satellite data integrated with climate data, can increase the speed and accuracy of land management practices, and promote sustainability.

To support both policy makers and farmers, the Ministry of Agriculture has crafted essential tools like the Standing Crop Information System (SISCrop) and Crop Calendar Information System (KATAM). These tools aid in the precise calculation of seed, fertilizer, pesticide, water, and agricultural tool requirements, fostering improved efficiency and effectiveness in land management practices (Apriyana

R. Shofiyati (✉) · M. I. Habibie
Research Center for Geoinformatics, National Research and Innovation Agency, Jakarta, Indonesia
e-mail: rizatus.shofiyati@brin.go.id

D. Cahyana · Z. Susanti
Research Center for Food Crops, National Research and Innovation Agency, Jakarta, Indonesia

P. Kumar, Aishwarya (eds.), *Technological Approaches for Climate Smart Agriculture*, https://doi.org/10.1007/978-3-031-52708-1_12

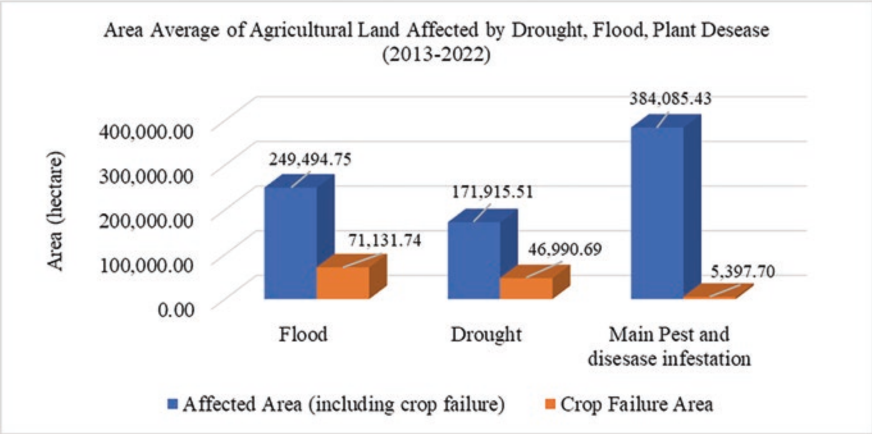

Fig. 1 Area average of agricultural land affected by drought, flood, plant disease (2013–2022) (Source: Directorate General of Food Crops, 2023)

et al., 2021; Sofyan, 2022). These tools demonstrate the potential for technology to help combat the impacts of climate change on agriculture (Yulianti et al., 2016).

This chapter explores the implementation of CSA models and practices in Indonesia, with a particular focus on the use of technology to enhance sustainable land management practices. By leveraging the power of technology and collaborating with farmers and policy makers, we can ensure the continued productivity of agricultural land in the face of the challenges posed by climate change.

2 Climate-Smart Agriculture

Climate-smart agriculture (CSA) is an approach to farming that aims to address the challenges of climate change while increasing agricultural productivity and reducing greenhouse gas emissions to enhance achievement of national food security and development goals (FAO, 2010). CSA emphasizes the need to sustainably manage land, water, and other natural resources while ensuring food security, improving livelihoods, and building resilience to climate change (Fig. 2).

Sawhney and Perkins (2015) mentioned that CSA practices have three main goals:

- Adaptation to climate change involves increasing the resilience of agricultural systems to extreme weather events, aiding farmers in mitigating the impacts of climate change, such as droughts, floods, and heatwaves. This encompasses the enhancement of soil health, diversification of crops, efficient water management, and effective control of pests and diseases.
- Mitigation of climate change by reducing greenhouse gas emissions from agricultural activities, such as livestock production, crop cultivation, and energy use.

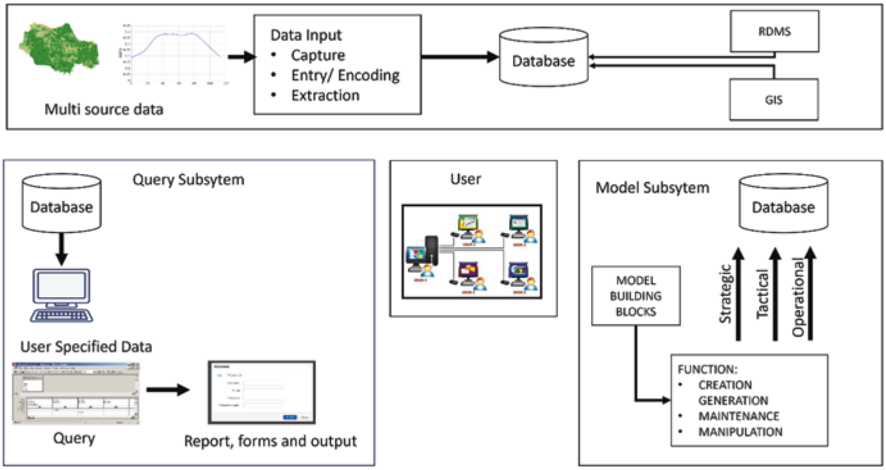

Fig. 2 CSA information system management (Runtunuwu et al., 2012)

This involves adopting low-emission technologies, reducing waste and loss, and promoting sustainable land use practices.

- Increased productivity and food security by increasing agricultural productivity and food security while maintaining the health of natural resources. This involves improving crop yields, diversifying production, and enhancing market access for small-scale farmers.

The significance of CSA in sustainable agriculture cannot be overstated. Agriculture is one of the sectors most affected by climate change, with negative impacts on crop yields, livestock productivity, and food security. By promoting sustainable and climate-resilient agricultural practices, CSA can help mitigate these impacts and ensure the long-term sustainability of agricultural production (Zhai & Zhuang, 2009).

Furthermore, CSA practices can help to reduce greenhouse gas emissions from agriculture, which is reported by World Bank (2021) to account for around 19–29% of global emissions. By adopting low-emission technologies and reducing waste and loss, farmers can contribute to global efforts to mitigate climate change.

CSA is a critical approach to sustainable agriculture that emphasizes the need to manage natural resources effectively, increase productivity, and build resilience to climate change. By promoting CSA practices, farmers can improve their livelihoods, reduce the impact of climate change on their production, and contribute to global efforts to mitigate climate change.

3 Technologies in CSA

Technologies play a critical role in climate-smart agriculture (CSA) by enabling farmers to make informed decisions about land management and crop production. In recent years, a range of technologies has been developed to support CSA practices, including space-based data integration, remote sensing, and other tools.

Space-based data integration refers to the use of satellite and other space-based technologies to collect data on land use, crop yields, weather patterns, and other variables. This data can then be analyzed and integrated with other sources of information to support decision-making by farmers, policy makers, and other stakeholders. Remote sensing is another important technology used in CSA. Remote sensing refers to the use of sensors and other instruments to collect data on land cover, crop growth, and other variables from a distance. This data can be used to monitor changes in land use, detect changes in crop health, and identify areas of land that may be vulnerable to climate change impacts.

Other tools used in CSA include mobile applications, decision support systems, and precision agriculture technologies. Mobile applications can provide farmers with real-time information on weather patterns, market prices, and other variables, enabling them to make more informed decisions about crop management. Decision support systems use data analytics and other tools to help farmers make decisions about crop rotation, irrigation, and other practices. Precision agriculture technologies, such as Global Positioning System (GPS)-guided tractors and drones, can help farmers to apply inputs, such as fertilizers and pesticides, more precisely, reducing waste, and increasing efficiency.

These technologies are used in a variety of ways in land management and agriculture. For example, space-based data integration and remote sensing can be used to monitor crop growth and detect changes in soil moisture and other variables, enabling farmers to adjust their irrigation practices accordingly. Mobile applications can provide farmers with real-time information on market prices, enabling them to make more informed decisions about when to sell their crops. Decision support systems can help farmers to identify the optimal crop rotation and other practices to maximize yields while reducing the impact on the environment.

Technologies play a critical role in supporting CSA practices by enabling farmers to make more informed decisions about land management and crop production. Space-based data integration, remote sensing, and other tools can provide farmers with real-time information on weather patterns, market prices, and other variables, enabling them to adjust their practices to meet the challenges of climate change. By adopting these technologies, farmers can improve their productivity, reduce their impact on the environment, and contribute to global efforts to mitigate climate change.

Increasing fertilizer efficiency could be one of the crucial keys in minimizing the impact of rice cultivation on the environment. The excessive use of nitrogen fertilizer in majority central rice-producing areas in Indonesia is widely reported; on the other hand, some areas lack nitrogen fertilizer due to difficulty in fertilizer distribution. Indonesian Center for Rice Research recorded the significant yield increase due to nitrogen fertilizer application from averaged 3 t/ha without fertilizers to 7 t/ha; however, in the long term, overuse of N is not economically effective and may result in pollution. Nitrogen fertilizer should be applied based on the real condition at the field. Leaf chlorophyll content is positively correlated to nitrogen content and could be identified by the level of leaf greenness. Several tools have been developed to determine the efficient dosage and effective time to apply nitrogen fertilizer. International Rice Research Institute has developed standard Leaf Color Chart (LCC) as a tool to estimate nitrogen content based on leaf color. The use of LCC in rice fertilization has not been widely applied for Indonesian farmers. One of the reasons was the use of LCC subjectively based on the eyes of farmers and the result of reading could be influenced by the environment condition particularly the sunlight. Recognizing the importance of LCC, the Ministry of Agriculture and National Agency for Research and Innovation have been developing an application in smartphone used digital leaf color. We collected leaf color images of popular varieties grown from cameras with Charge-Coupled Device (CCD) image sensors to predict nitrogen content in rice. Under-development tool is crucial to allow farmers to determine the efficient dosage of fertilizer at the right time.

4 Benefits of CSA

Climate-smart agriculture (CSA) practices are gaining popularity worldwide due to their potential to increase agricultural productivity, reduce greenhouse gas emissions, and improve food security. In this chapter, we will analyze the benefits of CSA practices for farmers and society.

4.1 Increased Yields

CSA practices are designed to improve agricultural productivity and yield while minimizing the negative impacts of farming on the environment. By implementing practices such as intercropping, conservation agriculture, and precision farming, farmers can increase their yields while using fewer inputs, such as water and fertilizer. Some methods for increasing yields through CSA are crop management, soil conservation, water management, agroforestry, and livestock management. For example, precision farming techniques, which use data and technology to optimize crop growth, have been shown to increase yields by up to 20% in some cases.

4.2 Reduced Environmental Impact

One of the primary benefits of CSA practices is their potential to reduce the environmental impact of agriculture. By using practices such as conservation agriculture, farmers can reduce soil erosion, improve soil health, and minimize the use of pesticides and fertilizers. This, in turn, can lead to a reduction in greenhouse gas emissions, as well as improved water quality and biodiversity. To reduce agriculture's environmental impact, CSA promotes the use of sustainable land management practices that improve soil health, stop soil erosion, and maintain biodiversity. They include crop rotation, intercropping, conservation agriculture, and agroforestry. By promoting soil health and reducing erosion, these measures help to mitigate the negative environmental effects of agriculture on water quality, biodiversity, and climate.

Increasing the efficiency of rice production inputs such as fertilizers and pesticides by applying agrochemicals effectively wisely at the correct dosage and time is crucial to minimize the environmental issues particularly in irrigated areas in Indonesia.

5 Improved Resilience

Another benefit of CSA practices is their potential to improve the resilience of farmers to the impacts of climate change. By adopting practices such as crop diversification and intercropping, farmers can reduce their dependence on single crops, which can be vulnerable to weather-related events such as droughts or floods. This, in turn, can improve farmers' income stability and food security. Climate-resilient rice varieties are crucial to maintain or increase grain yield under biotic or abiotic stresses. The Ministry of Agriculture has released rice varieties more tolerance to drought, flood, or submergence and enhanced salinity tolerance with early maturing cycle to help farmers adapted with climate change.

CSA is a crucial farming technique that aims to promote sustainable agricultural approaches that can help farmers and rural communities adapt to the effects of climate change. CSA aims to build a more resilient and sustainable food system that can meet the needs of a growing global population while also protecting the natural resources on which agriculture relies by encouraging sustainable farming practices, supporting the development of cutting-edge technologies and financing methods, and enhancing the knowledge and skills of farmers and farming communities.

6 Enhanced Food Security

CSA practices have the potential to improve food security by increasing agricultural productivity, particularly in regions where food insecurity is prevalent. By adopting practices such as precision farming and intercropping, farmers can increase their yields and reduce the risk of crop failure due to weather-related events. This, in turn, can increase food availability and reduce food prices, improving access to food for people living in poverty.

CSA has the potential to improve food security in the face of global warming. It delves into a variety of climate-smart agricultural approaches, such as the adoption of drought-resistant crop types, conservation agriculture, and climate-smart animal management strategies. In addition, the essay underlines the importance of institutional support, financial mechanisms, and public-private partnerships in promoting the adoption of climate-smart agriculture methods (Wassmann et al., 2019). The system is designed to help decision-makers by providing comprehensive information for effective agricultural planning.

Using decision support technologies, which may be particularly effective in encouraging the adoption of CSA practices, the development of climate-resilient agriculture can be accelerated. They recommend policy makers to prioritize the development and use of decision-support technologies in agricultural planning, as well as to provide the required institutional support and capacity-building.

As a decision maker in agriculture management in Indonesia, it is important to consider the implementation of climate-smart agriculture (CSA) practices, such as the Standing Crop Information System (SISCrop) and Crop Calendar Information System (KATAM). These tools can help policy makers and farmers calculate the need for seeds, fertilizers, pesticides, water, and agricultural tools, so that land management becomes more effective and efficient. By implementing these practices, you can help improve the productivity and resilience of agriculture in your region. These benefits can contribute to a more sustainable agriculture management plan, leading to better outcomes for both the environment and the economy.

CSA practices offer numerous benefits for farmers and society, including increased yields, reduced environmental impact, improved resilience, and enhanced food security. By adopting these practices, farmers can improve their livelihoods, while contributing to global efforts to mitigate climate change and reduce poverty.

7 Challenges of CSA

While climate-smart agriculture (CSA) practices offer numerous benefits for sustainable agriculture management, there are also several challenges and obstacles that can make it difficult to implement these practices. Decision makers should be aware of these challenges and take steps to address them in order to maximize the potential benefits of CSA. One of the major challenges of implementing CSA practices is the cost. Some of the practices, such as precision farming and the use of advanced technology, can be expensive to adopt and require significant investments. This can be a major barrier for small farmers or those with limited financial resources.

Another challenge is the lack of knowledge and training in CSA practices. Farmers may not be familiar with the latest methods and technologies and may need additional support and training in order to adopt these practices effectively. Additionally, there may be a lack of access to information and resources on CSA practices, particularly in rural areas.

The lack of access to technology and infrastructure is another obstacle to implementing CSA practices. In some regions, farmers may not have access to the necessary tools and equipment, such as precision farming equipment, to implement these practices effectively. Similarly, the lack of reliable internet or mobile connectivity can hinder the integration of space-based data and other technology into agriculture management.

Finally, there may be institutional barriers to implementing CSA practices, such as policy or regulatory obstacles. Decision makers should work to address these barriers and create an enabling environment that encourages the adoption of CSA practices. Overall, decision makers should be aware of these challenges and take steps to address them to promote the adoption of CSA practices. By providing support for training and education, reducing the costs of adoption, and improving access to technology and infrastructure, decision makers can help farmers and other stakeholders overcome these obstacles and realize the benefits of CSA practices.

8 Case Studies of Successful CSA Implementation in Indonesia

Indonesia is a country that is particularly vulnerable to the impacts of climate change. Prolonged droughts, flooding, and changes in rainfall patterns have had a significant impact on the agricultural sector in the country. In response to these challenges, the Indonesian government has developed and implemented several climate-smart agriculture (CSA) practices aimed at increasing the resilience of farmers and reducing the impact of climate change on agricultural production.

Promoting climate-smart sustainable agriculture is critical to increasing Indonesia's rice output, soil health, and food security. CSA supporting government policies and regulations are a key step toward reaching this aim. However, ongoing investment in institutional support, capacity building, and research is required to guarantee that CSSA practices are implemented and scaled up effectively in Indonesia (Simarmata et al., 2020).

In recent years, Indonesia has made significant strides in implementing climate-smart agriculture (CSA) practices, with a particular focus on improving land management, enhancing food security, and promoting sustainable agriculture. Two pivotal tools utilized in the implementation of Climate-Smart Agriculture (CSA) practices in Indonesia are the Standing Crop Information System (SISCrop) and the Crop Calendar Information System (KATAM). These systems have been developed by the Ministry of Agriculture and provide real-time data on crop growth, rainfall condition, farming input needs, and other variables to farmers and policy makers. The system uses remote sensing technologies and other tools to collect data on crop growth, which is then analyzed and integrated with other sources of information to provide farmers with detailed information on rice growth stages, productivity, and plant indexes. By adopting these practices, farmers in Indonesia can improve their resilience to the impacts of climate change, reduce their impact on the environment, and contribute to global efforts to mitigate climate change.

8.1 Satellite-Based Agriculture Monitoring

Remote sensing technology and sensors have rapidly developed with a wide range of data specifications. They can detect and monitor areas from a distance without touching the observed objects, making it useful for various purposes. It can cover vast areas and difficult-to-reach locations, with the ability to record periodically historical and real-time data. These technologies can fill the gap in inadequate technology to support agriculture, especially in precision farming. The Ministry of Agriculture has utilized satellite data and sensors to assist in land management for agriculture. Several applications also leverage satellite technology for assessing land suitability (Habibie et al., 2019).

8.1.1 Crop Monitoring

The Standing Crop Information System (SISCrop) is a web-based platform created by the Indonesian Ministry of Agriculture that utilizes satellite-based image information to provide farmers with real-time data on crop growth, planting patterns, and productivity. Developed since 1997/98, the system analyzes plant growth stages using optical or radar sensors, allowing for more detailed spatial resolution. SISCrop enables farmers to make informed decisions about crop selection, planting times, and inputs such as water and fertilizer. The Ministry first implemented the system in 2014, and it has since been continually improved with newer and more advanced satellite images. Some applications of satellite data and sensor that have been implemented are explained in the following paragraph.

8.1.2 Drought and Flood Identification

Satellite imagery plays a vital role in analyzing flood and drought patterns, which is also beneficial for agricultural insurance programs. With satellite images available in various specifications, they can be customized according to specific needs, including climate analysis, where high temporal resolution is essential. Daily satellite images can help identify flood-affected areas, and by analyzing flood frequency temporally, endemic flood regions can be identified, providing valuable information for disaster management planning. The Indonesian Ministry of Agriculture has implemented an agricultural insurance program called the Agricultural Insurance Program (API), which aims to provide financial protection to farmers against crop losses caused by natural disasters such as floods and droughts. Combining the use of satellite imagery with the API program, the Indonesian government has taken proactive steps to address the challenges posed by floods and droughts in the agricultural sector and help insurance companies and the government in implementing the API program. Research is being conducted on micro-level drought classifiers (Habibie et al., 2020).

8.1.3 Identification of Swampland Potential as a Food Supplier

The information shows that swamp land has the potential to be a food supplier, replacing rice production in areas experiencing drought. This can be done by considering when it will flood again and adjusting the crop variety accordingly. For example, local flood-tolerant varieties are typically planted in lowland swamps. Identification of potential land expansion using Landsat 7 images has been carried out in the Alabio area of South Kalimantan. Additionally, tidal swamps can also be used for agriculture by considering the salinity of the land. During the dry season, the tidal water is usually salty, and farmers typically use a similar system to "gogoranca" to plant crops.

8.1.4 Irrigation Supply Management

To utilize water efficiently and prevent unnecessary waste, regular water management is necessary to ensure that water is allocated appropriately to the crops planted in the field. Remote sensing technology can be used to detect shifts in crop types over a larger area, allowing for production variations to be observed on a region-by-region basis. Identification of crop patterns year over year, based on the growth phases of rice using multi-year Sentinel-1 satellite imagery, has been employed to monitor changes in crop patterns and compliance with the regulations governing irrigation water allocation in the Irrigation Area.

9 Agricultural Land Information System

9.1 Standing Crop Information System (SISCrop)

The Standing Crop Information System can be accessed through a website or an android application. Figure 3 shows the information available in the Standing Crop Information System, which includes rice growth stages, productivity, and plant indexes. In addition, the system also presents estimated harvest areas, rice production, and fertilizer requirements. This information system can still be developed according to the users' needs.

The implementation of these CSA practices has had a significant impact on policy makers and farmers in Indonesia. The SISCrop system has provided policy makers with valuable data on crop growth, which has helped them to develop policies aimed at increasing the resilience of farmers and reducing the impact of climate change on agricultural production. Farmers have also benefited from the system, as

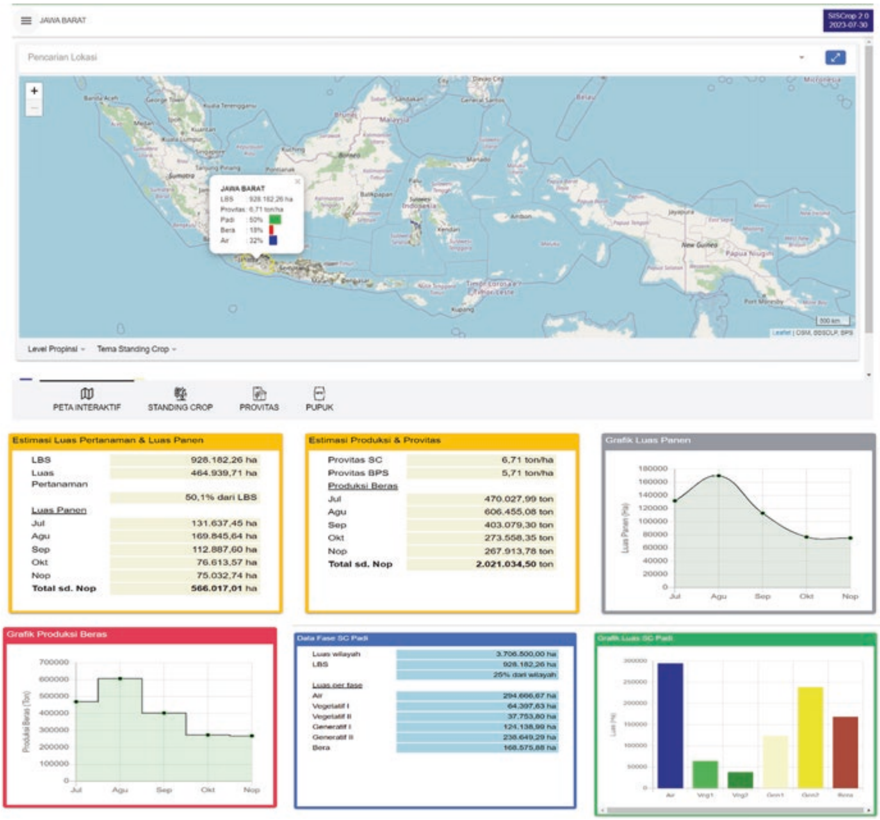

Fig. 3 Indonesia's Standing Crop Information Platform in http://scs1.bsip.pertanian.go.id/home

it has provided them with real-time information on crop growth and other variables, enabling them to adjust their practices to meet the challenges of climate change. Indonesia's agricultural information which is illuminated through the comprehensive Standing Crop Information Platform (Fig. 3), accessible at http://scs1.bsip.pertanian.go.id/home

9.1.1 Crop Calendar Information System (KATAM)

The Crop Calendar Information System (KATAM) is another web-based platform developed by the Indonesian Ministry of Agriculture, which provides farmers with information on the best planting times for different crops in different regions based on weather patterns and other variables. The system is designed to help farmers make informed decisions about crop management and reduce the risk of crop failure due to weather-related events on crop yields, pest infestations, and other variables.

Integrated Planting Calendar (KATAM) is an application program that provides information on the optimal planting time, areas vulnerable to droughts, floods, and pest attacks, as well as recommendations for varieties, seeds, fertilizers, and agricultural mechanization that need to be prepared before the next planting season. This information system was designed in the form of an atlas in 2007 and was later developed into a web-based information system in 2011. In the subsequent process, the dynamic planting calendar was enhanced to become an integrated planting calendar.

In addition to the two information systems KATAM and SISCrop, there are several other applications produced by the Agricultural Research and Development Agency that can be utilized to support precision agriculture, including the ones discussed in the following sections.

9.1.2 Agricultural Land Resource Information System (SISULTAN)

This system is developed by the Center for Agricultural Land Resources Research and Development (BBSDLP) of the Agricultural Research and Development Agency. This WebGIS-based information system presents information in the form of maps of agricultural land resources created/mapped by BBSDLP. The system provides data and information covering a) 1:1,000,000 scale maps, b) reconnaissance scale soil maps (1:250,000), c) detailed soil maps (1:50,000), and others (Sulaeman et al., 2015).

9.1.3 Land Suitability Assessment System (SPKL)

This application was developed to assist users in assessing or evaluating the suitability of land for various agricultural commodities. In addition to its function in land assessment, this application can also help in the preparation of agro-ecological zone (ZAE) maps. This user-friendly and flexible application is open and flexible in determining criteria for plant growth requirements as well as in the data input process (Bachri et al., 2015).

9.1.4 Phosphorus and Potassium Decision Support System (PKDSS)

This DSS was created by the Soil Research Institute. PKDSS is an application that can help calculate fertilizer requirements by considering the amount of nutrients needed by the plants and the content and dynamics of nutrients in the soil. PKDSS is useful in determining fertilizer doses for irrigated rice, upland rice, corn, and soybeans (Sulaeman, 2010; Sulaeman & Nursyamsi, 2018).

9.1.5 Land Resource Data Management Information System (SIMADAS)

This system can be used to assist in managing land resource data, including site data, horizon data, and laboratory analysis data. The program can be utilized by researchers at the Agricultural Research and Development Agency or other users who require similar data management (Agricultural Research and Development Agency 2014; Sulaeman et al., 2015).

Overall, these case studies demonstrate the significant benefits of implementing CSA practices in Indonesia, including increased crop yields, improved farmer income, and enhanced land management practices. By promoting the adoption of these practices and providing support for training and education, decision makers can help farmers and other stakeholders realize the full potential of CSA practices for sustainable agriculture management.

9.1.6 Precision Farming

Precision farming involves using technology to manage agriculture practices, utilizing sensors, drones, and other tools to monitor crop growth and identify areas for improvement. In Indonesia, precision farming practices have been successfully implemented in several regions. These practices have helped farmers optimize their use of inputs such as fertilizer and water, resulting in higher crop yields and improved profitability. The Ministry of Agriculture has also developed recommendations for balanced fertilization based on the soil nutrient content. The condition is detected using a tool called a Smart Soil Sensing Kit (S3K), which uses light wave sensors to measure soil nutrients. The S3K system can measure various soil properties, including pH, texture, cation exchange capacity (CEC), base saturation (BS), and several soil nutrient elements, such as C, N, P, K, Ca, Na, and Mg. The S3K 1.0 utilizes a near infrared (NIR) sensor with a wavelength range of 1300–2600 nm. By utilizing these recommendations and tools, farmers can further optimize their use of inputs, leading to increased efficiency and better economic outcomes.

9.1.7 Food Estate

Indonesia is one of the largest rice producing country in the world. Central Bureau of Statistics of Indonesia (2022) recorded 54.64 million ton grain yield produced in 2021, with 10.65 million ha harvested area. National rice production slightly increased by 0.08%; however, it is decreased by 8.32% compared to production in 2018 which reached up to 59.2 million ton. Central Bureau of Statistics reported that decreasing production due to the extreme climate resulted in flood and drought as well as greatly lost yield due to pest and diseases in some main rice production areas. Historically, in 1985–2005, approximately 55–60% of national rice production in Indonesia was recorded in Java Island (Irawan et al., 2013), of which 95% was harvested from irrigated area and the remaining 5% from rainfed lowland and dry land. Recently, the three provinces with the highest rice production in Indonesia are still dominated by three provinces in Java: East Java, West Java, and Central Java as shown in Fig. 4. Central Bureau Statistics (2022) recorded on 2020, East Java as the highest rice producer with 9.9 million ton unhusked rice, followed by East Java and West Java Province with 9.6 and 9.0 million ton, respectively.

Java has an important role in rice supply; however, Java is also renowned as the most densely populated island where 60% of the population lives in Indonesia. Due to its massive population, some limiting factors such as land conversion from agricultural sector to other usages such as housing and industrial sectors became serious problem. Nasoetion (1994) estimated about 30,000–50,000 ha of rice field has been converted per year. Recent data from 2012 to 2016 indicates that the conversion of rice fields was 96,500 hectares per year (Mulyani et al., 2022). In Java alone, over 63,000 ha of agricultural land has been converted every year. Therefore, the Indonesian government identifies avenues to boost national rice production by intensifying sub-optimal lands such as swampy areas outside Java. From early 2020 until 2022, the Indonesian government designates a food estate under swampy area at Blantisiam in Pulang Pisau regency in Central Kalimantan province to become a national rice barn. Establishing rice cultivation in swampy area in Central Kalimantan could be one of the solutions to maintain rice self-sufficiency and population

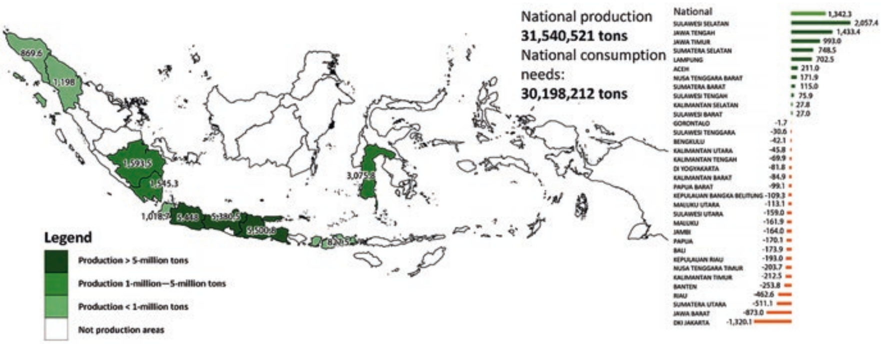

Fig. 4 National rice production (map) and rice balance sheet by provinces (graph) in Indonesia. (Badan Pangan Nasional, 2023)

problem; however, Fe toxicity could be the common problem that occurs in those area. Perfect levelling as the final result of land preparation without exposing Fe to soil surface is crucial to ensure good performance and yield of rice at swampy area. Moreover, levelling plays important role in facilitating easy seedling establishment under direct seeded method. Direct seeding method is suitable for rice production areas where farmers have large paddy field and lack of daily labor in agriculture. Farmers in Central Kalimantan generally have been shifting from transplanting method to direct seeding (DSR) due to the scarce of daily labor.

The food estate program is the government's response to the potential threat of a food crisis that was warned by Food and Agriculture Organization (FAO) at the beginning of pandemic of Covid 19. FAO released a report which stated that 55 countries were threatened with serious hunger problems within a few months due to the pandemic. FAO estimates that 135 million people will face acute hunger as a result of the crisis. The majority of them are in Africa, America Latin, the Caribbean, the Middle East, and Asia, especially in developing countries due to the difficulty in accessing adequate and nutritious food. These countries will find it difficult to achieve food security because they do not meet the criteria and public accessibility. Climate change is also adding to the burden of these countries. The Indonesian government responded to the warning with a food estate program to anticipate food problems occurring in Indonesia (Evi Kristhy & Harefa, 2022; Lasminingrat & Efriza, 2020).

Top-down models, such as the food estates program, have been implemented in previous eras. The Mega Rice Project (MRP), initiated during the presidency of Soeharto, was implemented in the southern regions of Kalimantan in 1996. the Merauke Integrated Rice Estate (MIRE) was established during the era of President Susilo Bambang Yudhoyono, and it subsequently transformed into the Merauke Special Economic Zone (KEK Merauke) during the initial period of President Joko Widodo. However, previous projects stalled because they could not meet the government's expectations. The project is considered slow to develop because the planning is immature so that the expected output within a certain period is not achieved (Lasminingrat & Efriza, 2020).

The food estate program concept is the development of food production centers in an integrated manner which includes the agricultural sub-sectors of food crops, horticulture, plantations, and livestock in agricultural areas. The basic concept of food estate is based on the principle of sector and sub-sector integration in a wide-scale food production value chain system in an agricultural area. Food estate development is designed in an integrated and consolidative manner starting from area arrangement, infrastructure development, utilization of production technology, digitization to the development of farmer corporations.

The food estate area is also designed by dividing it into several clusters or agro-clusters which are part of the food estate area. In each cluster, infrastructure will be built according to specific needs, such as water systems, agricultural tools and machinery, workshops, expansion of agricultural areas, post-harvest management and storage, as well as transportation within and outside the area.

In the initial stages, Indonesia built food estates in two locations, namely Kapuas Regency and Pulau Pisang Regency, in Central Kalimantan Province, which were then gradually implemented in other provinces such as Humbang Hasundutan Regency (North Sumatra), Wonosobo Regency (Central Java), Sumba Regency and Belu Regency (East Nusa Tenggara). Food estate is one of the 2020–2024 National Strategic Programs which is practically carried out by the Ministry of Agriculture (Kementan), Ministry of Public Works and Public Housing (PUPR), and Ministry of Defense (Kemhan).

The national food estate is divided into two planting focuses, namely rice covering an area of 165,000 ha which is carried out by the Ministry of Agriculture and cassava covering an area of 60,000 ha which is carried out by the Ministry of Defense in early 2021. Implemented in stages, the process commenced with the cultivation of rice on a 32,000 ha expanse, followed by efforts to enhance accessibility to the area and the repair of irrigation canals in October 2020. The entire initial process is targeted for completion in 2021 so that the full planting process can be carried out. The government is optimistic that rice productivity in the food estate area can reach 4–5 tons per hectare (Ministry of Public Works and Housing, 2020).

Conceptually, the production of food estate is intended as a food reserve that is used in emergency situations. In the community, food reserves are stored to face the threat of drought and natural disasters in various sectors, such as the family, farmers, mills, schools, restaurants, and Islamic boarding schools. Meanwhile, at the national level, food reserves are managed by the Logistics Agency (BULOG), which is spread to the district level.

The government uses the food estate concept to meet national food needs and security as well as to serve as a reserve for emergencies and export needs. In other words, food estates are expected to produce large and nutritious national food reserves to meet domestic needs when facing a crisis (Basundoro & Sulaeman, 2020).

9.1.8 Agroforestry

Agroforestry is a sustainable land management practice that involves growing trees or shrubs alongside traditional crops. This approach can improve soil health, reduce erosion, and increase biodiversity. In Indonesia, agroforestry practices have been successfully implemented in several regions. These practices have helped farmers diversify their income streams, reduce their reliance on monoculture crops, and improve their resilience to climate change.

10 Future of CSA

As the world continues to face the challenges of climate change, there is a growing recognition of the importance of implementing CSA practices to promote sustainable agriculture management. The future of CSA, including new technologies, policies, and initiatives, is being developed to advance the adoption of these practices. Indonesia offers insights into the future of CSA, including potential improvements in technology and policy, and the role of CSA in mitigating climate change and promoting sustainable agriculture. Several important steps taken by Indonesia in implementing climate-smart agriculture to deal with climate change can be explained in the following paragraphs.

10.1 Digital Technologies

Digital technologies are revolutionizing agriculture management and are expected to play an increasingly important role in the future of CSA. Advances in sensors, drones, and other tools are making it easier and more cost-effective to monitor crop growth, soil moisture, and other environmental factors. This, in turn, will help farmers make more informed decisions about crop management and input use, leading to improved yields, reduced environmental impact, and enhanced resilience.

10.2 Policy Support

Government policies and initiatives are crucial for promoting the adoption of CSA practices. In Indonesia, the Ministry of Agriculture has launched several initiatives to support the adoption of these practices, including the development of SISCrop and KATAM. Moving forward, decision makers must continue to prioritize policies that promote sustainable agriculture, including support for education and training programs, investment in research and development, and incentives for farmers to adopt sustainable practices.

10.3 International Collaboration

International collaboration and knowledge sharing are critical for advancing the adoption of CSA practices. Organizations such as the Food and Agriculture Organization (FAO) and the Global Alliance for Climate Smart Agriculture (GACSA) are working to promote the adoption of these practices in countries around the world. By collaborating with these organizations and other stakeholders, decision makers can leverage the expertise and resources needed to accelerate the adoption of CSA practices in Indonesia and beyond.

10.4 Resilience to Climate Change

As the impacts of climate change continue to intensify, the need for resilient agriculture practices becomes increasingly important. CSA practices, with their focus on adaptive and mitigative measures, can help build resilience in the face of changing weather patterns, droughts, and other climate-related challenges. By prioritizing these practices, decision makers can help ensure that Indonesia's agriculture sector is prepared for the challenges of the future.

Overall, the future of CSA is promising, with new technologies, policies, and initiatives being developed to promote sustainable agriculture management. By prioritizing these practices and providing the necessary support and resources, decision makers can help ensure that Indonesia's agriculture sector is sustainable, resilient, and prepared for the challenges of the future.

11 Conclusion

Climate-smart agriculture (CSA) offers solutions for both adaptation and mitigation of the impacts of climate change on agriculture. In Indonesia, the adoption of CSA practices has been supported by the development of digital technologies, policies, and initiatives, such as the Standing Crop Information System (SISCrop) and Crop Calendar Information System (KATAM), which have helped to improve land management and agricultural production. Despite the challenges and obstacles to implementing CSA practices, such as cost, knowledge gaps, and lack of access to technology, the benefits are clear. CSA practices offer increased yields, reduced environmental impact, improved resilience, and enhanced food security for farmers and society.

Looking to the future, the adoption of digital technologies, policy support, international collaboration, and a focus on resilience to climate change will be crucial for advancing the adoption of CSA practices and promoting sustainable agriculture management in Indonesia and beyond. It is up to decision makers to prioritize and invest in CSA practices to ensure that the agriculture sector in Indonesia is sustainable, resilient, and prepared for the challenges of the future. By doing so, we can build a more sustainable and secure future for our planet and its inhabitants.

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Geospatial Technology for Climate Change: Influence of ENSO and IOD on Soil Erosion

I Wayan Sandi Adnyana, Abd. Rahman As-syakur, R. Suyarto, I Nyoman Sunarta, I Wayan Nuarsa, I Wayan Diara, Moh. Saifulloh, and Wiyanti

1 Introduction

Indonesia is an archipelagic country located between two continents (Asia and Australia) and two oceans (Indian and Pacific Oceans). This condition causes Indonesia to be influenced by various regional and global climates (Apriyana et al., 2021; Lee et al., 2019; Putra et al., 2017; Tang et al., 2020). Regionally, Indonesia is influenced by two seasons, namely the east and west seasons (Kurniadi et al., 2021). Globally, Indonesia is also affected by natural phenomena such as El Niño–Southern Oscillation (ENSO) and the Indian Ocean Dipole (IOD) (As-syakur et al., 2014). The ENSO is a global climate phenomenon characterized by an anomaly in sea surface temperature and occurs in the Pacific Ocean, while the IOD occurs in the

I. W. S. Adnyana · I. W. Nuarsa
Center for Environmental Research (PPLH), Udayana University, Denpasar, Bali, Indonesia

A. R. As-syakur (✉) · M. Saifulloh
Spatial Data Infrastructure Development Center (PPIDS), Udayana University, Denpasar, Bali, Indonesia
e-mail: ar.assyakur@pplh.unud.ac.id

R. Suyarto
Center for Environmental Research (PPLH), Udayana University, Denpasar, Bali, Indonesia

Spatial Data Infrastructure Development Center (PPIDS), Udayana University, Denpasar, Bali, Indonesia

I. N. Sunarta
Geography of Tourism, Faculty of Tourism, Udayana University, Denpasar, Bali, Indonesia

I. W. Diara · Wiyanti
Spatial Data Infrastructure Development Center (PPIDS), Udayana University, Denpasar, Bali, Indonesia

Department of Soil Sciences and Environment, Faculty of Agriculture, Udayana University, Denpasar, Bali, Indonesia

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Indian Ocean (Bal et al., 2021; Devi & Sarangi, 2017). One of the water areas in Indonesia that are interesting to study, related to the influence of the two climates, is the Lombok Strait. The Lombok Strait is located between the islands of Bali and Lombok. The area is directly adjacent to the Pacific Ocean in the north and the Indian Ocean in the south (Bal et al., 2021; Setyohadi et al., 2021; Wijaya et al., 2020).

The ongoing El Niño phenomenon causes a decrease in cloud formation and rainfall in Indonesia, resulting in drought and a decrease in the amount of water in the soil (As-syakur et al., 2016). On the other hand, La Niña has the effect of increasing cloud formation and rainfall in Indonesia, resulting in flooding. Due to climate anomalies such as El Niño and La Niña that occur, this causes the change of seasons continues to be erratic. The extraordinary El Niño phenomenon in Indonesia occurred in 2015, due to which some areas in Indonesia experienced drought and forest fire (Jayarathne et al., 2018; Nugroho et al., 2021). On the other hand, the extraordinary La Niña event in Indonesia in 2016 caused a prolonged rainy season. As a result, hydro meteorological disasters such as floods, and landslides occurred (Barnard et al., 2017; Rodysill et al., 2019). Meanwhile, the positive IOD in 2019 caused drought events that caused forest fires in several areas in Indonesia (Susetyo et al., 2020).

Climatic changes, such as caused by ENSO and IOD, impact the occurrence of rainfall characteristic anomalies, which are believed to influence the increase and change in the erosion rate in the tropical area of Indonesia. Other scientific papers (Derakhshan-Babaei et al., 2020; Lal, 2001; Montgomery, 2007; Pandey et al., 2021) state that erosion breaks down and transports soil particles by geomorphological forces, such as water and wind. Naturally, erosion is said to not cause a problem if the erosion rate is lower or equal to the rate of soil formation, which is called normal erosion (geological erosion).

The Unda watershed area has the largest area in Bali Province, with an area of 91,585 ha, which is dominated by landforms of volcanic origin. The land use is 79.59%, including dry land; 68.41% of the total area includes regosol soil type, which is very susceptible to erosion, and 45.64% of the area includes undulating, hilly to mountainous (Karsun et al., 2015; Trigunasih et al., 2017). In the area of the Unda watershed, several illegal mining areas result from Mount Agung's eruption (Toban et al., 2016; Trigunasih et al., 2017). Currently, the function of the watershed is starting to decline because there are various problems in watershed management, such as changes in forest function, silting of river flows, landslides, erosion, and the presence of *C* excavation, which has an impact on changes towards critical land (Murtiyah et al., 2019; Toban et al., 2016).

Recent research has stated that climate change impacts the magnitude of erosion values, so quantifying erosion and its relationship to climate change can be used as a basis for soil and water conservation (Eekhout & de Vente, 2022). The impacts of climate change, such as changes in rainfall, vegetation cover, and land management, have implications for the variability of the rate of erosion (Chapman et al., 2021; Doulabian et al., 2021; Li & Fang, 2016). We quantified the rate of soil erosion using the Universal Soil Loss Equation (USLE) method. The USLE is a parametric model of erosion prediction method based on the relationship between the determinants of erosion and the amount of erosion (Wischmeier & Smith, 1978). Previous research used this method to compute the amount of erosion in watersheds, using remote sensing and geographic information system approach (Prasad & Tiwari, 2022; Saoud & Meddi, 2022). However, previous studies have only quantified the amount of erosion in one time without considering the dynamics of climate anomalies and changes in vegetation cover. At the same time, the area within the watershed has a changing nature due to the nature of natural influences.

Watersheds have specific characteristics closely related to the main elements such as rainfall, soil type, land use, and topography. Among these factors, humans can genetically engineer land use and slope and slope length. Changes in land use to forest areas (annual crops) and agricultural land (seasonal crops) affect the high erosion rate. The existence of climatic anomalies such as La Niña, El Niño, and the IOD increasingly triggers the rate of soil erosion. We quantify the soil erosion rate by integrating remote sensing and geographic information systems. The remote sensing data come from the Rainfall Estimates from Rain Gauge and Satellite Observations (CHIRPS) satellite during 2015, 2016, and 2019. Other data come from the Landsat 8 satellite on the Operational Land Imager (OLI) sensor to quantify the Normalized Difference Vegetation Index (NDVI)—supported by geospatial data of soil types, observations of field characteristics, and analysis of soil samples in the laboratory. The purpose of this study was to investigate the effect of La Niña, El Niño, and IOD phenomena on the magnitude of the erosion rate in the Unda watershed, Bali Province, Indonesia.

2 Method

2.1 Research Site

This research was conducted in the Unda watershed, Bali Province, Indonesia (Fig. 1a,b). Geographically, the research is located at the coordinates of latitude 8°17′15.03″S–8°34′29.80″S and longitude 115°24′5.15″E–115°26′8.02″E. Admini stratively, and the Unda watershed crosses three regencies namely Bangli Regency, Karangasem Regency and Klungkung Regency (Fig. 1b). Karangasem Regency and Klungkung Regency administratively have the largest area in the Unda watershed. The Unda watershed area in Rendang District is 38.20%, followed by Selat District (28.13%), while the area with the smallest area is Kubu District, with an area of 0.22% (BPDASHL UndaAnyar, 2018). The upstream area of the Unda watershed is a disaster-prone area for volcanic eruptions because there is an active volcano namely Mount Agung. Mount Agung experienced a mighty eruption in 1963, followed by 2017, which hit the agricultural sector in the watershed and tourism sectors. Volcanic landforms dominate the Unda watershed, followed by denudational landforms, which are spatially located in the middle of the watershed (Ardianto

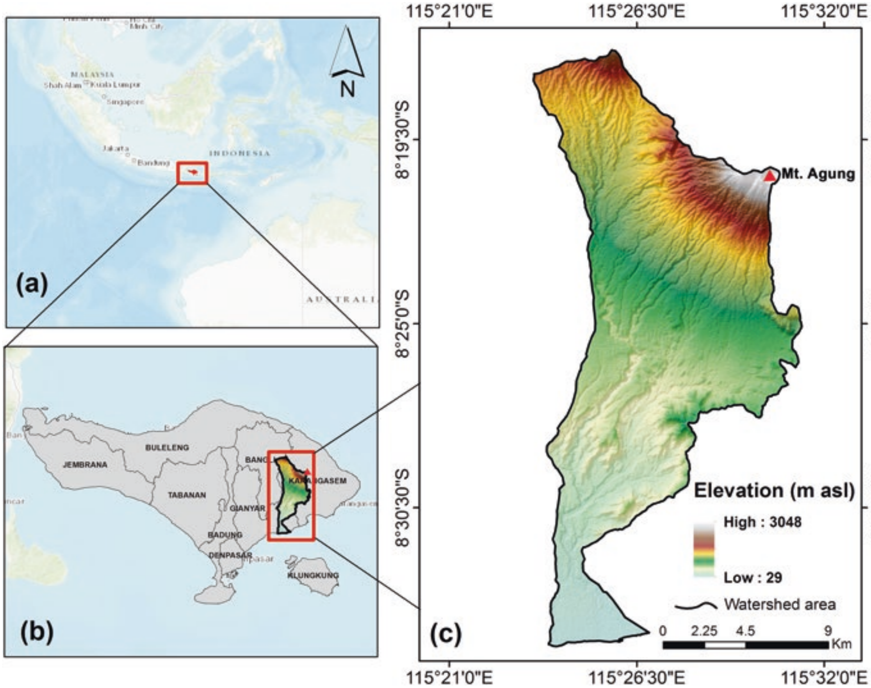

Fig. 1 The research location is viewed from (**a**) global, (**b**) regional and (**c**) local scales with varying topographic conditions

et al., 2021; Sutomo & Wahab, 2019; Syahbana et al., 2019; Wellik et al., 2021). The Unda watershed has four types of geology, including the Buyan-Bratan and ancient Batur volcanoes (Qvbb), the Agung volcano (Qhva), Tufa and Buyan-Bratan and Batur lava deposits (Qpbb) and the Ulakan Formation (Tomu) in which there are mountain breccias fire, lava, tuff and limestone inserts. The site's elevation ranges from 29 to 3048 m asl (Fig. 1c), with a flat to very steep slope. The slope in the upstream area is dominated by steep slopes (25–45%) to very steep (>45%), the middle part with gentle slopes (8–15%) to steep (15–25%), and the lower part with a gentle slope (0–8%). Types of land use include primary dry land, secondary dry land, mixed gardens, fields, rice fields, shrubs, and settlements (BPDASHL UndaAnyar).

2.2 Data

The data used to quantify this study's erosion include geospatial and remote sensing data. Geospatial data were obtained from local government agencies. The data obtained from Indonesian government agencies include maps of soil types to calculate erodibility values derived from Watershed Management Center and Protected Forest (BPDASHL UndaAnyar), Bali Province. Land use data were obtained from the Geospatial Information Agency (BIG) to calculate support practices. The most important remote sensing data are daily rainfall derived from CHIRPS and the NDVI from Landsat 8 imagery. The daily rainfall data in this study use a 40-year temporal from 1981 to 2021. The annual mean of the long time series data is used to compare the erosion conditions during the period of El Niño events 2015, La Niña 2016, and positive IOD 2019—likewise with NDVI parameters, using time series data from 2014 to 2021. Both parameters were acquired and analyzed through cloud computing, namely Google Earth Engine (GEE) (Gorelick et al., 2017a,b). Another remote sensing parameter is topography derived from AlosPalsar's Digital Elevation Model (DEM), which calculates slope length and steepness factors and supports the calculation of support practices. In summary, the data used to quantify the erosion rate are presented in Table 1.

3 Method

3.1 Calculation of Soil Erosion

The method used for calculating erosion is the USLE method (proposed by Wischmeier & Smith, 1978) with Eq. 1.

$$A = R \times K \times LS \times C \times P \tag{1}$$

where A is estimated annual soil loss (t ha^{-1} year^{-1}); R is rainfall erosivity factor (MJmmha^{-1} h^{-1} year^{-1}); K is soil erodibility factor (t ha^{-1} MJ^{-1} mm^{-1}); L is slope length and S is slope steepness factor (dimensionless); C is cover and management factor (dimensionless), and P is support and conservation practice factor (dimensionless). A flowchart of the methods used to estimate soil erosion is shown in Fig. 2.

The next description explains the flow diagram in Fig. 2. The first step is to calculate the R factor carried out on the GEE platform, followed by the K factor from secondary data based on soil laboratory analysis, the LS factor from AlosPalsar DEM, the C factor from Landsat time series images, and the P factor from secondary land use map data.

*3.2 Rainfall Erosivity (*R*)*

The quantification of the R factor value uses remote sensing data from weather satellites, namely CHIRPS, with a spatial resolution of 0.05 degrees. The research area covered as many as 24 pixels and then each pixel was used as a point for and interpolated with the Kriging method (Borrelli et al., 2016; Liao et al., 2019; Siska &

Table 1 Types of data, data sources and their use in calculating the erosion rate factor

No	Data	Sources	Data use
1	Daily rainfall during 1981–2021	Rainfall estimates from rain gauge and satellite observations (CHIRPS) 0.05° acquired by Google earth engine (GEE) https://developers.google.com/earth-engine/datasets/catalog/UCSB-CHG_CHIRPS_DAILY	To analyze the rainfall erosivity (R) factor
2	Soil type map 1:250.000	Watershed management center and protected Forest (BPDASHL UndaAnyar), Bali Province.	To analyze the erodibility factor (K)
3	Land use map 1:50.000	Geospatial information agency (BIG)	To analyze the support practices (P) factor
4	Normalized difference vegetation Index (NDVI) during 2014–2021	Landsat 8 level 2, collection 2, tier 1 (30 m) acquired and quantification by Google earth engine (GEE) https://developers.google.com/earth-engine/datasets/catalog/LANDSAT_LC08_C02_T1_L2	To analyze the vegetation cover (C) factor
5	Topography	AlosPalsar DEM (12.5 m) free access https://asf.alaska.edu/	To analyze the slope length and steepness (LS) factor and support practices (P) factor

Hung, 2001) to upscale the spatial resolution. Rain erosivity (R) is the ability of rainwater to cause erosion, which is calculated using Eq. 2 (Bols, 1978).

$$EI_{30} = 6.119(\text{RAIN})^{1.21} \times \text{DAYS}^{-0.47} \times \text{MAXP}^{0.53} \tag{2}$$

where EI_{30} is the monthly rainfall erosivity, RAIN is the average monthly rainfall (cm), DAYS is the average rainy day in one month and MAXP is the maximum rainy day in the month concerned (cm).

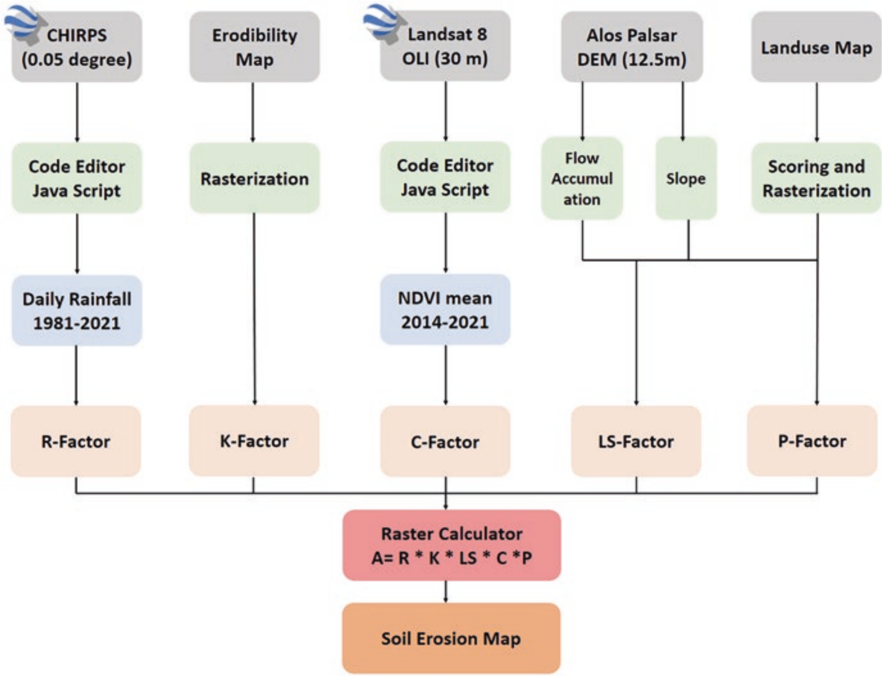

Fig. 2 Flowchart of the methods used to estimate soil erosion

3.3 *Soil Erodibility* (K)

Soil erodibility factor (*K*) reflects the influence of soil properties and profile characteristics on soil loss (Le Bissonnais, 1996; Renard et al., 1991). It measures the soil's potential susceptibility to release and transport by rainfall and soil runoff. The main factors that affect the K factor are soil texture, organic matter, soil structure, and soil profile permeability (Bryan, 2000; Carter, 2002; Mataix-Solera et al., 2011). This study obtained the K factor through secondary data from the government agency of the Permanent Nursery Center for Watershed and Forest Management (BPDASHL) UndaAnyar, Bali (BPDASHL UndaAnyar, 2018), based on laboratory soil analysis. They calculated soil erodibility using the Wischmeier and Smith (1978) equation.

3.4 *Topographic Factor (LS)*

Topographic factor (LS) reflects the effect of surface topography or slope length (meters) and slope steepness on the rate of soil erosion by water. For the calculation of the topographic factor (LS), refer to the statement (Moore & Burch, 1986) as in Eq. 3.

$$LS = \text{Flow accumulation} \times \left(\text{Cell size} / 22.13\right)^{0.4} \times \left(\sin \text{slope} / 0.0896\right)^{1.3} \tag{3}$$

3.5 Vegetation Cover (C)

For this study, the Normalized Difference Vegetation Index (NDVI) was used to estimate and map the crop and management (*C*) factor value of the watershed. The Normalized Difference Vegetation Index was calculated from the Landsat 8 satellite image by applying Eq. 4.

$$\text{NDVI} = \frac{\text{NIR} - \text{RED}}{\text{NIR} + \text{RED}} \tag{4}$$

where NDVI is the Normalized Difference Vegetation Index, NIR is the surface spectral reflectance in the near-infrared band and RED is the surface spectral reflectance in the red band. After calculating the NDVI, the next step is calculating factor C of Eq. 5. The equation was initiated by Durigon et al. (2014), for the tropics it is used to estimate the C-factor value of the NDVI.

$$C = 0.1 \times \frac{-\text{NDVI} + 1}{2} \tag{5}$$

where *C* is the crop and management (*C*) factor, the Landsat image with 30-m spatial resolution acquired from 2014 to 2021 was used to calculate the NDVI and to generate the *C*-factor value because soil erosion by water and vegetation cover is high during this season.

3.6 Supporting Factors and Conservation Practices (P)

Supporting factors and conservation practices (*P*) refer to the effect of conservation practices in reducing the quantity and rate of runoff and the amount of soil erosion (Lee, 2004). The *P* value can be determined by the type of conservation action implemented. The value is always between 0 and 1, where a value of 0 indicates an excellent erosion-resistant facility made by humans and a value of 1 indicates the absence of an erosion-resistant facility (Desmet & Govers, 1996). However, it is challenging to estimate the P value of the factor when there is a lack of data and there is no permanent support and conservation practice.

Generally, the *P*-factor value commonly used in Indonesia is the value of the conservation technique as proposed by Arsyad (1989). However, this approach is very difficult because it is necessary to conduct a field survey for the entire study area, so it is time consuming and costly. Another approach to getting the P-factor value is to assume it is 1 for the entire study area (e.g., Xiong et al., 2019). However, this value is quite biased because it assumes that the entire study area does not carry out soil conservation measures. In the previous study by Panagos et al. (2015a, b) in Europe, the calculation of the P-factor was estimated with consideration of: (a) contour farming (P_C), (b) maintenance of stone walls (P_{SW}), and (c) grass margins (P_{GM}), where P_{SW} and P_{GM} based on the land use approach. However, information on maintenance of stone walls and grass margins is very difficult to obtain in Indonesia. Therefore, the P factor in this study was carried out according to the estimation as proposed by As-syakur et al. (2022) for Indonesia and tropical area in which information on maintenance of stone walls subfactor and grass margins subfactor are replaced with the terrace types application (P_T) and the strip cropping application (P_{CT}) subfactor. The values of P_T and P_{CT} offered by As-syakur et al. (2022) used a land use types approach as suggested by Panagos et al. (2015a, b) and combined with the assumptions of conservation techniques described by Arsyad (1989). In this case, the P-factor estimation becomes:

$$P = P_C \times P_T \times P_{CT} \tag{6}$$

The values of contour farming subfactor (P_C) for a given slope are used based on modification from Panagos et al. (2015a, b), as displayed in Table 2. Meanwhile, the P_T and P_{CT} values used in this study are based on land use classes in Indonesia as offered by As-syakur et al. (2022). Assumptions used by As-syakur et al. (2022) are that each type of land use has a different application of soil conservation support practice, especially for terracing types and strip cropping application. For example, bare land is assumed to have no terracing and strip cropping planting method application. The values of P_T and P_{CT} and their assume are shown in Table 3.

The value of the erosion rate is divided into six classes, i.e., slight with a threshold value (0–1 t ha^{-1} yr^{-1}) to an extreme (>50 t ha^{-1} yr^{-1}). The threshold classification refers to the research of Almagro et al. (2019), as shown in Table 4.

Table 2 Value of support practice factor for contouring

Slope (%)	Support practice factor for contouring
0–3	0.4
4–8	0.5
9–12	0.6
13–16	0.7
17–20	0.8
21–25	0.9
>25	0.95

Table 3 Description about P_T and P_{CT} values and their assumption (As-syakur et al., 2022)

Land use types	P_T and P_{CT} values and their assumption		
	P_T	P_{CT}	Assumption
Water	0	0	Where water flows and does not allow erosion
Building	0.91	1	There is no terracing, but on steep slopes it has terraces and no planting method is applied
Forest	1	0.1	There is no terracing, but the planting method is assumed to be better than plantation
Plantation/ perennial plant	0.7	0.4	The terracing subfactor is the traditional terrace and the planting method is the average of the plantation crop management
Mangrove	1	0.1	There is no terracing, but the planting method is assumed to be better than plantation
Sand	1	1	There is no terracing and no planting method is applied
Settlement	0.9	1	There is no terracing, but on the steep slopes, it has terraces and no planting method is applied
Pond	0	0	Where the water is stagnant and does not allow erosion
Grass land	1	0.25	There is no terracing and the cropping method is the average of pasture management
Rice fields	0.4	0.3	In general, the terracing subfactor is the bench terrace, but the planting method is assumed to be no better than the pasture management
Scrubland	1	0.5	There is no terracing, but the planting method is assumed to be no better than pasture management
Bare land	1	1	There is no terracing and no planting method is applied
Dry land	0.6	0.6	The terracing subfactor is the traditional terrace, but the planting method is assumed to be no better than the poor pasture management

Table 4 Soil erosion class

Categories	Soil loss (t ha^{-1} yr^{-1})
Slight	0–1
Light	1–2
Moderate	2–5
Heavy	5–10
Severe	10–50
Extreme	>50

4 Result

4.1 Static Factor for Erosion Model

The calculation of the erosion rate in this study uses the USLE model. Static factors with the assumption that there are no changes are K, LS, and P factors. The statistical values of the factors for modelling erosion are presented in Table 5. The K factor

Table 5 Statistical value of K, LS and P factors

Variable	Statistical value			
	Min	Mean	Max	Standard deviation
K factor	0.102	0.329	0.800	0.128
LS factor	0.020	8.247	45.41	9.890
P factor	0.000	0.226	0.95	0.179

ranges from 0.102 to 0.800 yr MJ^{-1} mm^{-1}, with a mean of 0.329 t ha hr. MJ^{-1} ha^{-1} mm^{-1}. Spatially the highest K values are located in the upstream part of the watershed (Fig. 3a). Low K values are found in watershed areas with reddish brown latosol and lithosol soil types, as well as humus regosol. The highest K factor is spatially located in areas with gray–brown regosol soil types. Such conditions contribute to the rate of erosion of the watershed area. Furthermore, the LS factor was quantified with topographic data from DEM AlosPalsar. The lowest LS factor was 0.02, with a median value of 8.247, while the highest was 45.41. High LS factor values are in the upstream area with steep to very steep slopes (Fig. 3b). The P factor has a range of the lowest value of 0.00 to the highest of 0.95, with an average value of 0.22. The low P factor is in the type of forest land use and mixed gardens with high vegetation density, thus reducing erosion. The high P factor is located at the peak of Mt. Agung and spreads over several watershed areas with vacant land use types and dry land agriculture without terraces (Fig. 3c).

4.2 Dynamics Factor for Erosion Model

Dynamic factors in the estimation model for the amount of erosion in this study are the erosive factor (R) and the plant vegetation cover factor (C). The erosion model was developed spatiotemporal based on climate change phenomena such as the 2015 El Niño, La Niña 2016, and positive IOD 2019. We compared it with the R factor, with a long time series data (1981–2021), assuming neutral conditions. The calculation of the R factor with long time series data yielded the lowest value of 1278.98 MJ mm ha^{-1} yr^{-1}, the average value of 1709.59 MJ mm ha^{-1} yr^{-1} and the highest of 2442.22 MJ mm ha^{-1} yr^{-1}. When the El Niño event took place, the lowest R factor value decreased from the neutral condition, which was only 1129.53 MJ mm ha^{-1} yr^{-1}, and the highest value was 2426.71 MJ mm ha^{-1} yr^{-1}. During the La Niña phenomenon, the R factor increased dramatically, where the lowest value only reached 3096.03 MJ mm ha^{-1} yr^{-1} while the highest value reached 4504.21 MJ mm ha^{-1} yr^{-1}, twice the normal condition. In the next 2 years, there was a positive IOD phenomenon, which caused the condition of the R factor to decrease drastically, namely 670.99 MJ mm ha^{-1} yr^{-1}, and the highest value was only 1731.63 MJ mm ha^{-1} yr^{-1}. The overall standard deviation of the R factor in the watershed ranges from 299 to 356 MJ mm ha^{-1} yr^{-1}. The statistical value of erosivity (R) with a long time series, El Niño Event (2015), La Niña (2016), and positive IOD (2019) are shown in Table 6. The comparative spatial distribution of the R factor in watersheds

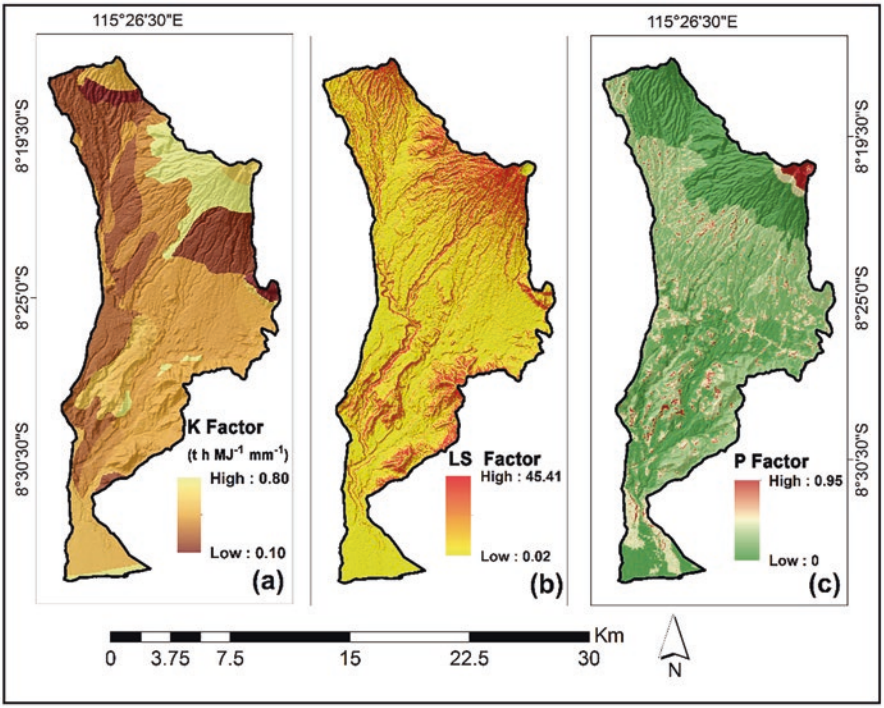

Fig. 3 Spatial distribution of (**a**) soil erodibility (*K*), (**b**) *LS* and (**c**) *P* factors in the Unda watershed

Table 6 The statistical value of erosivity (R) with a long time series, El Niño event (2015), La Niña (2016) and positive IOD (2019)

Year	*R* factor value			
	Min	Mean	Max	Standard deviation
1981–2021	1278.98	1708.59	2442.22	330.74
2015	1129.53	1587.44	2426.71	356.46
2016	3096.03	3577.67	4504.21	333.48
2019	670.99	1124.56	1731.63	299.15

is presented in Fig. 4. A red gradient indicates the *R* factor with the lowest R condition to blue with a high *R* condition. Figure 4c shows a La Niña effect, which has a blue spatial distribution that dominates almost the entire watershed area. Figure 4d shows a positive IOD effect so that almost the entire area has orange and red zones, which show the lowest erosive conditions compared to normal conditions (Fig. 4a), El Niño (Fig. 4b) and during La Niña events. A high *R* value affects the amount–f erosion, while a low R value is used to reduce erosion in the watershed.

We also quantify the effect of climate dynamics on plant vegetation cover (factor *C*), which influences the variability of erosion values. The value of factor *C* statistics with long data time series (2014–2021), El Niño Events (2015), La Niña (2016), and

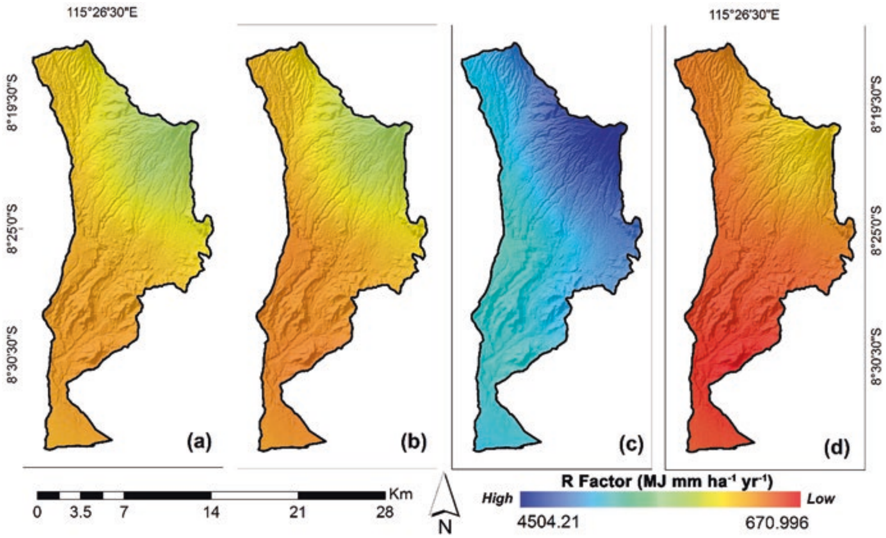

Fig. 4 Spatial distribution of erosivity (*R*): (**a**) with long data (1981–2021), (**b**) El Niño event (2015), (**c**) La Niña event (2019) and (**d**) positive IOD (2019)

Table 7 The value of factor C statistics with long data time series (2014–2021), El Niño events (2015), La Niña (2016) and positive IOD (2019)

Year	C factors value			
	Min	Mean	Max	Standard deviation
2014–2021	0.004	0.011	0.058	0.006
2015	0.004	0.012	0.062	0.006
2016	0.0007	0.010	0.056	0.006
2019	0.0004	0.012	0.062	0.007

positive IOD (2019), shown in Table 7. 2021, produces a factor C value of at least 0.004, mean 0.011 and maximum 0.058. During the La Niña phenomenon, the minimum *C* value decreased by 0.0007, the mean was 0.010, and the maximum was 0.056. The ongoing El Niño phenomenon and the positive IOD have implications for the increase in factor *C* with a mean value of 0.012 and a maximum of 0.62. This condition is in contrast to the erosive factor because the erosion increases during the La Niña phenomenon compared to the El Niño and positive IOD events. Spatial distribution of C factors with long data time series (2014–2021), El Niño events (2015), La Niña (2016), and positive IOD (2019) is shown in Fig. 5. The lowest R factor indicated by the orange zone in the section peak of Mt. Agung is partly located in the middle because, in that area, there is a lot of bare land for sand mining, which is also found in the southern coastal area. The pattern is relatively the same, but during the La Niña phenomenon, the condition looks greener than the neutral condition or when El Niño or positive IOD occurs.

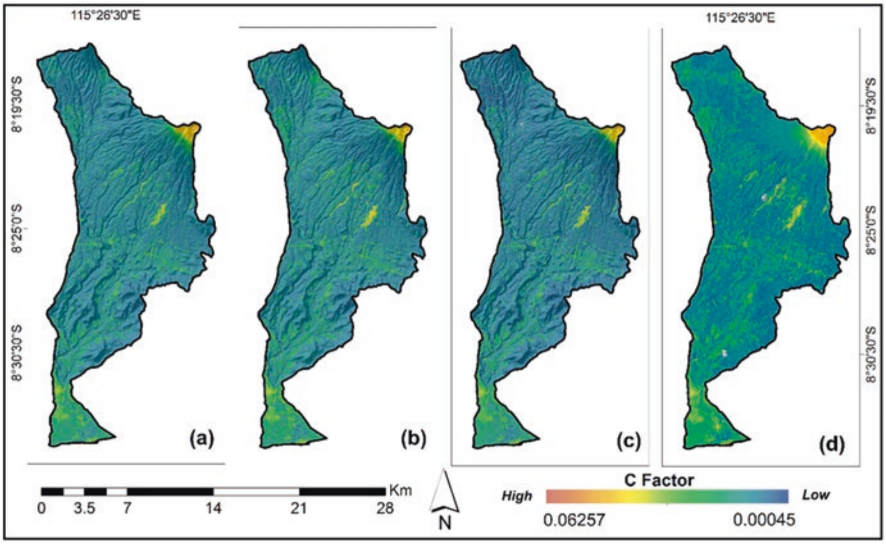

Fig. 5 Spatial distribution of *C* factors: (**a**) with long data time series (2014–2021), (**b**) El Niño events (2015), (**c**) La Niña (2016) and (**d**) positive IOD (2019)

4.3 Soil Erosion Map

The magnitude of the erosion rate in each dynamic climatic phenomenon is different in the watershed area. The mean value of erosion with long time series data or assumed to be in the neutral condition is 17.23 t ha^{-1} yr^{-1}, decreasing in the El Niño phenomenon and positive IOD, i.e., 15.70 and 14.24 t ha^{-1} yr^{-1}. The mean value increases when there is a La Niña phenomenon by 28.11 t ha^{-1} yr^{-1}. The maximum erosion rate during neutral conditions and El Niño events was relatively the same, ranging from 2397 to 2497 t ha^{-1} yr^{-1}, while when positive IOD, it decreased to 1832 t ha^{-1} yr^{-1}. The La Niña phenomenon in 2016 caused the maximum erosion rate to double normal and La Niña conditions, reaching 4437 t ha^{-1} yr^{-1}. The results of the soil loss or the erosion rate, along with their coverage area, are presented in Table 8.

The erosion rate in the slight category (0–1 t ha^{-1} yr^{-1}) uses long time series data spread over an area of 78.49 km^2. Erosion rates during El Niño, La Niña, and positive IOD phenomena are 79.47, 67.67 km^2, and 87.64 km^2. The erosion rate in the light category (1–2 t ha^{-1} yr^{-1}) ranges from 18 to 21 km^2, except for the La Niña phenomenon, which is only 11.91 km^2. The moderate (2–5 t ha^{-1} yr^{-1}), heavy (5–10 t ha^{-1} yr^{-1}), and severe (10–50 t ha^{-1} yr^{-1}) erosion rates have relatively the same distribution proportions. With an area ranging from 28 to 39 km^2, the erosion rate in the severe category (10–50 t ha^{-1} yr^{-1}) relatively dominates the distribution after the slight erosion category, ranging from 46 to 69 km^2. The erosion rate in the extreme category (>50) when conditions were neutral, El Niño, and positive IOD

Table 8 The statistical value of soil erosion comparison using long time series data, El Niño 2015 events, La Niña 2016 and positive IOD 2019

Categories	Threshold (t ha^{-1} yr^{-1})	Soil loss area (km^2)			
		Long time data	2015	2016	2019
Slight	0–1	78.49	79.47	67.67	87.64
Light	1–2	18.38	17.83	11.91	20.93
Moderate	2–5	36.37	36.26	28.33	39.36
Heavy	5–10	31.94	32.18	30.21	31.42
Severe	10–50	58.18	58.49	68.79	46.24
Extreme	>50	8.95	9.08	25.25	6.43
No data		1.07	0.07	1.22	1.36
Total area		233.38	233.38	233.38	233.38

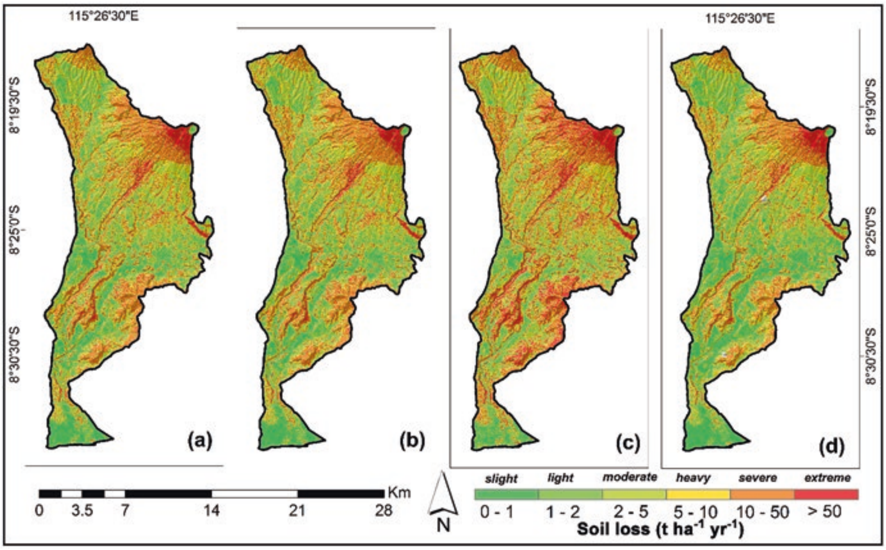

Fig. 6 Spatial distribution of soil erosion using the USLE model, comparison with, (**a**) using a long time series, (**b**) 2015 El Niño events, (**c**) 2016 La Niña events and (**d**) positive IOD 2019

ranged from 6 to 9 km^2. Meanwhile, during the 2016 La Niña event, the rate of extreme erosion increased by 25.25 km^2. Spatial distribution of soil erosion using the USLE model, comparison with, using a long time series, 2015 El Niño events, 2016 La Niña events and positive IOD 2019 is shown in Fig. 6. The entire watershed area, as well as the severe category of erosion, relatively dominates in the study area. The extreme erosion category is found in the upstream area of the watershed. The red zone on the erosion map for La Nia events is more widely distributed (Fig. 6c), followed by erosion rates for El Niño.

5 Discussions

Several predictive models of land erosion have also been developed, as discussed in various works of literature (Benavidez et al., 2018a, b; Djoukbala et al., 2019; Jain & Kothyari, 2000; Morgan et al., 1998). The models are primarily empirical (parametric) developed based on the hydrological and physical processes during erosion events and their transport from the watershed to the point under consideration. Ideally, the prediction method must meet seemingly contradictory requirements. Namely, the model must be reliable, can be used in general (universally applicable), easy to use with minimum data, comprehensive in terms of the factors used, and can be followed (sensitive to data) to changes in the watershed, such as land conservation measures (Morgan et al., 1998). However, considering the complexity of the process of land erosion, which is the interaction of various factors, no model can explain this phenomenon with a simple relationship and is easy to use. So there is still a vast opportunity to conduct research in this field. The most promising approach to developing predictive methods and procedures is formulating a conceptual model of the erosion process (Arsyad, 1989).

*5.1 Erosivity (*R *Factor)*

Factors that affect the occurrence of erosion are rain, air temperature, and wind speed. Rainfall is the most influential climatic factor. Air temperature affects surface runoff by changing the water content of the soil, thereby causing changes in the water absorption capacity of the soil infiltration (Nearing et al., 2005; Renard & Freimund, 1994). Air humidity and radiation play a role in influencing air temperature, and wind speed determines the speed and direction of falling raindrops. The ability of rain to destroy soil aggregates is determined by its kinetic energy (Nearing et al., 2005).

In tropical areas such as Indonesia, rainfall significantly impacts climate variability. The climate characteristics of an area can be seen from the variation in rainfall. Climate variability in the tropics is prone to occur due to the interaction of land, ocean, and atmosphere. Rainfall in Indonesia is generally influenced by significant phenomena such as the El Niño–Southern Oscillation (ENSO) and Dipole Mode (DM) (As-syakur et al., 2014). The influence of this phenomenon then interacts with monsoons and local patterns that affect the variability of annual, monthly rainfall, and extreme rainfall intensity (Luo et al., 2013). ENSO is an atmosphere–ocean interaction phenomenon that occurs in the tropical Pacific Ocean, which fluctuates periodically between cold (La Niña) and warm (El Niño) episodes. The influence of El Niño and La Niña was felt in Indonesia in the June to August period (Hendon, 2003; Meyers, 1996). DM is a reasonably significant phenomenon in tropical ocean–atmosphere interactions that occur in the Indian Ocean and has a significant influence on the climate in the surrounding area. DM has three anomalous phases (positive, neutral, and negative) that oscillate over time (Jianqi Zhang et al., 2019).

The positive phase of this phenomenon is related to reduce rainfall in Eastern Indonesia, whereas the negative phase causes an increase in rainfall in Eastern Indonesia. The DM develops in July to November, and changes in the temperature gradient in the Indian Ocean eventually affect convection in the eastern region of Indonesia (Pan et al., 2018). The variability of rainfall can cause several problems, such as floods and droughts. The variability of rainfall in recent years has significantly impacted the community. In 2015, the El Niño event caused a drought, which decreased the plant health index (VHI) (Amalo et al., 2018; Kogan & Guo, 2017).

Furthermore, a drought occurred at the end of 2019 due to the Dipole Mode phenomenon, whose impact was almost similar to the 1997 and 2015 El Niños (Amalo et al., 2018). This phenomenon affects the variability of rain, so it impacts its contribution to erosivity in the watershed. The effect on erosion in the Unda watershed is in the form of differences in the rate of erosion on the rainfall variability. In the year 2016, a La Niña phenomenon resulted in the highest average and maximum erosion magnitudes compared to customary conditions and other phenomena.

*5.2 Erodibility (*K *Factor)*

Soil properties affect the resistance of the soil structure to dispersion in erosion by raindrops and surface runoff. Thus, soil properties that affect erosion are texture, structure, organic matter content, soil depth, subsoil properties, and soil fertility. However, the content of organic matter affects the stability of the soil structure (Lal, 2001). The Unda watershed is dominated by regosol soil type, which has low organic matter characteristics and is dominated by a sand fraction. Soils with silt content with low clay content and little organic matter have a high erosion sensitivity. This high erosion sensitivity is called soil erodibility (K). Bryan (2000) states that the higher the value of soil erodibility, the easier the soil is eroded or vice versa. Soil erosion sensitivity shows the overall properties of the soil and is free from other erosion-causing factors. Based on the previous study (Jiang et al., 2020; Radziuk & Switoniak, 2021; Yusof et al., 2011) to provide an assessment of the sensitivity of soil erosion that has the above conditions so that it can be used in the implementation of soil preservation efforts, the concept of a soil erosion sensitivity factor has been developed.

5.3 Slope Length Dan Slope (LS Factor)

Variations in the shape of the earth's surface, which include mountainous and valley areas with a significant slope angle and low-lying areas with a flat surface, have an essential role in determining the stability associated with the erosion process (Schumm, 1956; Strahler, 1952). Logically, areas with large slopes are more prone to erosion than flat areas, so erosion cases are often found in mountainous or hilly areas. Furthermore, in excavated or embankment areas with large slope angles, slope stability is disturbed due to excessively steep slopes, weakening of the toe of the slope, and excessive load pressure at the head of the slope. This can happen because of the energy of water at the foot of the slope and the activities of backfilling or cutting the slopes of humans.

5.4 Vegetation Cover (C Factor) and Supporting Factors and Conservation Practices (P Factor)

Vegetation intercepts the falling rain with leaves and stems, which will reduce the falling speed and break down the raindrops into smaller ones. Rainfall that hits the leaves will evaporate back into the air, which is known as plant interception loss (Nearing et al., 2005). Stems, roots, and undergrowth reduce the velocity of surface runoff resulting in reduced erosion and flow. Plant roots and litter can also hold some sediment that passes through it, making the soil a nest for water to seep.

Vegetation reduces the blow of raindrops on the soil surface. Plants are also influential in reducing the rate of surface runoff and reducing water content through transpiration. The reduced soil water content causes the soil to be able to absorb more water so that the amount of runoff is reduced (Ludwig et al., 2005; Zhao et al., 2013). The effect of vegetation on erosion surface runoff can be divided into three parts: rain interception by plant crowns, reducing surface runoff velocity, and destructive power (Ludwig et al., 2005). Effects of roots and biological activities related to vegetative growth and their effects on soil porosity and transpiration result in dry soil (Smith et al., 2021).

Humans are a determining factor for erosion because humans can regulate the balance of other factors. Erosion can be reduced by utilizing land management and land use that are adapted to soil conservation measures. However, from humans themselves, many factors cause humans to use their land wisely or vice versa (Panagos et al., 2015a, b). One of the roles of humans in the research area is opening a sand mining area in the upstream area of the watershed. Such conditions need to be considered so that they do not penetrate forest areas or other vegetated areas (Fig. 7a) because there will be a higher erosion rate in the future. Another human role is land management in the form of terraces on agriculture land with steep-to-steep slopes (Fig. 7b). This agricultural system has become local wisdom in Bali called Subak. Farmer groups create organizations for irrigation water distribution, terracing, and traditional land management with minimum tillage (Roth, 2014). Land conservation has been carried out for generations and designated by UNESCO as a world cultural heritage since 2012.

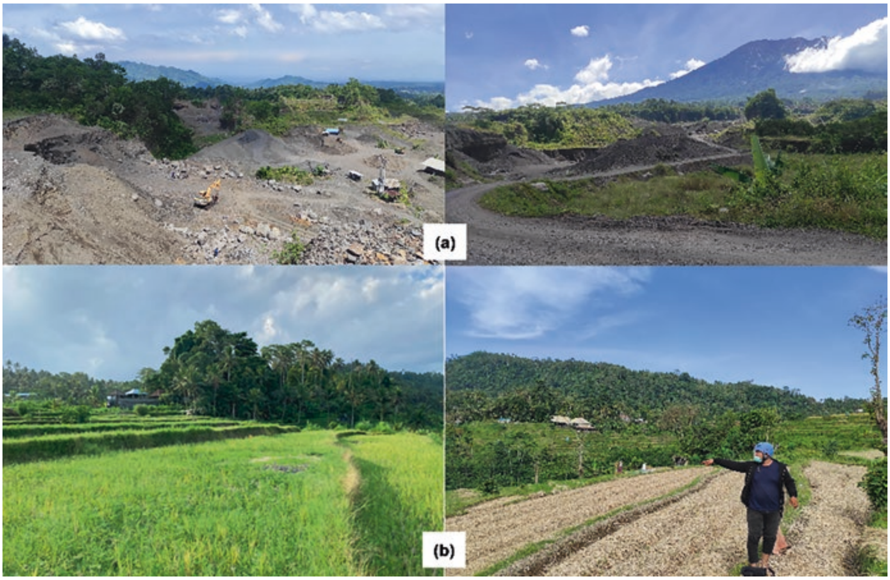

Fig. 7 Field conditions in (**a**) bare land areas in the upstream watershed areas, which are used as sand mining by the community (coordinate 8°24′4.47″S, 115°29′3.71″E). Field conditions in the middle of the watershed used as agricultural land (**b**), farmers apply terracing land management (coordinate 8°29′31.67″S, 115°26′17.91″E). Source: Research survey in 2021

5.5 Soil Erosion

The influence of climate variability causes soil erosion in the Unda watershed so that the factors for predicting erosion also change, such as factors R and C. Such conditions are shown by the wider spatial distribution of erosion quantities during the La Niña phenomenon (Fig. 6). Nevertheless, during the La Niña phenomenon, plant vegetation cover is relatively dense. These conditions can be used as a reducer due to high rainfall and frequent periods. Nonetheless, this circumstance is greatly contingent on the agricultural land management practices employed and the inherent characteristics of the Unda watershed soil.

Soil erosion occurs in three stages, namely the stage of releasing single particles from the soil mass and the stage of transportation by erosive media such as water flow and wind. In conditions where the available energy is no longer sufficient to transport the particles, a third stage will occur, namely deposition. Erosion by water can be seen as the start of the release of soil particles by the impact of falling rainwater (Panagos et al., 2015a, b). Raindrops are the primary medium for releasing soil particles because the kinetic energy of falling water droplets can splash soil into the air (Liao et al., 2019). On flat soils, the particles are distributed more or less evenly in all directions, but downward transport occurs in the slope direction on sloping soils. When raindrops hit the bare ground, soil particles can be released and thrown a few centimeters into the air. Soil particles are spread more or less evenly in all directions, but for sloping land, there is a downward dominance in the slope direction. These soil particles will clog the pores to reduce the capacity and rate of infiltration. Then there will be puddles on the soil surface, which will become surface runoff. This runoff provides the energy to transport the loose particles, either by splashing rainwater or by the surface runoff itself. When the energy or runoff decreases and no longer transports the loose soil particles, the soil particles will be deposited. The processes of splash and flow over the soil cause sheet erosion, which is a relatively even degradation of the soil surface (Guerra et al., 2017; Ahmad et al., 2020). Layer erosion is difficult to detect unless the soil surface is lower below the old soil marks on fence posts, visible tree roots or small pillars of soil covered by rocks still present.

Open land that is hit by heavy rains continuously will cause the soil to become rigid. Soil is also destroyed by weathering processes, both mechanically and biochemically. Besides that, the land is also disturbed by land cultivation and human and animal feet treading (Bakker et al., 2005; Yan et al., 2018; Jianxiang Zhang et al., 2021). Furthermore, the flow of water and wind also plays a role in releasing soil particles. All these processes cause the soil to become lost, so the transport medium quickly lifts it. The severity of erosion depends on the quantity of material supplied and the capacity of the transport medium. The transport media space has a larger capacity than the supply of released material, so the erosion process is limited by limited detachment. Conversely, if the quantity of material supply exceeds the capacity, then the erosion process is limited by limited capacity.

5.6 The Weaknesses and Uncertainties

The weakness of the USLE equation is that it provides a procedure for obtaining the value of the related factors, using a practical approach, so that errors in choosing the right price are possible. In particular, caution must be paid to selecting cropping patterns and land management prices. Usually, the values of *R* and *K* for a watershed are constant or do not have much variation. However, *C* and *LS* vary greatly depending on cropping patterns, land cultivation, and practical conservation measures (Alewell et al., 2019). Mathematically, the USLE does not describe the actual process of soil erosion. Calculation errors are always possible, especially in taking empirical coefficients (factors). Several researchers have introduced several formulas, exponents, and methods for calculating the value of *R* (Ramzi et al., 2017) where all of them do not apply in general and difficult to apply precisely to a particular location with the available data. The USLE estimates mean annual soil loss, so its use is limited to estimates of average annual soil loss in a given area. The USLE is used to predict sheet erosion and rill erosion but not gully erosion (Alewell et al., 2019). Ditch erosion due to concentrated flow is not considered in the equation and can lead to more significant erosion. The equation only estimates soil loss but does not predict sediment deposition (Benavidez, Jackson, et al., 2018; Kanito & Feyissa, 2021). Sedimentation at the bottom of the channel is smaller than the total loss of soil originating from the entire watershed. Once surface runoff from sloping land reaches the downstream end of the slope or enters the channel (flatter terrain), most sediment particles are deposited. The total eroded soil carried by surface runoff decreases with increasing path length (Majhi et al., 2021; Manaouch et al., 2021).

While this research provides valuable insights into soil erosion and their relation with climate changes, the interpretation of the results must be undertaken with caution due to some uncertainties. The remote sensing data employed in the USLE model calculations have not been validated, potentially introducing inaccuracies, for example rainfall erosivity data. Furthermore, the considerable cloud cover in the study area contributes to uncertainty in the results (Table 8). There is a column with no data, meaning clouds cover the area. The average research area covered by clouds is 1–1.4 km^2. The El Niño phenomenon has the least cloud cover, which is only 0.07 km^2 because the rain intensity in that phenomenon is almost nonexistent. Another limitation is the single P factor, which does not consider land use change. However, the watershed area is relatively dynamic caused by natural factors and human intervention. So it is recommended that future researchers validate the model (for example, through direct measurements in the field) and consider the factors of change in land use and management.

6 Conclusions

The integration of the use of geospatial data and remote sensing helps in the erosion quantification process of the USLE model. Remote sensing data are accessed for free with a long time series, while geospatial data are supported when the data cannot be reached by satellite imagery. Based on the computational results of the erosion rate, it turns out that global climate change affects the erosion rate in the Unda watershed, Bali Province, Indonesia. The maximum erosion rate during neutral conditions and El Niño events was relatively the same, ranging from 2397 to 2497 t ha^{-1} yr^{-1}, while during a positive IOD, it decreased to 1832 t ha^{-1} yr^{-1}. The La Niña phenomenon in 2016 caused the maximum erosion rate to double normal and La Nia conditions, reaching 4437 t ha^{-1} yr^{-1}. The distribution of erosion in the extreme normal period, La Niña, El Niño, and positive IOD categories is 8.95, 9.08, 25.25, and 6.43 km^2, respectively, spatially spread over the steep slope area, namely in the upstream watershed. The weakness and uncertainty of this research are that it ignores the supporting factors and conservation practices (P factor) and does not validate the erosion model results. The phenomenon in these factors tends to be dynamic. Future researchers are advised to develop a model by considering the factors of land use change and land management and validate it through field measurements.

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Dimensions of Climate Smart Agriculture

Sudhir Kumar Rajpoot, Adarsh Kumar, Gaurendra Gupta, Richa Chaudhary, Sanju Chaudhary, Raghavendra, Sunil Kumar Verma, S. Vijay Kumar, Chandra Bhushan, and Rivesh Bhusal

1 Introduction

One of the most important issues of our time is climate change, which has substantially altered or is altering the planet's ecosystems. Although the earth's climate has been changing continuously for the past 100 years or so, the speed of this variation has accelerated dramatically in that period (Arora, 2019). The consequences of climate change are already being felt, and they include higher average temperatures, more extreme weather, more mobile agroecosystem borders, invasive plant and insect invasions and more frequent extreme weather events. Climate change is affecting the agricultural sector, which is vital to the global food production and economy. Due to changing lifestyles and population growth, food consumption is rising. Crop yields are stalling in many regions of the world, and production is straining to keep up. Agriculture is a significant economic sector and a significant source of employment in many parts of the world, but more than 20% of people worldwide today experience food insecurity. According to a 2018 World Food Programme (WFP) report, food output per hectare growth is far slower than population growth rates. According to this, food and agriculture also play a

S. K. Rajpoot (✉) · R. Chaudhary · S. Chaudhary · S. K. Verma · C. Bhushan · R. Bhusal
Institute of Agricultural Sciences, BHU, Varanasi, Uttar Pradesh, India
e-mail: sudhir.k.rajpoot@bhu.ac.in

A. Kumar
ICAR-National Bureau of Agriculturally Important Microorganisms (NBAIM), Kushmaur, Mau Nath Bhanjan, India

G. Gupta
ICAR-Indian Grassland and Fodder Research Institute, Jhansi, Uttar Pradesh, India

Raghavendra
ICAR-Indian Institute of Soybean Research, Khandwa Road, Indore, Madhya Pradesh, India

S. V. Kumar
ICAR-Indian Institute of Rice Research, Hyderabad, Telangana, India

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significant role in global warming. Presently, it produces 19–29% of the world's greenhouse gas (GHG) emissions (World Bank, 2019). The types of agriculture that produce the most greenhouse gases are enteric fermentation, manure spread on pasture, synthetic fertilizer, paddy rice farming and biomass burning. According to the Food and Agriculture Organization (FAO), by the year 2100, there will be a drop in the output of the main cereal crops (20–45% in maize yields, 55% in wheat and 20–30% in rice) if the current GHG emissions and climate change trends continue. It will be more challenging to meet the increasing needs of a growing population if the same trends continue (FAO, 2016).

In order to combat these losses, we must adopt an integrated approach to managing croplands, livestock, forests and fisheries that addresses the interrelated issues of the agricultural sector and the speeding up of climate change. This will ensure food security for both humans and other living things. The many climate-smart agriculture strategies are covered in this chapter. These practices can assist to address existing environmental problems and ensure farmers' access to food by making agricultural production more efficient (Fig. 1).

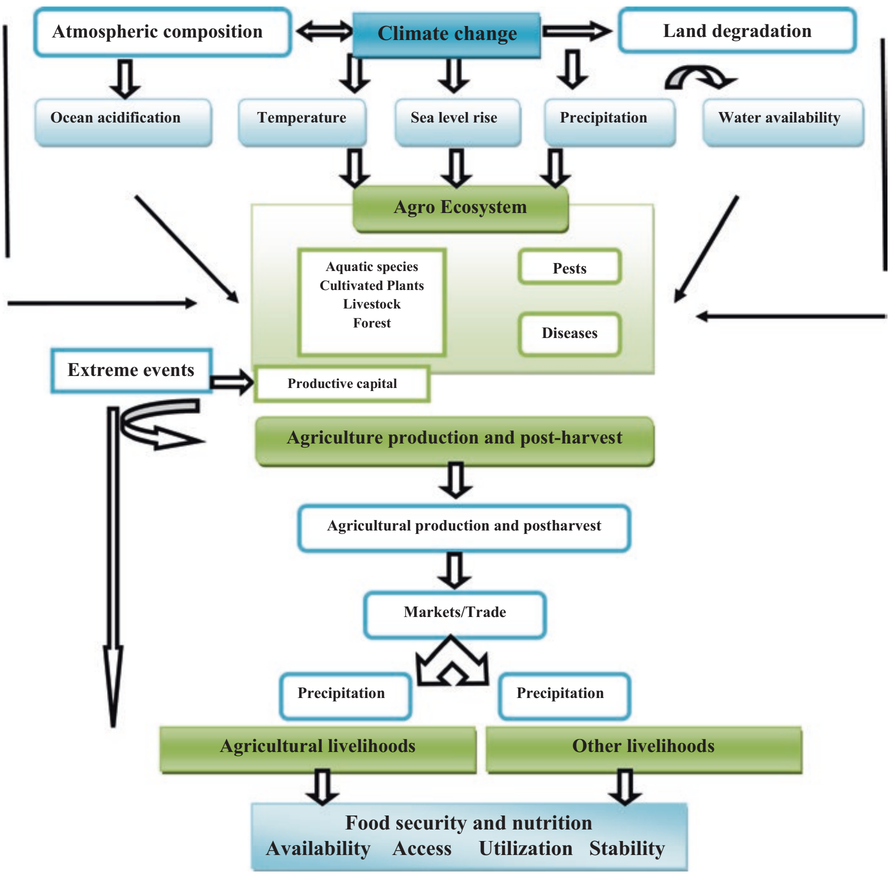

Fig. 1 Illustration showing the cascading consequences of climate change on nutrition and food security

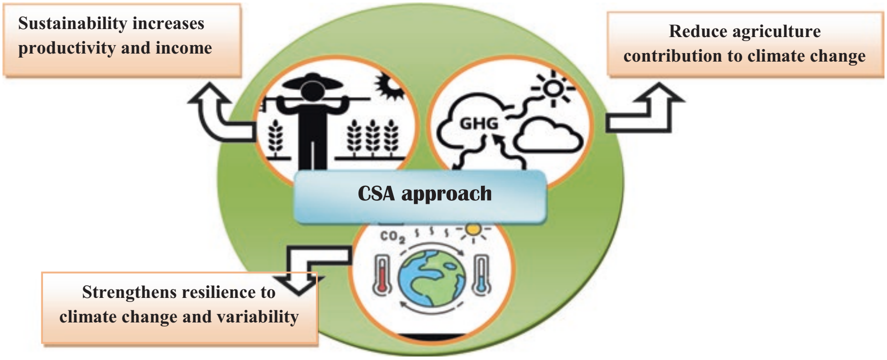

Fig. 2 Climate-smart agriculture approach

2 CSA Approach

To the projected Malthusian problem, the World Bank and the Food and Agriculture Organization (FAO) have praised a global transition to 'climate-smart agriculture' (CSA) (Fig. 2). It has a single governance structure that aims to propagate agricultural innovations and practices that increase crop productivity while also strengthening resistance to climate change and reducing greenhouse gas emissions. The definition of CSA is a 'triple-win' strategy that unifies aims for intensification, adaptation and mitigation under a single framework (Taylor, 2018).

Climate-smart agriculture (CSA) emphasizes synergies and trade-offs between agricultural production, food security, adaptive ability and mitigation benefits to transform and reorient agricultural systems to sustain food security in the face of climate change (Campbell et al., 2014). Incremental change might not be sufficient to bring about the societal adjustments required to lessen, adapt to and increase food security in the long run (Rickards & Howden, 2012; Cooper et al., 2013) when the effects of climate change become more apparent (Biermann et al., 2012; FAO, 2018).

Mathews et al.'s (2018) study found that understanding the advantages and disadvantages of various CSA choices is essential for enhancing the wellbeing of small-scale farmers in both short- and long-term efforts. According to Hellin and Fisher's (2019) study, agricultural researchers have created a variety of agricultural technologies and techniques, collectively known as CSA, as part of efforts for climate change adaptation and mitigation.

3 Seven Dimensions of Climate-Smart Agricultural Practices

The FAO Strategic Framework 2022–2031 is supported by CSA because it is built on the four betters: better production, better nutrition, a better environment and a better living for everyone, leaving no one behind. A CSA approach depends on the local socioeconomic, environmental and climate change conditions and is context-specific (Table 1). The FAO suggests that the strategy be put into practice through five action points: increasing the body of CSA-related evidence, promoting enabling policy frameworks, bolstering national and local institutions, improving funding and financing options and putting CSA practices into practice at the field level. Numerous agricultural techniques and technologies, such as minimal tillage, various crop establishment techniques, nutrient and irrigation management and residue incorporation, can increase crop yields, increase the effectiveness of the use of water and nutrients and decrease the emissions of greenhouse gases (GHGs) from agricultural activities (Jat et al., 2011; Sapkota et al., 2015). Similar to how enhanced seeds, information and communication technology (ICT)-based agro-advisories and crop/livestock insurances can assist farmers lessen the effects of climate unpredictability and change, rainwater gathering is another strategy (Mittal, 2012; Altieri & Nicholls, 2017). CSA choices, in general, combine conventional and cutting-edge methods, tools and services appropriate for a given place to adapt to climate change and variability (CIAT, 2014).

Table 1 Climate-smart practices for adaptation and mitigation options in agriculture

Dimensions of CSA practices	Adaptation/mitigation potential
Water smart: Water-smart technologies include furrow irrigation, laser land levelling, microirrigation, sensors and IoT. They also include cover crops and polythene/residue mulch.	Interventions to increase water productivity include good irrigation and drainage control, minimizing surface runoff of rainwater and reducing water loss from agricultural areas.
Nutrient smart: SSNM, leaf colour chart, soil health card, green-and-brown manuring and optical sensors.	Interventions that increase the effectiveness of nutrient utilization, such as balanced nutrient availability, improved soil quality and optimal fertilizer application to match crop needs.
Weather smart: Weather-smart practices include climate analogues, weather index-based crop insurance and ICT-based agricultural advisories.	Interventions to offer farmers weather advice and services relevant to income security, as well as crop-specific insurance to make up for income loss caused by weather-related whims.
Carbon smart: Agroforestry, fodder management and integrated pest management.	The promotion of carbon sequestration, the reduction of nutrient losses and the use of chemical fertilizers are a few examples of interventions to minimize GHG emissions.
Smart crop management: Conservation of genetic diversity, conservation agriculture IFS, INM, agroforestry, resilient cropping system	Drought, flood and heat/cold-resistant crop cultivars.
Smart weed management practices: Tillage, crop establishment, crop residue retention, crop diversification, AI, drone and sensor technology	Weed control in the context of climate change, e.g. decrease weed population, use pesticides sparingly, avoid weed shift etc.
Knowledge smart: Improved crop varieties, seed and fodder banks, adaptation/mitigation potential	Using climate risk management, a blend of science and local knowledge, to deal with significant weather-related emergencies.

The application of CSA technologies (hereinafter referred to as CSA technologies) singly or in combination has a significant potential to lessen the effects of climate change on agriculture. Adoption of CSA technologies may enhance crop yields, boost input usage efficiency, raise net income and reduce greenhouse gas emissions, according to several farm-level studies (Khatri-Chhetri et al., 2017). Basically, by creating an investment portfolio across multiple agro-ecological zones, the identification and prioritization of CSA technologies enable climate change adaptation strategy in agriculture. One must take into account adaption options that are carefully examined and prioritized by local farmers in relation to the significant climatic hazards in that region when developing CSA implementation plans at the farm level (FAO, 2012). For the correct application of these technologies, there are a number of prioritization techniques available, including the use of simulation models, expert judgment, household and key informant surveys, participatory appraisal and hybrid methodologies (Claessens et al., 2012; Mwongera et al., 2014; Taneja et al., 2019).

4 Water-Smart Practices

Water resources are impacted by climate change either directly or indirectly. To combat the anticipated water scarcity challenge, global water management in irrigated and rain-fed agriculture is becoming increasingly complex (Zohry & Ouda, 2022). At the global level, 70% of smallholder farmers will need to produce 70% more food by 2050 without exceeding current levels of water withdrawals (Mancosu et al., 2015). The strain from persistent dry spells and droughts, low water productivity and a decreased ability to use and manage green water must all be taken into account. Water-smart practices offer development professionals a set of water management methods that may be contextualized to adapt to the effects of climate change in order to maintain the sustainability of agricultural systems. The idea of water-smart behaviours is not new. It draws on well-known strategies' water-related actions, including climate-smart agriculture. CSA is heavily marketed as a means for smallholder farmers (SHFs) to lessen the impact of climate change and rainfall variability (Fig. 3). The goal of conservation agriculture (CA) and agroforestry is to make more water available in soils. However, these measures are not always adopted and do not necessarily lead to the sustainable use of water resources.

The added value of water-smart practices is in determining where investments in water access are required and what kinds of investments will have an impact, such as advocating at local, regional and national levels to increase the funding allocation for preserving, developing and sustaining water resources (Tables 2, 3 and 4). It is therefore essential:

- Recognizing the value of all water resources (rainfall, surface water, groundwater and wastewater) in areas with limited water supplies in order to achieve food security.

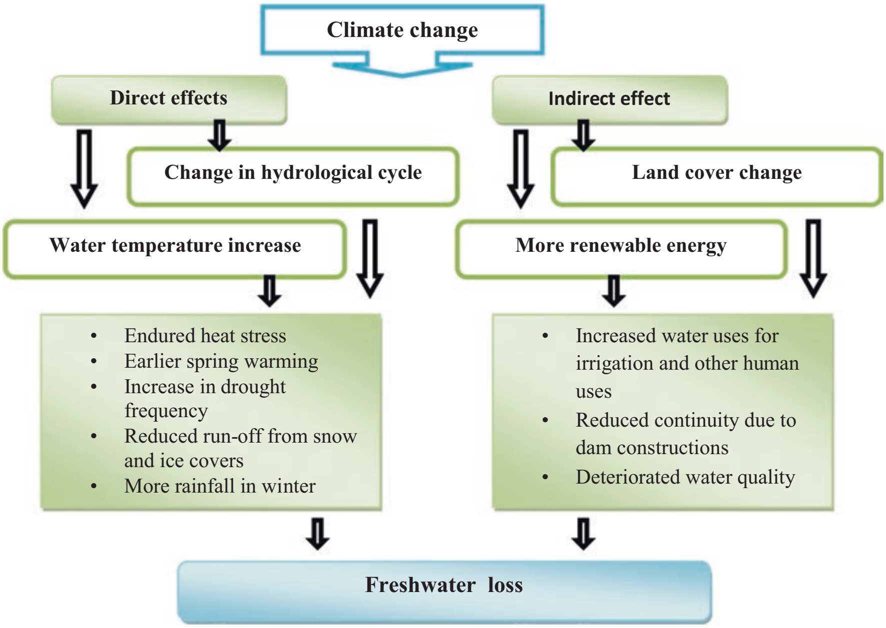

Fig. 3 Impact of climate change on water

Table 2 Water management Strategies for different regions under CSA

Parameters	Practices	Benefits
Drought management	Methods for conserving soil moisture include: mulching; ridge and furrow; elevated bed and furrows; and broad bed furrow. Farm ponds and check dams. Percolation tanks and ponds for recharging wells. Preparedness for uncertainty in crop production: Modified planting methods and recycling of crop residue.	Improvements in water productivity, crop intensity, resource conservation, system resilience and yields, as well as resource conservation and sustainability, are all highlighted.
Floods; cyclone: Excess rainfall conditions	Land shape for vulnerable coastal tracts; efficient drainage/ conveyance system; flood-tolerant crops; increased water productivity; integrated agricultural system	Production sustainability; improved water use efficiency. Enhanced water productivity and resilience. Livelihood security; income increment.

Source: Sikka et al. (2018)

Table 3 Water-smart practices for CSA and their potential benefits

Water-smart practices	Description	Potential benefits
Rainwater harvesting	Surface runoff is efficiently captured using a method called rainwater harvesting (RWH) during periods of productive rain (Helmreich & Horn, 2009). RWH includes three stages, which are receiving, storing and using the rainfall in the given location.	The use of rainwater harvesting systems has a series of advantages. Capturing water ensures part of the water demand for irrigation and alleviates the periods of scarcity due to droughts and dry seasons (Bafdal & Dwiratna, 2018).
Drip irrigation	The method consists of water source, pumping unit, mixing chamber, mainline, sub-main, laterals and emitters. The main line delivers water to the sub-mains and they carry water into the laterals. Irrigation is accomplished by emitters or drippers installed near the plants (Jamrey & Nigam, 2018).	Increases water use efficiency (60–200%), fertilizer use efficiency (20–33%), reduces cost of irrigation, maximizes the nutrient uptake while using minimum amount of water and fertilizer (Kumari & Kaushal, 2014).
Laser land levelling	Laser land levelling is a process of smoothing the land surface (±2 cm) from its average elevation using laser-equipped drag buckets and this technique is well known for achieving higher levels of accuracy in land levelling (Das et al., 2018)	The land levelling has resulted smoother soil surface, more uniform distribution of water in the field, more uniform germination of crops, reduction in seed weight, fertilizer, chemicals and fuel use.
Furrow-irrigated raised beds	In this system, the crop is planted on the top of beds and irrigation water is applied in furrows. The width of the bed and furrows commonly used is 40–45 and 25–30 cm, respectively, and the bed height is 15–20 cm (Kumar et al., 2010)	Maximum harvesting and utilization under low rainfall, avoidance of temporary flooding, improved drainage under high-intensity rainfall, higher N-use efficiency and less lodging.
Cover crops	Close growing crops like grasses and legume residues are kept in the field for soil protection.	Cover crops are the most effective way to prevent soil erosion, decrease ground water contamination, increase the amount of organic matter in the soil, improve the structure of the soil, preserve moisture in the soil and effectively manage weeds and soil-borne illnesses.

- To develop the best institutions, policies and market incentives to boost agricultural water use productivity.
- Changing the focus of water management from one that was supply-driven to one that was demand-driven and service-oriented, realizing that investments in areas other than irrigation may be more beneficial for rural development. The ideal choice is determined by the local conditions in each area.

Table 4 Research findings on water-smart practices for CSA

Technology	Findings	References
Precision irrigation	In the study effects of climate-smart agriculture (CSA) methods on the output of cotton and the livelihood of farmers in Punjab, Pakistan, it was found that the adoption of water-smart CSA practices and technologies, including as the prudent use of water and fertilizer, groundwater quality, availability to extension services and the proper manner and time of picking, significantly affects the gross value of cotton products.	Imran et al. (2018)
Supplemental irrigation	Adoption of supplemental irrigation has been proven to be a successful method for reducing the negative effects of soil moisture stress on the yield of crops grown with rain during dry spells. Supplemental irrigation can increase crop output and water productivity, particularly during crucial crop growth stages.	Nangia et al. (2018)
Drip irrigation	Adoption of drip irrigation instead of surface irrigation increases agricultural yields and crop quality while saving 30–50% on irrigation water use, depending on how well it is designed, installed and managed.	Cetin and Kara (2019)
Subsurface drip irrigation	In comparison to flood-irrigated CA-based systems, the adoption of subsurface drip irrigation (SDI) on a system basis reduced irrigation water use in mung bean fields by 46.7% and 44.7% respectively.	Dhayal et al. (2023)
Laser land levelling	The impact of laser land levelling on water conservation, crop yields and household income was assessed using a primary dataset from 350 farmers in the rice–wheat region of Punjab, Pakistan. It was found that the use of laser land levelling has a positive effect on household income, wheat and rice harvests and irrigation water savings.	Ali et al. (2018)
Mulching	Mulches minimize soil erosion, preserve moisture, improve nutrient status, reduce weed growth in agricultural crops and remove pesticide, fertilizer and heavy metal residues. Mulches enhance agricultural landscapes.	Iqbal et al. (2020)
Furrow-irrigated raised beds	In aerobic rice, use of furrow-irrigated raised beds, measuring 1.0 m in width and 30 cm deep, gives higher grain and straw yield. With this technology, water use efficiency (WUE) was also higher.	Yigezu et al. (2021)

5 Nutrient-Smart Practices

Droughts, soil acidity, nutrient-deficient and degraded soils that cause the depletion of native nutrient reserves and the formation of multinutrient deficiencies, which are causing a fall in factor productivity, are just a few of the obstacles that affect agricultural development (Das et al., 2016). Imbalanced fertilizer application makes a nutrient shortage worse, is unprofitable and is hazardous to the environment. The availability of water, nutrients and a stable soil structure will be necessary for the majority of effective CSA alternatives. These are the essential components required to promote efficient plant growth and lower crop failure (Fig. 4). Site-specific nutrient management strategies (SSNM), nitrogen application based on leaf colour charts (LCC), nutrient management based on soil health cards (SHC), green manuring (GM) and brown manuring (BM) all seem to be potential nutrition-smart CSA choices (Tables 5 and 6). CA-based crop management techniques drastically change the physical, chemical and biological characteristics of soil (Jat et al., 2018).

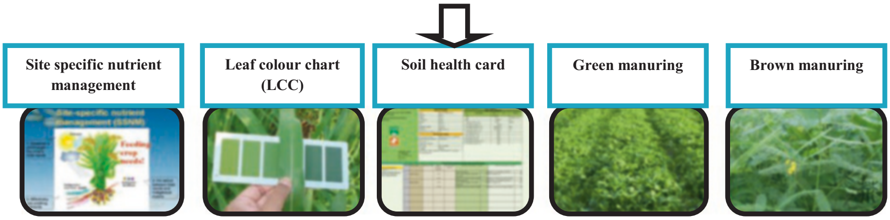

Fig. 4 Components of nutrient-smart practices for CSA

Table 5 Nutrient-smart practices for CSA

Technology	Description	Benefits
Site-specific nutrient management (SSNM)	Site-specific nutrient management (SSNM) is a strategy to supply crops with nutrients as needed (Singh, 2019). The primary objectives of SSNM are to increase crop output, profit and soil productivity through balanced and timely fertilizer usage. For SSNM, a variety of tools are available, including Crop Manager (CM), Nutrient Expert (NE) and Green Seeker.	Site-specific application of nitrogen, phosphorus and potassium and secondary and micronutrients based on soil tests are followed. Optimal use of existing nutrients, such as from soil, residues and manures.SSNM further provides guidelines for selection of the most economic combinations of nutrients (Hasanain et al., 2021).
Leaf colour chart (LCC)	In general, farmers use leaf colour to visually and subjectively assess the demand for N fertilizer. To better direct need-based fertilizer N applications, the spectral characteristics of leaves should be taken into consideration. No matter where the applied source of N comes from, it is the perfect instrument for optimizing N utilization (Kumar et al., 2018a, b). The leaf colour chart (LCC) is a high-quality plastic strip on which a number of panels with colours based on the wavelength properties of leaves are inserted (Gudadhe & Thanki, 2021).	Real-time corrective N management can be done based on periodic assessment of plant N status through LCC (Ahirwar & Jatav, 2021).
Soil health card (SHC)	The soil health card is a simple document, which contains useful data on soil-based chemical analysis of the soil to describe soil health in term of its nutrient availability and its physical and chemical properties (Purakayastha et al., 2019). The soil health card (SHC) was developed from four physical parameters, eleven chemical parameters and three biological parameters.	This approach helps to improve the soil health and save costly chemical fertilizer and maintain environmental quality over excessive use of chemical fertilizer responsible for greenhouse gas emission (Patel et al., 2017).
Green manuring	Green manuring is the process of incorporating living, decomposing plant material into soil. Green manure crops increase soil organic matter. The soil's nitrogen supply may increase due to the addition (Das et al., 2020).	The major benefits to the use of green manures in a crop rotation system include organic matter and nitrogen addition, nutrient conservation and protection of the soil surface during erosion-prone periods of the year (Naidu et al., 2022).
Brown manuring	Brown manuring is a technique for cultivating Sesbania with direct seeded rice and killing it with a herbicide (Maitra & Zaman, 2017).	Brown manuring can conserve soil moisture and reduce runoff and wind erosion. Enhanced soil fertility, lesser weed competition.

Table 6 Research findings on nutrient-smart practices for CSA

Technology	Findings	References
Site-specific nutrient management (SSNM)	Using decision-support software, on-farm trials were carried out in the northern Philippines to characterize farmers' nutrient management (FP) practices in rainfed lowland environments and compare them to site-specific nutrient management guidelines (Rice crop manager; RCM) the total cost of fertilizer was comparable to or less in RCM than FP, thus increasing net revenue. The findings of this study demonstrated that site-specific nitrogen management enhanced lowland productivity and profitability.	Banayo et al. (2018)
Soil health card (SHC)	According to a study on the soil Health card scheme, farmers' net income increased for the three primary kharif crops of paddy, soybeans and maize in Madhya Pradesh following soil testing by the farmers. Following the farmers' use of RDF based on the soil health card, the BC ratio increased. Thus, the soil health card programme was proven to be quite advantageous for farmers in terms of raising their income.	Reddy (2019)
Leaf colour chart (LCC)	In the Madhya Pradesh area of Balaghat, a study was done to compare how farmers applied nitrogen fertilizer to how they applied nitrogen fertilizer based on the colour of the leaves. In comparison to farmers' practices, the N fertilizer application as seen in the leaf colour chart showed superior growth and yield features. The net income and benefit/cost ratio was recorded higher in N application as per LCC.	Ahirwar and Jatav (2021)
Green manuring	Rice yield and nutrient uptake in southern China are improved by combining rice straw with green manure, according to a study suggested that using rice straw and leguminous green manure in combination is a potential method to increase grain output in subtropical double-rice farming with fewer fertilizer inputs.	Yang et al. (2019)

6 Weather-Smart Practices

The agricultural environment in many developing countries has become more uncertain due to increased climate variability over the past four decades, increasing their exposure to risk when growing crops (Issahaku & Abdulai, 2020). The idea of 'weather-smart agriculture' has been introduced to address this. The components of weather-smart practices include real-time weather monitoring and reporting, weather-based crop advisory services, real-time crop insurance based on variation, climate awareness and climate-smart housing for livestock.

6.1 Agro-Advisory Services

Agro-advisory services have evolved as an efficient communication medium for the transfer of technology regarding information related to climate change. Agro-advisory services are able to provide up-to-date and accurate weather forecasts, in

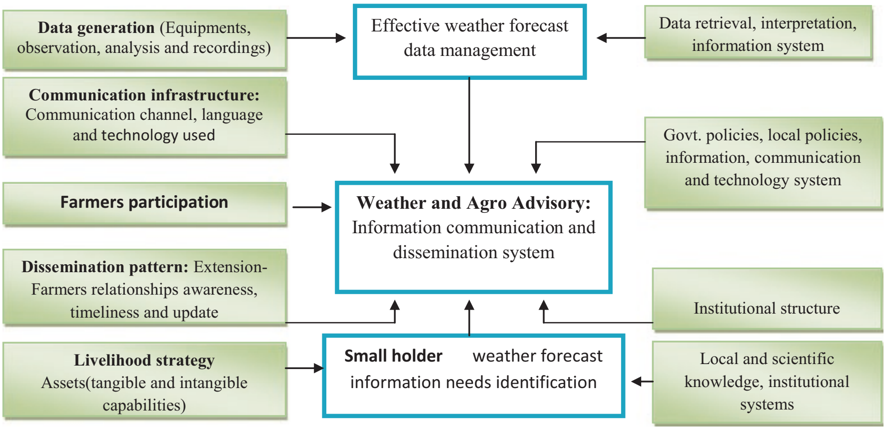

Fig. 5 Conceptual framework for enhancing the access to and utilization of agro-advisory services

addition to a variety of agricultural operations that need to be done for better crop growth and development (Ramachandrappa et al., 2018). In order to assist farmers in efficiently managing climate risks for sustainable and lucrative agricultural production, agro-advisory services (AAS) were established. The transmission of climate-smart agriculture (CSA) technologies, practices and services to rural farmers is increasingly being done through the use of information and communication technologies (ICTs), such as cell phones, televisions, radios and Internet services. Farmers can choose superior technologies, marketing strategies and in-season crop management decisions with the use of ICT-based climatic information and agro-advisory services (Fig. 5) (Gangopadhyay et al., 2019).

The role of ICTs goes beyond simply publishing CSA data; rather, it has decreased the costs of data collection, processing and decision-making while also spreading timely data that enables farmers to manage climate risks. In order to shape future initiatives for managing climate risks in agriculture, it is therefore helpful to determine where climate information services are needed and what ICT tool may be utilized to disseminate climate information-based agro-advisories.

6.2 *Climate-Smart Housing for Livestock*

Systems for efficient livestock production are hampered by the weather. The foundation for logical decision-making among available options to limit climatic stress in cattle has continued to advance, especially with the creation of basic functional correlations between animal performance and environmental variables (Fig. 6) (Thornton et al., 2009). Such correlations allow for the prediction of the decline in cattle performance under natural conditions or of the advantages to be gained from suggested housing or management measures when paired with

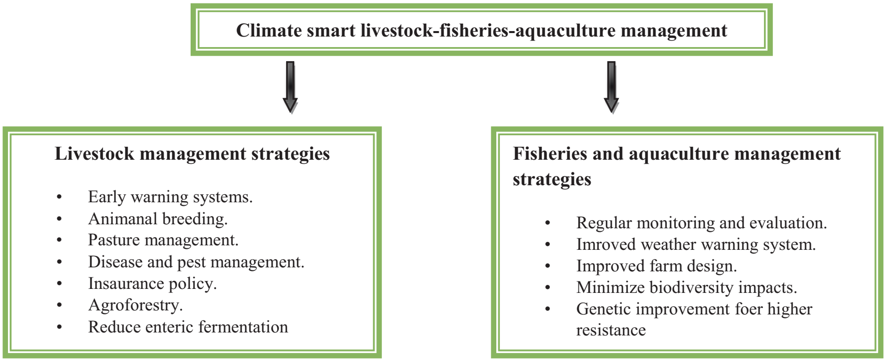

Fig. **6** Options for livestock-fisheries-aquaculture management practices

Table 7 Research findings on weather-smart practices for CSA

Technology	Findings	References
Weather-smart	According to a study on the importance of weather information given via smartphones, mobile phone weather information may assist close the knowledge gap among farmers and may even increase output and maximize the potential of this strategy.	Mittal and Hariharan (2018)
Weather-smart	The use of mobile phones to get weather information, listening to the radio or watching TV for weather information, getting education or training on how to get weather information, buying index-based insurance (IBI) to protect against weather events and getting weather information through localized information centres have all been shown to positively influence the adoption of CS weather mechanisms to reduce the effects of climate change in most agroecological systems.	Anuga et al. (2019)
Weather-smart	Farmers are naturally encouraged to apply weather-smart tactics when adopting pest-resistant crops, water management strategies and multiple cropping techniques. Utilizing weather-smart techniques boosts the utilization of multiple cropping techniques and water management methods by 6.8% and 5.6% respectively.	Djido et al. (2021)

probabilistic information of the weather parameters (Bett et al., 2017). When compared to the current broad generalizations used as guidelines, such knowledge gives livestock managers better bases for making sensible decisions about the housing or management of their animals, even with the imprecision still inherent in current models. Smart sensors, detectors, cameras and microphones, which are currently available, can help integrate management systems for animal husbandry that are based on continuous, real-time monitoring and control of production, animal welfare and health, as well as environmental conditions (Westhoek et al., 2011). These management systems allow farmers to instantly identify issues with air quality, illness or thermal stress and respond with prompt action (Weindl et al., 2015). Their decision-making will be further improved by the improvement of the current livestock response relationships and the creation of new models, which should be pursued as quickly as resources allow (Table 7).

7 Carbon-Smart Practices

A natural carbon storage system, soil may hold up to three times as much carbon as the atmosphere. A quarter of the carbon produced by humans during the Industrial Revolution, or more than 130 billion tonnes, is thought to have been lost from soils globally (Maraseni et al., 2021). Photosynthesis and soil respiration govern terrestrial carbon balance and agricultural carbon budgeting (Fig. 7). The difference between gross primary production (GPP) and ecosystem respiration (RE) is the net ecosystem carbon dioxide exchange (Bai et al., 2019). Gross primary production shows that all photosynthetic assimilation occurs, in contrast to RE, which shows the respiratory CO_2 fluxes from autotrophic roots, the rhizosphere, the soil and the microbial fauna (heterotrophs).

As part of the climate solution, carbon-smart farming provides a better method of land management (Kichamu-Wachira et al., 2021). By using the proper management techniques, we may enhance the quantity of carbon stored in our soils. It has been demonstrated that reducing tillage, growing cover crops and adding organic matter amendments like compost can improve the amount of carbon sequestered in the soil. Additionally, soil carbon serves as a resource for guaranteeing food security. Farmers can take advantage of the carbon contained in soil organic matter, which is the portion of the soil made up of anything that once existed, including decayed plant and animal stuff. Organic matter in the soil increases agriculture

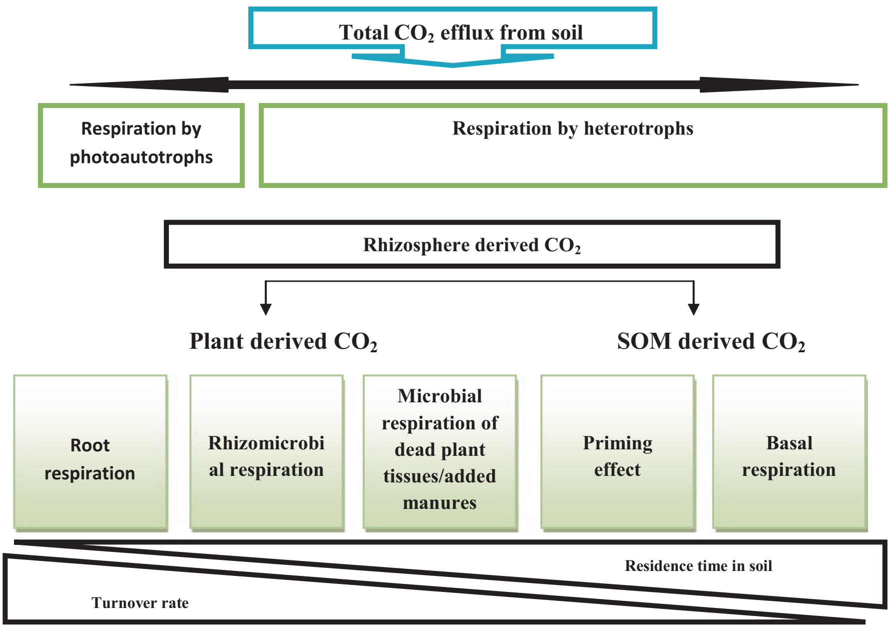

Fig. 7 The CO_2 flux partitioning in soil plant system

Table 8 Carbon-smart practices for CSA

Mitigation narratives	Conventional agriculture	CSA
Soil organic carbon (SOC)	Results in the burning of crop residues and the use of fossil fuel-intensive inputs like mechanized ploughs, which erode soil organic carbon (C) stores. Use of chemical fertilizers has increased. And higher use of chemical fertilizers.	Promotes C sequestration and storage, prevents soil erosion and maintains cover crops, especially when done with trees. Encourages the recycling of trash and organic wastes, which reduces the need for outside inputs like inorganic fertilizer.
Agroforestry (carbon stock changes)	For new agricultural lands and farm expansions, forests are removed or degraded.	Increases the number of trees, which aids in expansion, encouraging soil carbon as well as above- and below-ground biomass. By increased output and better practices, lessens the destruction of the forest.
Livestock enteric emissions (LEM)	Intensive systems yield less livestock. Poor management practices, such as an insufficient diet and a diet of poor quality, raise CH_4.	The intensification of livestock production is frequently linked to mitigation methods. Reducing grazing time, adding more concentrated (less fibrous) feed to the diet and fertilizing grasslands to boost pasture productivity are all methods for lowering emissions.
Livestock manure management (LMM)	Low manure management; illegal disposal; lack of a surface crust; liquid manure discharged into the environment; lack of collection at one location; and excessive anaerobic conditions.	Composting, better manure handling and storage and application methods (such as covering manure heaps) (e.g. rapid incorporation). Biogas is one alternative use for manure that can lower greenhouse gas emissions.
Fertilization	Synthetic fertilizers can boost soil fertility but have negative effects on water quality, over time lower soil fertility, deteriorate soil texture and make soil more prone to erosion. Increased nitrogen fertilization of soils results in greater N_2O emission.	Organic fertilizers strengthen and sustain productive soils, encourage plant development and increase soil fertility without harming the environment.

productivity, controls erosion and strengthens the soil, all of which improve the quality of both surface and groundwater (Table 8). All of this lessens the adverse effects of climate change on the ecosystem as a whole (Khanal & Mandal, 2019). Carbon- and energy-smart technologies' main goal is to lower GHG emissions, which will help to slow down climate change. Agroforestry, integrated pest management (IPM), conservation agriculture (CA), resource conservation technologies (RCTs) and conservation agriculture (RCTs) are a few examples of 'carbon/energy-smart' agricultural methods (Bhattacharyya et al., 2020).

Based on the area and the crops/livestock employed, these strategies aid in carbon sequestration and lower CO_2, CH_4 and N_2O emissions by 15–25%. Global greenhouse gas emissions could perhaps be stored by soil carbon sequestration (Daniels,

Table 9 Research findings on carbon-smart practices for CSA

Technology	Findings	References
Carbon-smart practices	Climate-smart agriculture (CSA) management practices like conservation tillage, cover crops and biochar applications have been widely implemented to boost soil organic carbon (SOC) absorption and minimize greenhouse gas emissions while sustaining the crop productivity.	Bai et al. (2019)
	Zero-till, crop establishment, crop residue management and crop diversification can boost rice–wheat system production by improving SOC and soil biological quality over time.	Jat et al. (2019)
	Crop output and SOC concentrations dramatically increased with the adoption of CSA techniques. SOC was raised by 16.4% and 13% respectively, via conservation tillage and crop residue (CR). Under lower nitrogen fertilizer levels, it was proposed that CSA technique integration (conservation tillage and GM; conservation tillage and CR) had a more noticeable impact on both SOC concentration and production.	Kichamu-Wachira et al. (2021)
	Climate-wise farming approaches were shown to have greater soil carbon levels (0.19% compared to 0.13%) when compared to traditional practices, improving soil quality through the enrichment of organic carbon and lowering greenhouse gas emissions.	Datta and Behera (2022)
	Biochar had the biggest influence on SOC stocks on agricultural fields (25.38%) in tropical and subtropical climates, followed by conservation tillage (18.81%) and cover crop (15.8%).	Das et al. (2022)

2022). Even though there is a limit to how much carbon can be stored in soils, soil organic carbon will not increase until saturation is reached. Better land management could significantly boost croplands' capacity to store carbon. Furthermore, because underground carbon is probably better able to survive the effects of natural forces like fire and wind, it may be more durable than carbon stored in aboveground biomass like trees (Watts, 2013). In the end, there is broad agreement that carbon-wise farming has the ability to enhance soil health and to somewhat mitigate climate change. Because carbon-smart farming has numerous advantages, is relatively simple to implement and can effectively include the agriculture sector in climate solutions, more governments and organizations are becoming interested in using soil organic carbon as a natural climate solution (Toensmeier, 2016). However, additional study will be required before scientists can fully trust carbon-smart farming's ability to combat climate change (Table 9).

8 **Smart Crop** Management **Practices**

Due to its high reliance on weather variability and the fact that it is practised primarily (>70%) by small and marginal (resource-poor) farmers worldwide, agriculture is vulnerable to the effects of climate change (irregular rainfall, drought, floods, cyclones, heat waves, fluctuation of the monsoon, cold wave, hailstorm etc. (Fig. 8) (Rao et al., 2016).

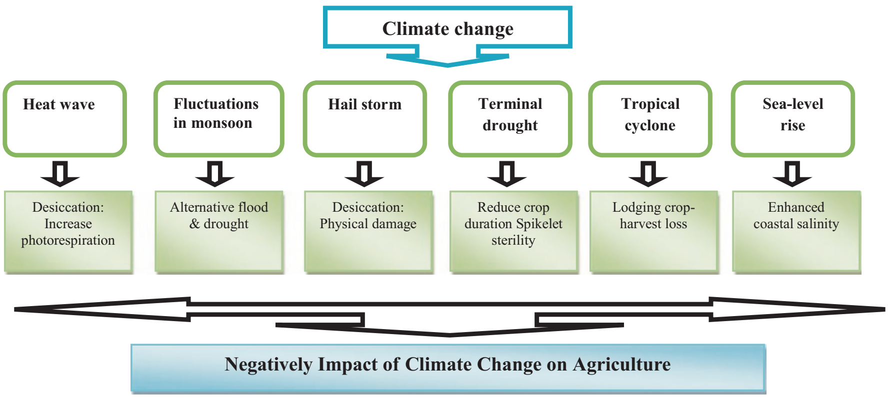

Fig. 8 Climatic aberration and potential negative impact of climate change on crops

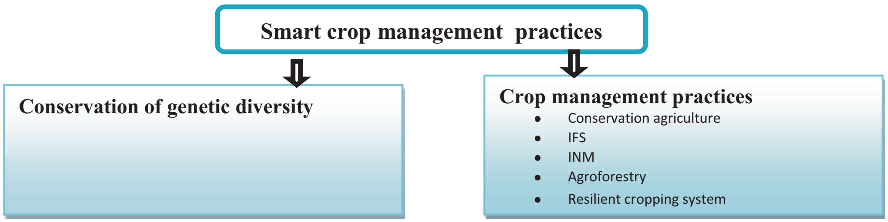

Fig. 9 Components of crop management smart practices

Any of the crop management strategies that have been employed and promoted for sustainable agricultural objectives are also appropriate for CSA. By increasing input utilization efficiency, minimizing harm to natural resources, protecting soil health and fostering ecosystem services, crop management maintains higher agricultural output (Fig. 9 and Table 10) (Lal, 2015). Important elements of climate-smart agricultural management include the preservation of plant genetic diversity and the production of diverse crop varieties in rotations or sequences with a variety of plant species. Effective water management and integrated nutrient (fertilizers, manures, soil amendments and crop wastes) and pest management are crucial elements of CSA (insects, diseases and weeds).

9 Institute and Knowledge-Smart Practices for CSA

Making agricultural ‘knowledge smart’ requires the institutionalization of technology distribution and maintenance systems as well as a strong knowledge foundation (a synthesis of traditional and modern scientific knowledge). The delivery method for technological innovation, however, needs to be institutionalized by CSA. We

Table 10 Components of crop management smart practices for CSA

Components of crop management practices	Description
Conservation of genetic diversity	In addition to being crucial for agriculture and agricultural production, maintaining biodiversity is also important for meeting the diverse demands of the community as a whole. It improves the agro-resilience ecosystems, lowers the vulnerability of farmers to the risks associated with climate change and is the primary regulator of how well agro-ecosystems function (McDonald et al., 2018)
Conservation agriculture	Three essential components of conservation agriculture are crop variety, residue retention and reduced tillage (CA). Being 'climate-smart', by providing sufficient nutrients and water and facilitating the use of high-yielding varieties, it ensures sustainable crop yield. Adding residue to the field (organic matter/carbon addition) gradually improves the soil's carbon and nutrient status, reducing the need for fertilizer and lowering GHG emissions (Bhattacharyya et al., 2019).
Integrated farming system (IFS)	The IFS combined site-specific crop+animal components to minimize system risk, boost productivity, utilize fewer inputs, recycle bioresources and consume less crop residue (Kumar et al., 2018a, b).
Integrated nutrient management (INM)	By matching crop needs with the amount of nutrients in the soil, nutrient losses can be reduced. The three main pillars of INM are (i) making the best use of available nutrient sources to keep soil healthy; (ii) matching soil nutrient supply with crop demand in real time to maximize crop production and (iii) improving NUE and lowering pollution (Wu & Ma, 2015).
Agroforestry	The planned integration of crops, trees and bushes into agricultural systems is a prime example of 'climate-smart agriculture' (CSA). In addition to preventing soil erosion and supporting soil aggregation, it also reduces the negative effects of climate change (Blaser et al., 2018). It meets all three CSA criteria, which are to keep food secure, make systems more resilient and slow climate change.
Resilient cropping system	Resilient cropping systems promote food security and resilience to global warming and climate extremes.
Approaches based on site-specific agro-ecosystems and stress-tolerant cultivars	The main criterion for selecting the crop types to be cultivated and the cropping system are traditional and stress-tolerant cultivars with the minimal input need. Ecosystem resilience and farmer practices for adaptability are given more importance.

commonly talk about how organizations may promote new technology to increase adoption (Prasad et al., 2015). A few of these include village-climate-risk management committee (VCRMC), the community-based seed and fodder bank, the participatory community nursery for rice, the CHC and the transparent custom hiring centre for farm machinery (Fig. 10).

Examples of the typical 'knowledge-smart' CSA include gender equality, ICTs, farm youth capacity building and farmers through an awareness campaign and on-site training. Mobile apps for controlling nutrients, pests and illnesses are gaining popularity due to their smart recommendations in the local language. It appeals to

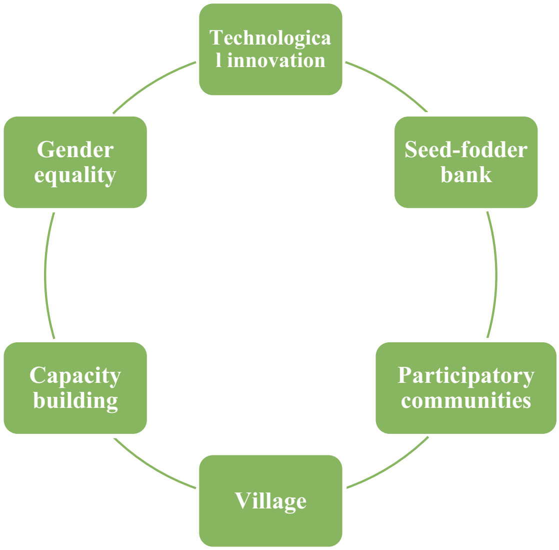

Fig. 10 Components of institute and knowledge-smart practices for CSA

young people interested in agriculture and makes the system visible, enabling quick, affordable solutions in real time. Social issues and gender equality play a similar role in CSA, as they do in other strategies for promoting higher adaptation. Women farmers are an important component of CSA because they form the backbone of farming and the rural economy (approximately 43–45% of farm labour). CSA ought to be ‘gender wise’ as a result. The CSA policy needs to give women the chance to develop their skills, share resources fairly, access credit, get better at communicating and take part in conversations about climate change, food security and resilience. The creation of women’s self-help groups (SHG), the growth of leadership and adequate training are the three key pillars of ‘knowledge-smart’ CSA.

10 Weeds-Smart Practices

Weeds have a negative impact on crop productivity and the effective use of resources (light, water and nutrients). Crop yield is adversely affected by weed infestation. Infestation of weeds may result in a yield reduction of up to 100%. Globally, weeds are responsible for 40% of crop losses, which is more than the combined effects of diseases, insects and pests. Geographic range expansions (migration or introduction to new areas), changes in species life cycles and population dynamics may all be ways that climate change will affect weedy vegetation. In response to climate change, changes in weed biology, ecology and interference potential will lead to complicated interactions between crops and weeds that need for different adaptation mechanisms (Fig. 11).

Crop management practices affect weed density, diversity and composition, which may offer weed management options. In CSA-based weed management,

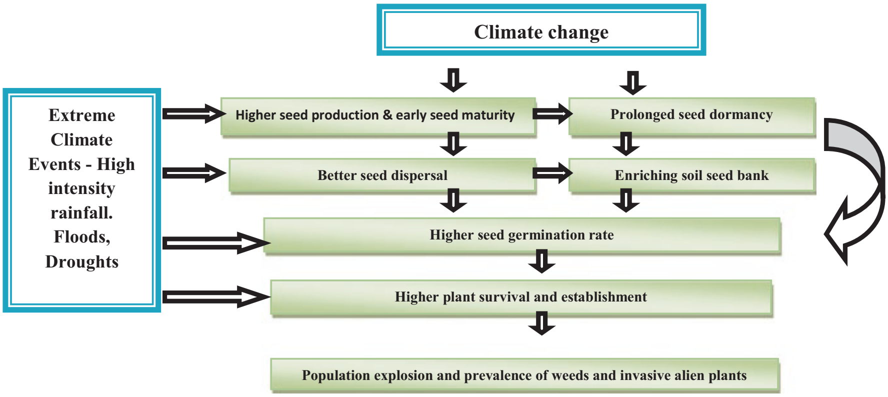

Fig. 11 Effect of climate change on weed dynamics

indicators include tillage, crop establishment, crop residue retention, crop diversity and precise water and fertilizer management. ICTs are also used to ensure that crop activities are implemented on schedule. Due to decreased sunshine and moisture at the soil surface, maintaining soil mulch throughout the year (crop residue retention) and layering it with precise water distribution by subsurface drip irrigation (SDI) assist in increasing weed predation and reducing weed seed germination. In addition to the SDI system's well-known advantages, which include decreasing soil evaporation, effective water and fertilizer administration and use and decreased labour costs, the SDI system also deters weed germination and growth (Fig. 12).

For integrated weed management in wheat-based agricultural systems, research on the evaluation of weed community reactions to CSA is insufficiently known. Understanding changes in plant community diversity and composition requires CSA-based approaches, which may also provide insight on long-term effects and the best ecological indicators (or 'weed species') for various management techniques. Under diverse cropping systems, these CSA management scenarios (layering of multiple indicators/practices) could lower weed diversity, composition and density indices without having a negative effect on crop performance (Table 11).

11 Conclusion

Climate change affects agricultural production and food systems, which impacts global food security and poverty reduction strategies. To achieve scale and rate of change, an integrated, evidence-based and transformative approach to food and climate security at all scales requires coordinated actions from the global to local levels, from research to policies and investments and across the private, public and civil society sectors. With the right practices, laws and investments, the agriculture sector may shift to CSA pathways, reducing food insecurity and poverty in the short term and climate change's long-term threat to food security.

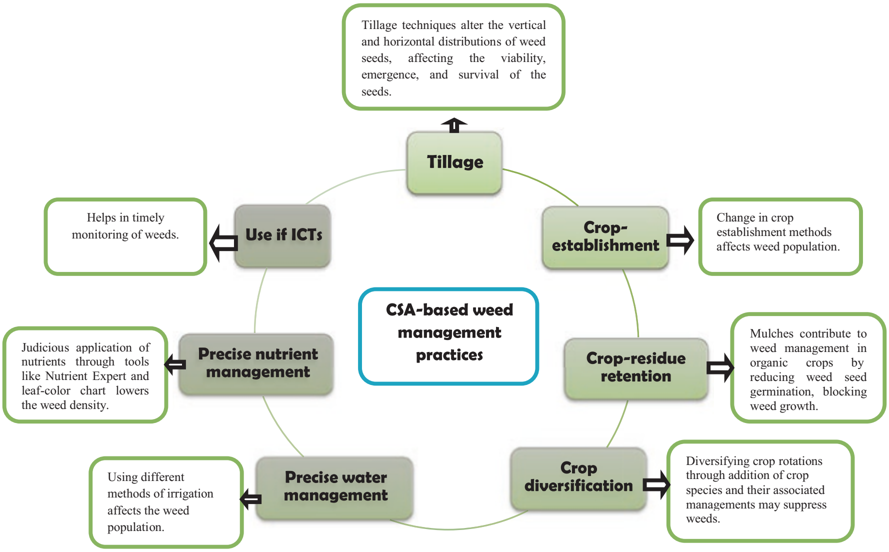

Fig. 12 CSA-based weed management practices

Table 11 Research findings on weed-smart practices for CSA

Technology	Findings	References
Weed-smart practices	Using climate-smart farming techniques affects weed density. Long-term effects of CSAPs were more noticeable since they repressed these species and benefited *Solanum nigrum* and *Rumex dentatus*. In Northwest India, a CSA-based maize–wheat system could control weeds better than rice.	Jat et al. (2021)
	A study on smart weed management revealed that using it can increase farmers' incomes, decrease weed-related losses, lower cultivation costs and improve nutrient use.	Yaduraju and Mishra (2018)
	WSNs, IoT sensors, UAS, optimization methods and machine learning algorithms can improve precision farming by maximizing crop potential. These important new technologies have the potential to greatly advance weed control, agricultural output and quality.	Boursianis et al. (2022)

12 Future Prospects for Climate-Smart Practices

Market disruptions caused by climate change put the availability of food at risk for the entire population. It will be difficult to feed the approximately nine million people on the planet by the year 2050 if only 60% additional food is produced. The challenges are made more severe by the threat of climate change and the tightening constraints on the resources available to the agriculture sector. The quantification of agricultural productivity can always be improved in the realm of agriculture. The management of natural resources is still not well understood at the field or farm level, and this knowledge is critically important to enhance the productivity and food security estimates. This is crucial since both resources are scarce, and the strain on land and water resources will only intensify as a result of rising population and climate change. Implementing a longer-term strategy of climate-smart farming practices appears to be a realistic alternative in such circumstances. Across all CSA pillars, more work is needed to integrate theoretical and empirical approaches. This involves integrating analyses of household survey data with models of production and food security, field-based GHG monitoring with biogeochemical models, mapping of susceptible zones and the danger of climate hazards, changes in sociocultural and political outlooks and more. These effects may significantly affect smallholder farmers' means of subsistence. In order to jointly address the problems of climate change and food security, 'technology innovation',' 'investment' and 'site-specific action' must be encouraged.

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Strategic Intervention for Climate-Smart Agriculture

Michael Sakha and Joseph P. Gweyi-Onyango

1 Introduction

Agroecology is defined variously as a science, as practices, and as a movement, depending on the country and organization that embraces this vision (Wezel et al., 2009). As a set of agricultural practices, agroecology seeks ways to improve agricultural systems by harnessing natural processes, creating beneficial biological interactions and synergies amongst the components of agroecosystems (Gliessman, 1990), minimizing synthetic and toxic external inputs and using ecological processes and ecosystem services for the development and implementation of agricultural practices (IRRI, 1990; Mishra, 2009; Pitiwut, 2014; Wezel et al., 2014). Generally, agroecological practices are seen as new, modified or adapted practices or techniques that contribute to a more environmentally friendly, ecological, organic or alternative agriculture, and they are used to improve traditional or indigenous agriculture in developing countries (Wezel et al., 2009).

These practices are so important and have been packaged to offer solutions required to transform food systems (IPES-Food, 2016; HLPE, 2019) and to boost the resilience of livelihoods and landscapes in the face of the global climate change (Sinclair & Coe, 2019). This is perhaps upon realization as a fact that at the beginning of the twenty-first century, regions specifically in the developing world, characterized by traditional agriculture, have remained poorly served by the top-down transfer of technologies, due to its bias in favor of modern scientific knowledge that neglects local participation and traditional knowledge (Altieri, 2002). Moreover, not only were the modern technologies inappropriate for poor peasant farmers, but coincidentally they were excluded from access to credit, information, technical support, and other services that would have helped them adopt and use these new technologies if they so desired (Pingali et al., 1997). It is against this backdrop that

M. Sakha (✉) · J. P. Gweyi-Onyango
Department of Agricultural Science and Technology, Kenyatta University, Nairobi, Kenya

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agroecology is being championed since it has become a third-way model of addressing the trade-offs between food security and other ecosystem services and has raised interest globally among governments, development agencies, scientists, and farmers (HLPE, 2019; WWF, 2020).

Rice (*Oryza sativa* L.) is a staple food crop for more than 50% of the world's population (Atera et al., 2018), with ~50% of them depending on it as their major source of caloric intake (Zhu et al., 2018). Worldwide it is estimated that about 160 million ha of land are under rice cultivation, and this accounts for about 500 million metric tons (Kirby et al., 2017). However, the effects of climate change are exposing rice production systems to a range of stressors and shocks including drought, increased pests and diseases and heightened vulnerability to damage from frequent extreme weather events (McNally, 2022). These impacts by 2050 are estimated to cause increase in the average rice prices by 32–37%, on the other hand reducing yields by up to 10–15% (IRRI, 2014). Therefore, to meet growing global food demand, Alexandratos and Bruinsma (2012) stated that rice yields should be increased by ~28% in the next three decades.

In sub-Saharan Africa, concerted effort should be made to increase rice productivity within the existing schemes rather than expanding irrigated areas due to limited arable land, low usage of efficient production practices, and water scarcity (IPCC, 2007). In this scenario, there is an urgent need to pick out agroecological practices that have the capacity of increasing rice production, conserve the environment, and reduce greenhouse gas emissions. In spite of the advantages offered by various agroecological typologies based on agroecology principles, few publications offer a general overview of the existing typologies in rice production. Here, we give a detailed account of how various agroecological typologies have been exploited for rice production successfully. This will enable rice producers to reshape their rice production systems to help in addressing the critical issues of economic, social, and environmental sustainability. Further, this chapter is intended to stimulate knowledge co-creation and broader thinking on how to adopt these typologies for sustainable rice production across the globe.

1.1 Agroecological Typologies in Rice Production

1.1.1 Integrated Rice–Animal Farming

1.1.1.1 Integrated Rice–Duck Farming System

The integrated rice and duck farming system (IRDFS) concept was brought to the fore in Mekong Delta by farmers, and the practice has been going on for many years. This system fits within the agroecology principles such as synergies, input reduction, economic diversification and soil health. The system initially involved allowing the ducks (*Anas platyrhynchos*) into the paddies after rice harvesting to eat residues. Fast forward, in the early 1990s, Mr. Takao Furuno, a farmer from Japan took up this Asian technology, systematized it and coined a method known as "rice–duck farming." In the method, rice grows in concurrent with rearing of ducks in the paddies as shown in Fig. 1.

In Japan, nongovernmental organizations (NGOs), such as Commune Development Committee (CDC), come through to support the community of place by establishing "duck banks." Then farmers receive technical training, and individual smallholder farmers borrow 25 ducklings per 1000 m^2 of land to apply rice–duck farming. After training, the farmers sow rice, and exactly after 14 days, when rice has developed strong roots, the ducklings are allowed into the field for rearing until the rice reaches the flowering stage. These ducks are later transferred to be raised in huts for another 21 days before being sold, such that the target customers are the locals. After rice production for one season, the farmers return their initial loan to the bank to keep the fund sustainable.

The practice has spread to other areas, and as stated by Mayu (2016), this technology was introduced by a Japanese NGO to Vietnamese farmers in Hai Phong City, Hanoi, and the provinces of Bac Can, HoaBinh, Son La, Thua Thien Hue, Dong Thap, and Ben Tre in 1994. In Bangladesh an experiment showed that rice yields increased by an average of 20%. Furthermore, duck eggs and meat not only increased food for farmers, but also provided them with cash (Khan et al., 2005). In India, Mishra (2016) stated that an optimum population of 200–300 ducks/hectare of paddy field is recommended to obtain a good harvest for both rice and duck. However, this number can be adjusted based on the available feed sources (weeds, insect and snails) in paddy fields. Other considerations in this system are as follows: (i) ducklings are introduced into the paddies at 3–4 weeks of age after the transplanted seedlings have rooted, and point to note, before introduction the ducklings

Fig. 1 Rice duck farming in Nepal

must be trained to get into the habit of flocking and oiling their feathers; (ii) a protective fence is required to protect ducks from predators such as dogs, wild cats and foxes and also to prevent the ducklings from escaping; and (iii) the water in the paddies should be kept at a level in which ducks can both swim and walk.

The benefits of this system range from the diversified field since rice and duck grow together. In this period, the ducklings feed on insects and weeds in the paddies. Hossain et al. (2005) found that insect infestation results in Barisal showed that the insects' populations of brown plant hopper, zigzag leaf hopper, green leafhopper, rice bug, short-horned grasshopper, and long-horned grasshopper significantly reduced in rice–duck plots compared to farmers' plots without ducks. Furthermore, this study revealed significantly lower number of weed counts per m^2 of land in the rice–duck plots as compared to the farmers' sole–rice plots. This finding corroborates with those reported by Isobe et al. (1998), Kim et al. (1994), and Choi et al. (1996). Besides Singh et al. (2021) results underscore a definite decrease in weed and insect counts over control with weed control efficiency as high as 85.5% and insect pest control efficiency of 74.50% over control. In addition, in Japan, Furuno (1996) and Manda (1992) reported that total number of weed biomass was higher in plots controlled with agrochemicals compared to rice–duck cultivation plots. This means that farmers can avoid the application of herbicides and pesticides and have to do less manual weeding in paddies. Over and above, Zhong et al. (2011) in South China divulged that the rice–duck integration system was favorable in maintenance of arthropod diversity in the paddies. In IRDFS, ducks remain active in the paddy field, and the intertillage effect is obvious as illustrated in Fig. 2.

Rearing of ducks also leads to the loosening of paddy soil, promotion of gaseous exchange, improves soil permeability, and improves the organic carbon, total nitrogen (N), and available N levels in the soil (Li et al., 2008). Previous researches have revealed that ducks' foraging and activities in paddies improve soil aeration conditions, texture and structure (Ebissa et al., 2018; Long et al., 2013). Further reports indicate that a duck can produce approximately 10 kg of excrement during the rice–duck cropping period, which equates to 47 g of nitrogen, 70 g of phosphorous (P), and 31 g of potassium (K), thus fertilizing the paddies (CANSA, 2022; Civilsdaily, 2022; Zhao et al., 2005). Hossain et al. (2005) showed that the results of soil analysis had 0.10% N, 15.8 ppm P, 0.32 meq/100 g K, 5.26 ppm Ca, and 29.65 meq/100 g S levels in the soils of the rice–duck plots were higher after cultivation than before cultivation. This is an indicator that the grazing of the ducks encourages to improve the soil's fertility, through their excreta. Besides, Furuno (1996) observed that ducks' movement and feeding activity in the rice–duck plots disturbed the soil, resulting in the improvement of the soil's physical property, hence, enhancing the rice root systems.

Generally, farmers purchase ducklings from the hatcheries, 3–4 weeks before the rice harvest, and in this system, the selected ducks include the native meat type, and crossbred local × exotic varieties. When the ducklings can consume whole rice grains, that is after 3 weeks of age, they are permitted to enter the newly harvested rice cropping fields. Here, they are allowed to forage the whole day on shellfishes,

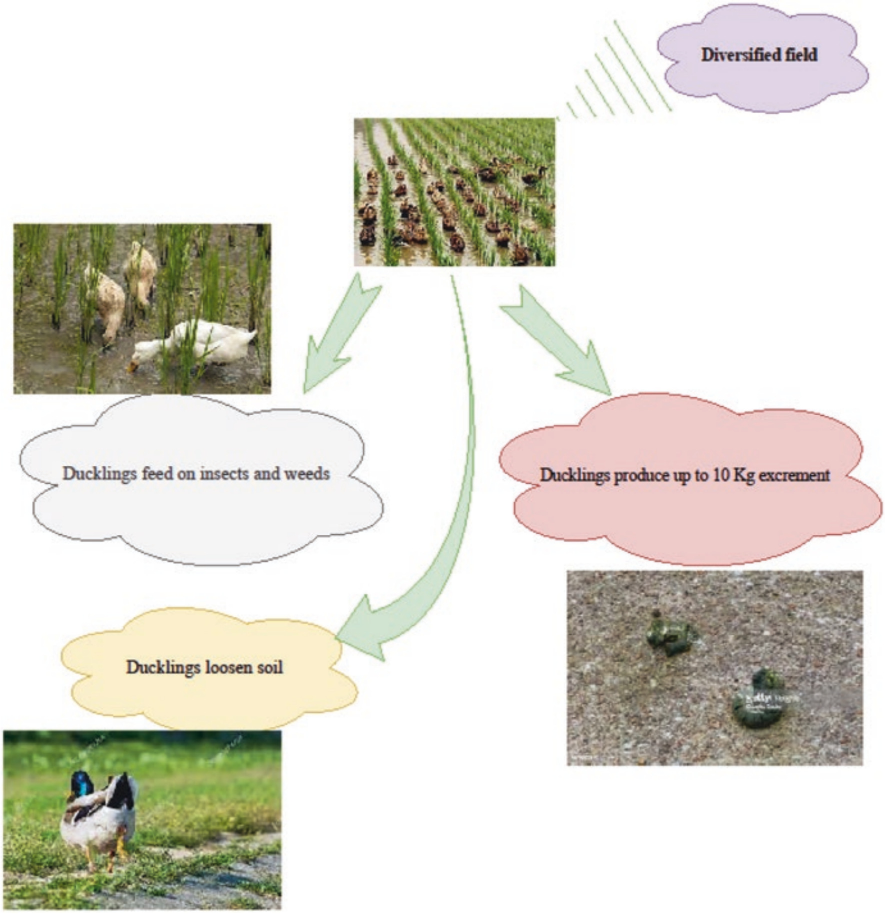

Fig. 2 Benefits of Integrated Rice–Duck Farming System

small-frog, fish, water plants, leftover or fallen rice grains, and insects (Mishra, 2016). In the late afternoon, the ducks are moved back to their pens or sheds near the household till next morning. The ducks raised in this system are usually ready at 2.5–3 months of age, when they achieve live weights of 1.6–2.0 kg, especially for crossbred varieties (Mishra, 2016).

1.1.1.2 Rice–Aquaculture Integrated System

The rice–aquaculture integrated system is not new and exists naturally and the natural ecosystem is in itself a big example of an integrated culture where several flora and fauna live in conjunction on the same piece of land (Reddy & Kishori, 2018). FAO (2014) noted that in this system, rice production takes place while allowing fish and other aquatic species that are harvested to coexist naturally, and/or introduced through cultured fish populations.

This farming model involves rice cultivation and rearing fish (the term "fish" in this book chapter refers to a wide range of aquatic animals notably carp, crab, crayfish or crawdad, soft-shelled turtles, and frogs) (Fernando, 1993) as shown in Fig. 3. Other aquatic species that can be incorporated into the system include eels, catfish, prawns, milkfish, mullets, cyprinids, and tilapias (Halwart & Gupta, 2004; Mishra & Mohanty, 2004; Frei & Becker, 2005; Hu et al., 2016), and mola (Karim et al., 2017). In this system, there is the interaction of different components as shown in Fig. 4.

The rice–fish farming model is an integrated agroecosystem practice, believed to be an effective method for increasing food production in fields through ecological agriculture (Jintong, 1996). This system fits within the agroecology principles namely synergies, input reduction, economic diversification and soil health, since rice and fish are habitually integrated within the same physical, temporal, and social space as shown in Fig. 5. However, it varies substantially among the types of "fish" being used. A scope of aquatic environmental conditions like, rainfed, irrigated, and deep-water rice fields provide opportunities for fish culture (Rothuis et al., 1998; Mohanty et al., 2009; Mishra et al., 2014). In China, this system has a long history of more than 1200 years and farmers have successfully been able to create a diverse range of cultivation patterns and techniques (Wang 1997; You, 2006). Over the years, this practice has dominated in many countries across Asia but it is still common in southeastern China (Halwart & Gupta, 2004).

The most predominant type of fish in use in this system is crayfish, which are raised in ditches dug around the rice cropping fields, during the rice-growing season (Sun et al., 2022). This system is part of the circular economy that improves economic efficiency and promotes the development of fish rearing, crawfish breeding,

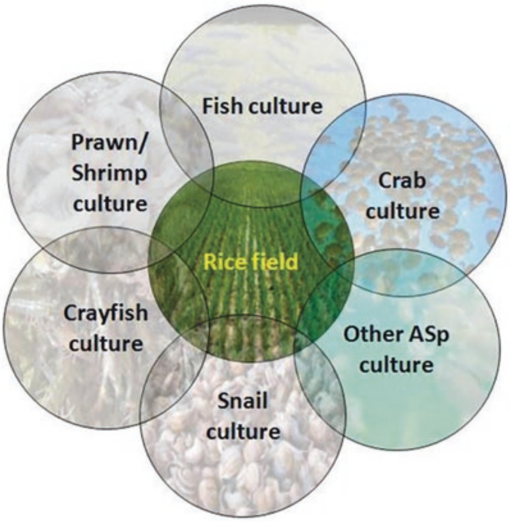

Fig. 3 Components of the rice–aquaculture integrated system

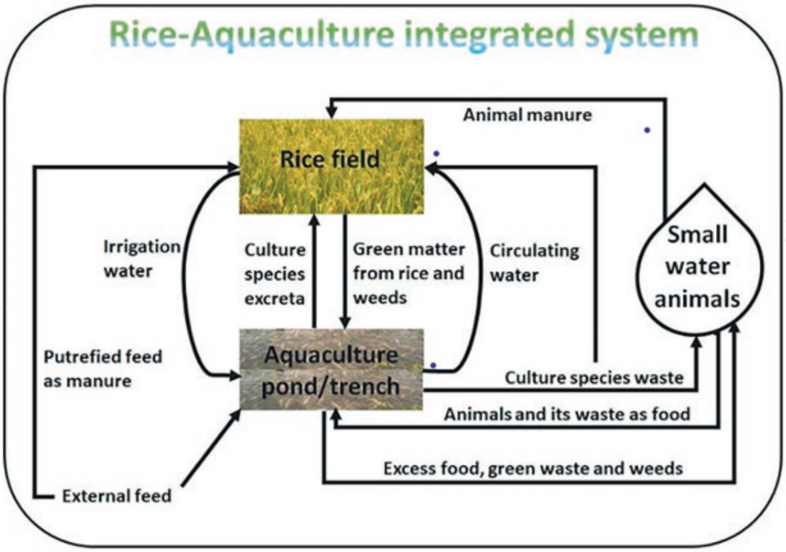

Fig. 4 Interplay of different components in integrated rice–aquaculture systems

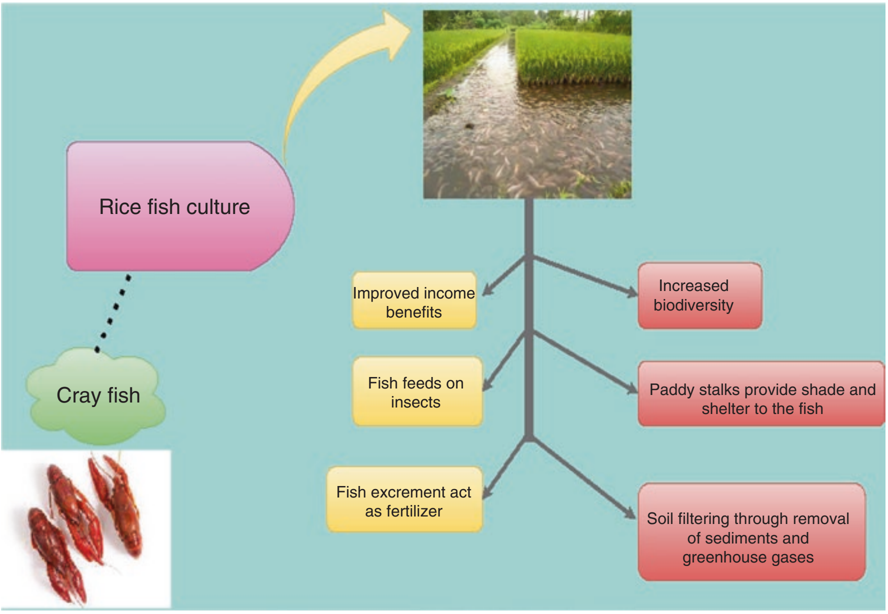

Fig. 5 Integrated rice field aquaculture

and rice farming. In this model, two categories of fish exit: (1) capture, and (2) culture (Ahmed et al., 2022). The capture system consists of wild fish that enters the rice ecosystems during downpour, while the culture system comprises of fish stock externally sourced by farmers. Rice–fish culture can again be categorized into (1) integrated, and (2) alternate (Ahmed et al., 2022).

The system is usually adopted individually by smallholder farmers as an ideal practice for land and natural resource utilization, as well as a source of rice grains and an easy source of cheap, fresh, and convenient animal protein (Fernando, 1993; Bashir et al., 2021). According to Ong (2021), the model is a multi-cropping technique that helps in achieving a symbiotic ecosystem and effectively improves utilization rate of rice cropping fields. Furthermore, the rice–crayfish system is characterized by improved income benefits (Hortle et al., 2008), socioeconomic and environmental sustainability, i.e. the rice stalks give shade and shelter to the fish, which improves their survival rate, and if upscaled in the current scenario of dwindling fish supply, it could help in increasing fish supply. It also generates more revenue per hectare than rice monoculture (Dwiyana & Mendoza, 2008).

Field experiments show that, compared with rice monoculture, the total output, profit, and ratio of output to input in the rice–crayfish model increased by 46,818.0 CNY ha^{-1}, 40,188.0 CNY ha^{-1} and 100.0%, respectively (Si et al., 2017). In China this system significantly increased farmers' income, in 2012 such that crayfish farming in paddies produced \$168.5 million, and in 2014, the revenue grew to \$172 million from 108.5 million pounds of Louisiana crawfish (Courville, 2016). Lin and Wu (2020) indicated that paddy yield in the rice–fish system was principally higher than yield in the rice monoculture by 6.8%. Therefore, this system besides the fact that it promotes sustainable agricultural and aquaculture development also reduces poverty (Tang et al., 2020). However, the yields rely on several factors, namely rice varieties, types of fish species, the prevailing environmental conditions of the surrounding area, cultivation duration, and management status (Datta et al., 1985).

On top of that, this system increases agrobiodiversity, which touches on variety and variability of animals, plants, and microorganisms on (FAO, 1998; Liu et al., 2013; Freed et al., 2020). Furthermore, the rice–fish farming model can be used to filter sediment and ammonia from the water, thus cleaning the water. Huang et al. (2019) report that this system helps in the reduction of the emission of N_2O and NH_3 gases. Concomitantly, crawfish feeds on insects in the paddies, reducing the need for overreliance on agrochemicals for rice production (Halwart, 1994; Cheng-Fang et al., 2008; Xie et al., 2011). The feces act as fertilizers to stimulate rice growth and thus decrease the usage of chemical fertilizers (Khoshnevisan et al., 2021). Xie et al. (2011) showed that the rice–fish system requires approximately 19% less nitrogen fertilizer than the rice cultivated under monoculture. In addition, the system improves soil quality (Yuan et al., 2020), enhances nitrogen use efficiency (Xie et al., 2011) and has been classified as a sustainable production system in several countries. Yuan et al. (2022) evaluated the relative economics of concurrent rice–wheat (RW), crayfish monoculture (CM), and rice–crayfish (RC) models in waterlogged land areas. The report stipulates that farmers use minimum nitrogen amount but have higher net income in the rice–crayfish model than in rice–wheat and crayfish monocultures. They also go further to state that it is necessary to sustainably develop integrated farming technologies such as proper field configurations and combination with other existing technologies in each agroecological living landscape context for rice production.

Research under this system has been done on various rice–animal typologies including rice–frog. In China, Lin and Wu (2020) performed a 9-year field experiment in which they compared the phosphorus fraction in soil and their relationship with rice yield in rice–frog–fish (RFF) cultures, rice–fish (RF) cultures, and rice-only (RO) cultures. The yields in the RFF and RF cultures were principally higher than those in the RO culture, by 22.1% and 6.8%, respectively. Soil total P ranged from 345.5 to 385.6 mg kg^{-1} among all the farming systems, with the smallest amount being recorded in the RO culture.

2 System of Rice Intensification (SRI)

System of rice intensification (SRI) was first synthesized in 1983 by Father Henri de Laulanié, a French Jesuit priest in Madagascar (Stoop et al., 2002). The drought conditions of that year made him carry transplant 15 days old immature seedlings. The yields were so high and this surprised everybody since the yields surpassed the expected yield. In subsequent years, reliable yields ranging from 7 to 15 t/ha were obtained by small-scale farmers in low-fertile soils, under reduced irrigation rates, and without an addition of any mineral fertilizers or other agricultural chemicals (Stoop et al., 2002). Later on in 1990, Laulanié and several of his close friends in Malagasy registered a local non-governmental organization, namely Association Tefy Saina, to promote SRI and rural development in Madagascar (Laulanié, 1993). According to Glover (2011), Mati (2010), Randriamiharisoa et al. (2006), Stoop et al. (2002), and Uphoff and Kassam (2009), the SRI involves a set of principles that can be related to some from agroecology such as input reduction. The principles are captured in Fig. 6.

1. Seedlings are transplanted at a very young age: ranging about 8–12 days old, but at most it should be 15 days old, instead of the usual transplanting age of 3–4 weeks or more.
2. Seedlings should not be densely planted. They should be raised in unflooded nurseries but be supplied well with organic matter. There is an option of direct seeding, although transplanting is the most common practice.
3. Seedlings should be transplanted quickly, carefully, and shallowly: making sure there is reduction in root disturbances and ensuring the roots are not inverted upwards at the tips since this delay’s resumption of normal growth.
4. Seedlings should be transplanted at a wider distance and singly (one seedling only per hole), instead of clumps of three to four seedlings per hole, and this should be done in a square pattern, usually 25 × 25 cm, giving the roots and leaves more space for growing.

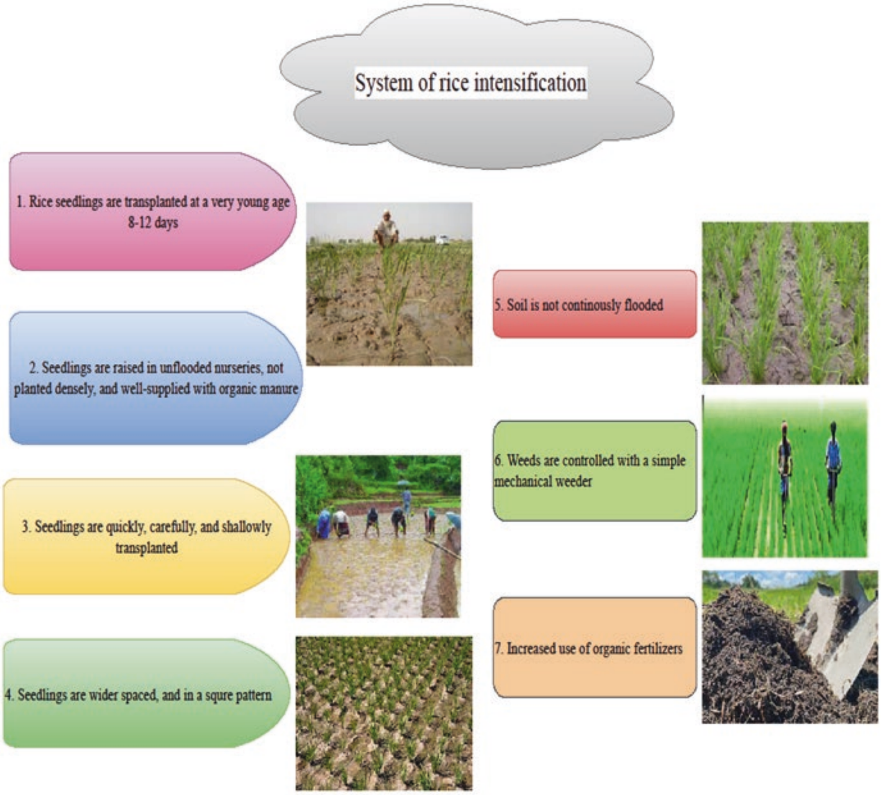

Fig. 6 The system of rice intensification

5. Continuous flooding of the soil should be avoided: Saturating the soil causes plant roots to degenerate and also suppresses soil organisms by denying them oxygen. The water can be applied in small amounts daily, to keep soil moist but not saturated, or alternatively to be flooded and then dried.
6. Weeds should be controlled with a simple mechanical hand weeder: This stimulates the soil aeration as the weeds are being eliminated. This gives promising results than either hand weeding or herbicides.
7. Increase the organic matter as possible in the soil: While chemical fertilizer gives positive results with SRI practices, the best yields come from manures or organic fertilizers. This is because they feed the soil, which feeds the plants.

All these practices focus on improving the rice productivity as shown in Fig. 7, through obtaining healthier, more productive plants in more fertile soil that supports greater root growth and nurturing the abundance and diversity of soil organisms (World Bank Institute, 2008; Stoop et al., 2002). Reports indicate that rice yield under the SRI increases even on poorest soils ranging from 50% to 100% while irrigation water is reduced by between 25% and 50% (Bera, 2009; Berkelaar, 2001;

Fig. 7 An illustration showing factors that explain the increased grain yield of rice plants grown under SRI management practices

Sarath & Thilak, 2004; World Bank Institute, 2008).Therefore, this system probably increases rice production at an affordable cost by smallholder farmers, as it also reduces the negative effect to the environment (Stoop et al., 2002; Mishra et al., 2007). Consequently, the SRI has spread widely, in more than 50 countries, and the system is being backed strongly by many international agencies such as Africare, OXFAM, WWF, and the World Bank. For example, in a recent large-scale project across multiple countries in West Africa, more than 50,000 farmers were inspired to apply the SRI in their farms (Styger & Traoré, 2018). The system is also broadly being promoted in several Asian countries by non-governmental and governmental organizations (European Technology Assessment Group, 2009).

In Kenya, the SRI was introduced as an on-farm trial during the August to December 2009 cropping season (Mati et al., 2011). Since then, several capacity-building forums have been carried out with farmers to get understand their interests and further popularize SRI. The forums included video conferencing, field days, classroom training, and workshops, to study tours and dissemination of training materials. Ndiiri et al. (2013) divulged that average yield under SRI management increased by up to 1.6 t/ha (33%), with seed requirements being reduced by 87% and, water being saved by 28%. However, on average, SRI required about 9% more labor than farmer practice (FP), although these factors of rice production manifest great variability; in three Mwea plots, labor costs were reduced by roughly 13%. Further, SRI required 30% more weeding labor than FP in the first season, but this was reduced to 15% in the second season when push-weeders became available. The results exhibit SRI as a system that gives a higher cost–benefit ratio of about 1.76 and 1.88 in the first and second seasons, respectively, compared to 1.3 and 1.35 for FP. In another study carried out in Mwea, about 71% yield increase in rice was obtained in SRI for three rice varieties (Nyamai et al., 2012).

Reports of studies carried out in many countries indicated higher yields with SRI as compared with the conventional method. In China, research by the National Hybrid Rice Research and Development Centre using the Super-I hybrid gave a record yield of 16 t/ha, which was equivalent to 35.6% higher than the 11.8 t/ha obtained under the conventional water-intensive method (Yuan, 2002). This underscores the far-reaching effects of the SRI on rice growth and yield.

3 Organic Manure

Organic manure as a source of plant nutrients varies greatly in all countries. In most-cases, the types of organic manure in use in a region are determined by crop residues available locally, except for commercial organic fertilizers. Different organic manures are used in rice cropping fields such as vermicompost, farmyard manure, green manure, and organic compost.

3.1 Vermicompost

Vermicomposting is an ecofriendly process that entails accelerated conversion of organic matter from waste materials into nutrient-rich humus through the interaction of microorganisms and earthworms (Mupambwa & Mnkeni, 2018). The final product of the vermicomposting process is a substance known as vermicompost or worm castings (Dominguez & Edwards, 2013). In this process, the microbes are involved in the biochemical degradation of the organic matter whilst earthworms are the important drivers that condition the substrate and alter the biological activity (Domínguez et al., 2002). In comparison with composting, vermicomposting results in the bioconversion of solid wastes into two useful products: the earthworm biomass and the vermicompost that exhibits lower mass in less processing time and greater organic fertilizer value with high humus percentage and less phytotoxicity (Garg & Gupta, 2009; Sim & Wu, 2010).

Vermicompost can be used successfully as a component of integrated nutrient management for paddies (Banik & Sharma, 2009; Bejbaruha et al., 2009). This is because it is an outstanding soil amendment that increases soil aeration, porosity, drainage, bulk density, water-holding capacity, and microbial activity of soil (Sharma & Mitra, 1990; Lim et al., 2014), and improves soil fertility in even in continuous cropping (Zhang et al., 2010). This nutrient-rich organic substance can be mixed with the soils to enhance soil organic matter content, available nutrients, and quality (Lazcano et al., 2011; Papathanasiou et al., 2012; Zhang et al., 2012). In accordance with Lim et al. (2014), vermicompost provides macroelements, such as nitrogen, phosphorus, potassium, calcium, and manganese and microelements, such as iron, zinc, and copper (Lim et al., 2014). Furthermore, studies suggest that vermicompost can help soil in retaining more moisture and thus aid in reducing the demand for irrigation by about 30–40% (Suhane, 2007; Suhane et al., 2008).

In rice productivity the use of vermicompost results in significantly higher yields than the use of chemicals (Rahman & Barmon, 2019). However, profitability gain is not significantly different mostly because of the high cost of vermicompost. In fragrant rice raising in the nursery, Ruan et al. (2021) reported that the application of vermicompost in comparison with the control increased the plant height, stem diameter, fresh weight, and dry weight of the seedlings by 11.22–24.73%, 38.34–65.87%, 16.74–30.46%, and 16.61–35.16%, respectively. In addition, raising seedlings with vermicompost significantly increases the net photosynthetic rate by 5.99–12.93% as compared with the control. Barmon and Tarafder (2019) stipulated that averagely sampled rice farmers who applied vermicompost used less proportion of inorganic fertilizers such as triple superphosphate, urea, gypsum, zinc, and manure except for muriate of potash. The yield of modern varieties (MV) of paddy showed that MV boro yield and the net profit per hectare was much higher (about 1.91 times) in farms that were applied with vermicompost compared to the controls. Additionally, the household income of the farmers who used vermicompost with irrigation rose significantly (about 1.19 times).

In an experimental study that encompassed three split applications of vermicompost targeting different rice growth stages (that is end of tillering, panicle initiation, and flowering), the results showed that split applications of vermicompost gave high yield parameters, namely panicles (294 m^{-2}), filled grains per panicle (138), and total spikelets per panicle (142), grain yield (3.91 t ha^{-1}), and NUE, but only when vermicompost was applied at two or three doses (Bejbaruah et al., 2013). Likewise, Dhanuja et al. (2020) in their mini-review assessed and summarized that 27 studies had been reported to use vermicompost. Half of these studies divulged that vermicompost emerged superior to all the other fertilizers tested.

3.2 Farmyard Manure

Farmyard manure (FYM) is an excellent organic source of nutrients that is widely accessible in most farms. It is a heterogeneous composted organic material consisting of dung, crop residue, and/or household wastes in various phases of decomposition (Motavalli et al., 1994). The manure nutritional richness depends on factors such as (a) the nutritional value of animal feeds, especially feeds rich in protein and minerals produce rich dung and (b) the amount of straw used: high straw content results in slow manure decomposition (Lockhart & Wiseman, 2012). When applied, FYM increases the soil organic carbon levels (Chettri et al., 2003), and it enhances soil nutrient availability, either directly by acting as a nutrient source or indirectly through improvement of soil physical properties (Palm et al., 1997). Averagely, well-composted FYM holds approximately 0.5–1.0% N, 0.15–0.20% P_2O_5, and 0.5–0.6% K_2O, and the desired carbon/nitrogen (C:N) ratio of FYM is about 15–20:1. In addition to NPK, FYM may contain about 1–500 ppm Fe, 7 ppm Mn, 5 ppm B, 20 ppm Mo, 10 ppm Co, 2–800 ppm Al, 12 ppm Cr and up to 120 ppm lead (Pb) (Tennakoon & Bandara, 2010).

Reports also indicate that FYM supports rice production in various agroecological zones worldwide. Andriamananjara et al. (2016) aforementioned that the positive effects of FYM on P uptake were correlated with its P application to irrigated rice soils. Andriamananjara et al. (2018) speculated that FYM alleviated moisture stress or aluminium toxicity. Moreover, rice straw compost or FYM was reported to be effective in reducing methane gas emissions from the rice field, with the co-benefits of improved soil fertility and crop productivity. Asai et al. (2021) concluded that FYM application was effective in soils with low P at high altitudes and acts as an alternative to mineral P fertilizer. Furthermore, Rakotoson and Tsujimoto (2020) reported that the effect of FYM application on biomass and phosphorus uptake in rice per P applied was nearly equivalent to that of mineral P and was greater in soils with lower total carbon and pH. Isotope tracing of P in rice suggested that the FYM application could increase rice P uptake by solubilizing nonlabile P pools in soils while mineral P could be directly utilized by rice from labile P pools. Furthermore, Satyanarayana et al.'s (2002) results exhibited that the application of FYM manure at 10 t/ha increased rice grain yield by up to 25% compared to the control. Similar observations were also made on straw yield, number of tiller, filled grains per panicle, and 1000-grain weight. Besides, Saidia and Mrema (2017) found that the application of FYM manure increased upland rice yields from 1.35 to 3.31 t/ha.

3.3 Green Manure/Cover Cropping System

The term "green manure" corresponds to legume crop residue with low C:N ratio that can provide substantial amount of nitrogen (N) to the following crop (Ojiem et al., 2006). Thus, green manure is used as an efficient source of nutrients in agrarian systems worldwide (Herrera et al., 1997; Mangalassery et al., 2019). In this system, the leguminous crops are grown as cover crops and then slashed and left on the soil surface to decompose and increase soil organic matter. To this end, green manure enhances agriculture sustainability, thanks to its ability of recycling of nutrients that would need otherwise to be provided by mineral fertilizers (Ranaivoson et al., 2022).

Some common green manures for rice are sun hemp, *Sesbania* and wild indigo (*Indigofera tinctoria*), and *Azolla*. Green manuring with annual leguminous crops like *Sesbania aculeata* is a widely investigated practice and is found beneficial not only for realizing potential yields but also for N economy and improving soil fertility (Singh et al., 1991). In the Philippines, green manuring research showed that *Sesbania*, when plowed at 50–60 days, can add up to 150 kg N/ha to the soil (Morris et al., 1989; Meelu & Morris, 1986), even under flooded conditions because of its ability to fix nitrogen with stem nodules (Dreyfus & Dommergues, 1981; Saint Macary et al., 1985). *Sesbania* is characterized by rapid growth and waterlogging tolerance traits that enables it to grow in the early wet season before sufficient water accumulates to transplant rice.

Azolla or duckweed fern is a common green manure used in rice production globally. It is an aquatic fern that is free-floating and rapidly raises its biomass over

3–5 days, fixing atmospheric nitrogen by establishing a symbiotic relationship with cyanobacterium *Anabaena azollae* (Carrapico, 2002). It is regarded as a "live nitrogen manufacturing factory" because of its ability to fix nitrogen (Shin et al., 2018). *Azolla* is native to Asia, Africa, and America, and it has been massively utilized as a biofertilizer in Asia (Costa et al., 2009). The biofertilizer potential of *Azolla* has also been exploited in rice cultivation systems in Italy (Milicia & Favilli, 1992). In Kenya, *Azolla* exists in Mwea, Ahero, West Kano, Bunyala, Taveta, and TARDA rice irrigation schemes. At the Ahero irrigation scheme, the positive nitrogen potential of the native species *Azolla nilotica* was reported in 1982 and 1987 (AIRS, report no. 34 and 57).

The use of *Azolla* as a green manure can either be through its incorporation into paddy soil at the beginning of land preparation before rice transplanting or grown as a dual crop along with rice plants (Xu et al., 2017). *Azolla* flourishes well in flooded rice fields as shown in Fig. 8. Sometimes it is usually cultivated in organically managed paddy fields, especially in rice–fish–*Azolla* or rice–duck–*Azolla* multi-eco-production systems in Asia (Cagauan et al., 2000; Lu & Li, 2006; Cheng et al., 2015). *Azolla* has been substantially utilized successfully as a suitable biofertilizer in paddy fields to improve the nitrogen content within a few weeks of its incorporation (Bhuvaneshwari & Singh, 2015). For instance, in Vietnam and south China, Cheng et al. (2015) and Lu and Li (2006) reveal that *Azolla* can be used as a green manure to improve the N balance in lowland paddies, due to its symbiotic relationship with nitrogen (N)-fixing cyanobacteria *Anabaena azollae*. The findings of Malyan et al. (2019) suggested that use of *Azolla* in rice cultivation can help in reducing the application of urea fertilizer by up to 25% without affecting the yields.

Fig. 8 Paddy soil surface covered by *Azolla:* a greenish species decomposing on the dry soil surface

Armstrong (1979) and Raja et al. (2012) indicated that *Azolla* biomass can be used in paddy fields as a partial or complete replacement for synthetic fertilizers because of its ability to provide 1.5–2.0 million tons of nitrogen. Furthermore, Ferentinos et al. (2002) reported that the *Azolla anabaena* complex can fix up to 390 tons N/ha. *Azolla* also increases soil N recovery and therefore improves soil fertility in the long run (Kumarasinghe & Eskew, 1993). The report also indicates that *Azolla* multiplies rapidly and doubles its biomass within 7–10 days (Campbell, 2011). Through this mechanism, it can therefore attain a biomass coverage of up to 5 kg/m^2, which is capable of shielding up to 10% light (Yanni et al., 1994). Even so, the beneficial uses of *Azolla* are not only linked to N fixation, but also as a source of organic content and weed control (Pabby et al., 2004; Singh & Strong, 2016; Yadav et al., 2014) and reduction in mosquito proliferation (Pabby et al., 2004). *Azolla* as well decreases soil pH, water temperature, and inhibits ammonia gas volatilization (Vlek et al., 1995). Kimani et al. (2018) reported that *Azolla* incorporation greatly helps in mitigating methane emissions from paddy fields. Bharati et al. (2000) demonstrated that the incorporation of *Azolla* plus dual cropping significantly decreased methane emissions by increasing the soil redox potential due to higher levels of dissolved oxygen concentration in the stagnant water affected by the floating *Azolla* cover.

3.4 Compost

Composting is an aerobic process where soil microorganisms degrade and transform complex degradable materials into organic and inorganic byproducts (Toledo et al., 2018). Compost can be defined as organic manure or fertilizer produced on-farm as a result of aerobic, anaerobic or partially aerobic decomposition of a wide variety of crop, animal, human and industrial wastes (Senanayaka, 2022). The byproducts can safely be utilized beneficially as biofertilizers and soil amendments (Yu et al., 2019). Although many organic waste products can be added directly into the soil, most of them have a better soil-improving effect after undergoing the decomposition process (Senanayaka, 2022). The organic wastes for composting can be anything from crop residues to animal droppings or dung.

Long-term rice experiments found out that approximately 30–70% of inorganic fertilizers can be substituted with manure, and this still maintained or even increased rice yields in subtropical of China (Bi et al., 2009). A meta-analysis revealed that manure amendment increases rice yield, soil organic carbon concentration, and soil available macroelements (NPK) (Du et al., 2020). Zhu et al. (2022) proposed that by increasing soil fertility, manure amendment increased net photosynthetic rate and plant physiological resistance to extreme temperatures, and without considering the impact of other global change factors, they estimated that manure amendment could potentially reduce global losses of rice yield due to extreme temperatures from 33.6% to 25.1%. Furthermore, Kadoglidou et al. (2019) reported an increase in plant height and biomass and this was attributed to the enhanced soil nutrient levels induced by the compost, which lead to the continuous assimilation of nutrients in available forms by the plants (or to a slow-release fertilization). This hypothesis for the positive influence of compost on rice straw height and biomass has also been made by other researchers such as Kavitha and Subramanian (2007) and Diacono and Montemurro (2010). Kadoglidou et al.'s (2019) study also reported that the application of 3.0 Mg/ha of compost increased the yield to 28.5% compared to the control.

Cow dung compost (CDC) is reported to cause less greenhouse gas (GHG) emissions from paddy fields compared with field application of rice straws (Yagi & Minami, 1990; Kumagai et al., 2010; Das & Adhya, 2014). CDC therefore appeared to be the best organic matter for application in paddy fields in terms of GHG emissions, especially in cold temperate regions of Japan. CDC application also led to improved soil fertility in paddy fields (Maeda & Hirai, 2002; Sumida et al., 2002; Miura & Kusaba, 2013; Shahid et al., 2013). Hasegawa et al. (2005) measured high levels of phosphorus in CDC fields than in fields applied with rice straw.

4 Crop Rotation System

Crop diversification is a cardinal principle for long-term agricultural sustainability (Cabell & Oelofse, 2012) and it is one of the principles of agroecology. Under this practice, rice is grown as the major crop followed by subsequent cultivation of a rotation of crops such as cereals, pulses, oilseeds, cotton, sugarcane, green manures, and vegetable. This type of cropping system may include both lowland and upland crops (Deep et al., 2018). The main pattern of rice and upland crop rotations in China has been rice–wheat, rice–oilseed rape, rice–milk vetch, rice–ryegrass (Witt et al., 2000), rice–potato (Zhu et al., 2016), and rice–soybean (Scherner et al., 2018). In conventional paddy-upland rotation systems, farmers drain the fields after harvesting rice and then upland crops are planted (Qunhua et al., 2004).

Crop rotation plays an important role of reducing weed communities by affecting their seed bank dynamics. For instance, the adoption of rice–soybean rotation is reported to be one of the most important factors for weed management in rice fields (Scherner et al., 2018). It is believed that a crop rotation program composed of several crops possessing great variability in their biological traits can be the most effective tool for controlling weeds (Nichols et al., 2015; Rosenberg et al., 2022; Scherner et al., 2018) and avoiding weed resistance. Designing a new cropping system creates an unstable environment for annual weed species, which prevents their recurrence (Bond, 2002). Crop rotation also allows use of different types of herbicides, which have different modes of action (Kayeke et al., 2017). This also allows for the utilization of integrated weed management tools, including aerobic irrigation systems and cultivation techniques, which both help manage different weed species, reduced reliance on herbicides, and soil health, which decreases the need for fertilizer and pesticide inputs (Rosenberg et al., 2022). Furthermore, in China, the inclusion of winter crops in rotations increased the soil nitrogen supply available for the subsequent rice crop, and average rice productivity in rotations that included winter crops was greater than that in a rice and winter fallow rotation (Chen et al., 2018). However, crop rotation strategies may not eradicate troublesome species, but they can limit their growth and reproduction.

5 Rice Polyculture Systems

Intercropping involves growing of two or more crop species concurrently in the same field during a growing season, which is a common practice among smallholder farmers to increase the species diversity of their produce (Belel et al., 2014; Okonji et al., 2012). The rice-based cropping system is described as a mix of agronomic practices that comprises intercropping of rice with other rice varieties and/or with other crops simultaneously. This practice is common under upland conditions and rice can be intercropped with crops such as water spinach (Liang et al., 2016), cassava (Okonji et al., 2012), Okra (Okonji et al., 2020), sweet flag (Raj, 2017), beans, groundnuts, maize (Mugisa et al., 2020; Riyanto et al., 2021), cowpea, groundnut, pigeon pea (Ramakrishna & Ong, 1994), forage grasses (Crusciol et al., 2020), black gram, green gram, sesame, maize, finger millet or other minor millets. Meanwhile, the ratio of rice and intercrop is preferred to be 3–4:1 (Deep et al., 2018). Also, relay intercropping can be practised under this system and the seed of succeeding crops like lentil, gram, pea, lathyrus, berseem, and linseed is sown by broadcasting in maturing rice crops. This practice therefore saves time and money (to be spent on land preparation, etc.) and utilizes residual fertility. This practice is common in both upland and lowland rice cultures. Additionally, sequential cropping can be carried out in rice production (Deep et al., 2018).

In designing this cropping system, Singh and Singh (2014) and Singh et al. (2013) pointed out that a suitable intercropping pattern and crop geometry must be examined to enhance yield and economic returns to farmers. An excellent example is the successful control of rice blast disease (*Magnaporthe grisea*) demonstrated by the large-scale field experiment with mixed planting of traditional and modern rice varieties (Zhu et al., 2000). This substantiates the fact that "intraspecific crop diversification provides an ecological approach to disease control that can be highly effective over a large area and contribute to the sustainability of crop production" (Zhu et al., 2000). Moreover, Liang et al.'s (2016) result demonstrated that the occurrence of rice blast disease, sheath blight disease and *Cnaphalocrocis medinalis* was substantially lower in pure stands than in the rice–water spinach cropping system. This cropping system is among the most effective and environmentally friendly ways of controlling plant diseases in modern agricultural systems through the use of ecological approaches (Risch et al., 1983; Altieri, 1999; Tilman et al., 2001). The crop heterogeneity created in the system provides substantial disease suppression (Garrett & Mundt, 2000; Zhu et al., 2000; Leung et al., 2003).

The intercropping of two different rice varieties can effectively control the outbreak of rice pests, and it is one of the most significant biodiversity-based methods used in rice production (Luo & Zhang, 2018). In this context, the differences in genetic diversity parameters between the two cultivars should be identified by checking the similarity of their pest-resistance genes. This can be evaluated by comparing their resistance gene analogies (RGA), microsatellite or simple sequence repeat (SSR), or Indel markers for genetic diversity among different cultivars (Mundt, 1994). To achieve a well uniform rice–rice intercropping pattern, during sowing by intercropping, it is necessary to adjust the sowing date of each variety according to the difference in their maturity duration to ensure that the maturation and harvest of both varieties occur at the same time. Therefore, rice seeds of early-maturing varieties should be sowed later and rice seeds of late-maturing varieties should be sowed earlier (FAO, 2018).

6 Pest Management

In agroecology, it is demonstrated that soils with high organic matter and active microorganisms exhibit good soil fertility as well as complex food webs that prevent plant infection (Altieri & Nicholls, 2003). Interestingly, Phelan et al. (1995) showed a significant variation in egg laying among chemical fertilizer treatments within the conventionally managed soil, but in plants under the organic soil management, egg laying was uniformly high. In addition, a small group of farmers in Kuruvai village, near Vadakkencherry, in Kerala's Palakkad district demonstrated that rice can be cultivated without chemical pesticides resulting in a high yield and profit rise (Martin, 2016). Farmers in the region adopted pest surveillance and agroecology-based plant health management, a concept promoted by the National Institute of Plant Health Management, Hyderabad. In practice, pheromone traps and inundative release of egg parasitoids were used to control yellow stem borers. Furthermore, *Trichogramma chilonis* a type of parasitoid was released to control leaf folders (Martin, 2016).

In the context of Hong-Xing et al. (2017), though not referred to as agroecology practices, some of the suggested practices falls under agroecology principles that include reducing initial population sizes of rice insect pests, which is done through low-stubble harvest, killing pupae by tillage, and performing submerged irrigation before field preparation. Adjusting rice sowing time, for example postponing sowing, and transplanting time can significantly reduce the density and damage of striped stem borer in transplanted and directly seeded rice fields (Zhu et al., 2011). Furthermore, in the regions where rice virus diseases annually occur, the fields far away from virus sources are selected for raising rice seedlings to escape virus infections. Cheng et al. (2008) emphasized decreasing insect pest population growth rates by enhancing the resistance of rice varieties, and in this case, pest management strategies should focus on limiting the initial pest recruitments to reduce future generations. In addition, manipulation of the landscape for natural enemy conservation through maintaining graminaceous flora around fields, planting alternative crops, keeping rice straw in paddy fields, and growing the green manure crop such as

Astragalus sinicus after the rice harvest can provide hosts and shelters for native natural enemies to safely overwinter (Huang et al., 2005).

7 Conclusion

Employing a systematic literature review of empirical studies from various regions worldwide starting from 1979 to 2022, we consolidate evidence that agroecology in rice production can be classified into several typologies that can contribute to food and nutrition security by acting toward sustainability at the farm level. Therefore, adjustment of rice production modes calls for the adoption of the appropriate typologies that suit local conditions.

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Climate Policies for Climate-Smart Approach

Sahat M. Pasaribu, Rizatus Shofiyati, Juni Hestina, and Woro Estiningtyas

1 Introduction

Global climate change is one of the most significant environmental challenges of our time, and it poses a severe threat to the agricultural sector. The changing weather patterns have resulted in uncontrolled climate fluctuations, including floods, droughts, and pest and disease infestations that have impacted farmers worldwide. Small-scale farmers are particularly vulnerable to the impact of natural farm risks caused by climate change, which can lead to significant agricultural damages and loss of income.

Indonesia is a tropical country located between two continents and two oceans. This position makes Indonesia's climate very complex and dynamic. Climate anomalies in Indonesia are influenced by various factors that control climate variability with different timescales that are non-seasonal, ranging from intra-season to

S. M. Pasaribu (✉)
Research Center for Economics of Industry, Services and Trade, National Research and InnovationAgency (BRIN), Jakarta, Indonesia

R. Shofiyati
Research Center for Geoinformatics, National Research and Innovation Agency (BRIN), Kawasan Sains dan Teknologi Soekarno, Bogor, Indonesia
e-mail: rizatus.shofiyati@brin.go.id

J. Hestina
Research Center for Behavioral and Circular Economy, National Research and Innovation Agency (BRIN), Jakarta, Indonesia
e-mail: juni004@brin.go.id

W. Estiningtyas
Research Center for Climate and Atmosphere, National Research and Innovation Agency (BRIN), Kawasan Sains dan Teknologi Samadikun, Bandung, Indonesia
e-mail: woro004@brin.go.id

P. Kumar, Aishwarya (eds.), *Technological Approaches for Climate Smart Agriculture*, https://doi.org/10.1007/978-3-031-52708-1_16

inter-decade scales. On the interannual timescale, there are two closely related climatic phenomena, not only to the amount of rainfall but also to various climate disaster events in Indonesia, particularly floods and droughts. The two extreme climate phenomena are the El Nino-Southern Oscillation (ENSO) (Philander, 1983, 1990) in the Pacific Ocean and the Indian Ocean Dipole (IOD) (Saji et al., 1999; Webster et al., 1999) in the Indian Ocean.

According to Boer & Subbiah (2005) more than 75% of droughts in Indonesia are associated with El-Niño events. Extreme weather causes floods and droughts, pest and disease infestations, and damage to agricultural infrastructure. The Ministry of Agriculture of the Republic of Indonesia reported that the highest damage to paddy fields due to drought occurred in El Niño years, ranging from 350 to 870 thousand hectares. In contrast, during a La Nina year, the area damaged by floods reached a maximum of 311 thousand hectares (Fig. 1).

The indirect impact of extreme climate events is pest and disease attacks. During 1989–2019, each La-Niña occurrence of brown planthopper attacks ranged from 90 to 250 thousand hectares, while under normal conditions it ranged from 10 to 85 thousand hectares (Fig. 2).

Agricultural sector remains one of the main bases for Indonesia's economic development. Agricultural sector is not only as a provider of food but also as contributor to the value of GDP and a very significant opportunity to employment. The contribution of the agricultural sector (food crops, horticulture crops, plantation crops, and animal production) in 2022 was 9.19% to GDP (BPS, 2023) and absorb about 27% of the workforce. However, the agricultural sector also deals with farm risks, such as land resource degradation, agricultural land pollution, and land conversion. In recent years, the agricultural sector has also faced increasingly difficult challenges, namely extreme climate events which have shown an increasing trend. In fact, most of the agricultural centers in Indonesia are areas that are highly affected by climate change and extreme climates. The impacts include (a) a shift in the season that causes the conventional planting time to be inapplicable; (b) increasing temperatures and changes in rain patterns that lead to a reduction in the potential for cultivated areas; (c) n increase in temperature that causes a decrease in plant

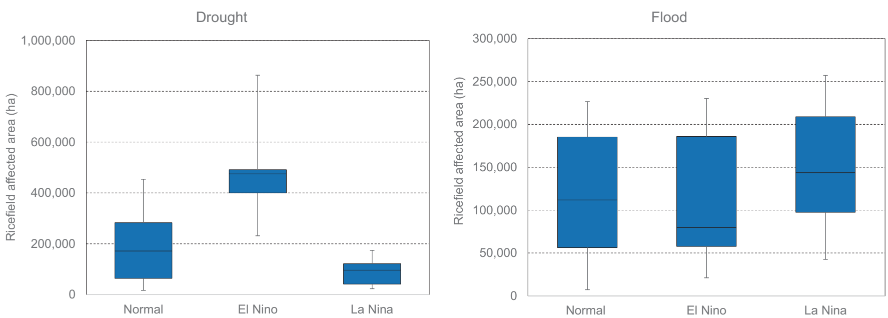

Fig. 1 The extent of rice damage due to drought (left) and flood (right). (Source: Subagyono et al., 2022)

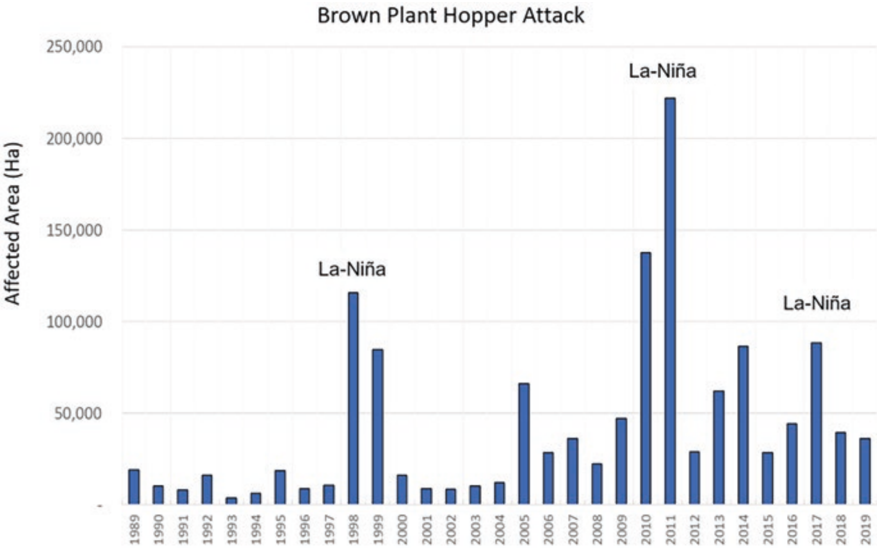

Fig. 2 The extent of brown planthopper attack on rice plants. (Source: Directorate General of Food Crops, Ministry of Agriculture, 2020, processed data)

productivity; (d) the shift in seasons that indirectly encourages the emergence of pests and diseases; and (e) rising sea levels and salinity that reduce the planted area in coastal areas.

The extreme climate could severely affect agricultural resources causing an increase in flood and drought events. Reducing water discharge and increasing population that can endanger the stability and sustainability of water supply (Pujiraharjo et al., 2015; Flörke et al., 2018; Koutroulis et al., 2018). Hatfields (2017) revealed that climate change has an impact on biological systems through increasing temperatures, more varied rainfall, and increasing CO_2 in the atmosphere which has a very influential impact on agriculture. Therefore, special efforts are needed so that impacts and risks due to such global climate change can be minimized. Food farming is a vulnerable subsector and is experiencing the most significant impact due to climate change. Identification of factors that influence rice farming in assessing the level of vulnerability is key in adapting to climate change (Estiningtyas et al., 2024), including crop protection through agricultural insurance.

As a response to the impact of climate change on agriculture, policymakers have recognized the need for policy initiatives that can protect farmers from the impact of natural disasters. One such initiative is the use of agricultural insurance schemes that provide appropriate protection to farmers. These insurance schemes can help farmers mitigate the financial risks associated with climate change and reduce the adverse impact of natural disasters on agricultural production. In this chapter, we examine the experience of Indonesia in crop insurance and explore policy alternatives that can enforce agricultural protection programs. We focus on the prioritization of food crop insurance for food security, while other crops are insured to maintain production sustainability and improve farmers' welfare. We also explore the importance of socialization, promotion, and advocacy before implementing insurance schemes, and we recommend the application of technology to strengthen insurance schemes.

The findings of this study have significant implications for policymakers and stakeholders seeking to protect farmers from the impact of global climate change on agriculture. By prioritizing food crop insurance for food security, promoting the use of technology, and increasing farmers' capacity, policymakers can help improve agricultural performance and contribute to the sustainable development of the agricultural sector.

2 Importance of Agricultural Insurance Schemes

The World Bank predicts that global food demand will increase by 50% by 2050. Climate change, population growth, changes in dietary preferences, pandemics, and global conflicts have threatened food security and the development of the agri-food sector (WB, 2022). Meanwhile, according to the Asian Development Bank (ADB, 2020), global climate change has a significant impact on agriculture. The Asia and Pacific region are highly affected by climate change with lower insurance penetration rates.

Business activities in the agricultural sector will always be faced with a fairly high risk of disposal. The risks from these claims include the damage to agriculture and the crop failure due to various natural disasters, such as floods, droughts, as well as pest and disease attacks caused by the global climate change. The risk of uncertainty in business often results in losses which are generally caused by natural disasters due to global climate change. This greatly affects the performance of farming and the lives of rural farmers (FAO, 2015; Ceballos & Robles, 2014). The uncertainty and high risk allow farmers to switch to other commodities that have high economic value. If left unchecked, it is feared that it will have an impact on the stability of national food security, especially the production and availability of staple food for the majority of Indonesia's population.

Agricultural insurance is offered as an alternative financing scheme related to risk sharing in farming activities. Agricultural insurance has been used in many countries as an instrument to protect farmers from financial loss due to natural disasters, pests, and other risks. Agricultural insurance is an important program for mitigating the impacts of climate change. In addition, insurance facilitates post-disaster recovery of farmers to continue the production process in the next planting season (Pasaribu, 2014). The expansion of coverage and the effectiveness of agricultural insurance schemes attract many enthusiasts, so that many insurance features can be developed for various commodities. This will create cooperation between governments, international organizations, and smallholders (ADB, 2017). Agricultural insurance schemes are a critical tool for mitigating the financial risks associated with natural disasters, climate change, and other agricultural risks. These schemes aim to protect farmers from losses due to unexpected events such as floods, droughts, and pest infestations that can devastate crops and livestock.

There are several types of agricultural insurance schemes, each with its specific focus. Crop insurance protects farmers against losses due to crop failure caused by weather, pests, and other events beyond their control. Livestock insurance, on the other hand, covers losses related to the death or injury of livestock. The insurance schemes model in Indonesia is the indemnity-based as the claim filed by the farmers was based on their expenses. However, different models are necessary to provide other options with advantage in favor of the farmers. Area yield-based or weather insurance models could be the other schemes that provide protection against farm risks (Haryastuti et al., 2021).

3 Indonesia's Crop Insurance Experience

3.1 Rice Crop Insurance Scheme

Indonesia's agriculture sector is a vital part of the country's economy, with millions of small-scale farmers relying on it for their livelihoods. However, these farmers are often exposed to various risks that threaten their agricultural productivity and income. Natural disasters such as floods, droughts, and pests and diseases can cause significant damage to crops and lead to significant losses for farmers. To address these challenges, Indonesia has implemented two types of insurance schemes over the years. These schemes aim to protect farmers from losses due to natural disasters, pests, and diseases, and the death of animal, and provide financial stability for their businesses. The government has taken several steps to promote the uptake of crop insurance among farmers.

The Indonesian Agriculture Insurance Program (IASP) was officially launched in 2015 (rice crop) and 2016 (cattle) after several trials started from 2012. The IASP provides crop insurance to small-scale farmers and aims to promote food security and increase the productivity of rice. Similarly, the livestock insurance scheme was introduced to help the small-scale farmers. The program covers various crops, including rice, corn, soybeans, and others.

In addition to the IASP, there is another insurance scheme available in Indonesia—corn insurance scheme implemented by private insurance companies. However, despite its benefits, the uptake of this scheme among farmers is still relatively low. One reason for this is the lack of awareness and education about the benefits of crop insurance. Therefore, a comprehensive socialization and promotion about agricultural insurance and the embedded insurance products are very important to build awareness of, particularly small-scale farmers. The use of technology has also played a significant role in strengthening crop insurance schemes in Indonesia. Digital platforms have been used to facilitate the enrollment process, claims processing, and communication between farmers and insurance providers. The use of satellite imagery and weather data has also improved the accuracy of insurance payouts and reduced the risk of fraudulent claims.

3.2 Potential Agricultural Insurance Schemes

The crop insurance model currently applied and developed in Indonesia is still based on high production costs and is proposed to cover losses due to floods, droughts, or pest and disease attacks. The same is true for the proposed cattle scheme to cover losses due to death, loss, or accidents. Going forward, several models of agricultural insurance schemes need to be created and introduced. This is necessary to anticipate the participation of farmers in various agro-ecosystems, various regions, and various types of commodities. Several preliminary studies have been conducted (by Indonesian Center for Agricultural Socio-Economic and Policy Studies, Ministry of Agriculture) to explore the possibility of implementing insurance schemes for a number of strategic agricultural commodities. Among these studies are the following:

3.2.1 Sugarcane

Sugarcane is resistant to drought and flood as well as pests and diseases, so that the protection of sugarcane commodities in the form of agricultural insurance needs to be discussed further. Based on information at the farmer level, there are several types of pests that are very susceptible to causing damage of the plant, such as borers, maggots, and rats. Technically the small-scale sugarcane farming has been carried out through partnership activities between the farmers and the sugar factory. Initiation of sugarcane insurance which will be directed at guaranteeing risks from cultivation to harvest should also involve or be known by the sugar factory because majority of the farmers are the factory partners. Cooperation has been long time carried out through a partnership scheme between the factory and sugarcane farmers. This could be further explored for applicable insurance scheme on sugarcane.

3.2.2 Corn

Corn is a food commodity. On the technical aspect, pest attacks and diseases of corn plants are closely related to the weather. In the rainy season there is an attack that can threaten crop damage resulting in crop failure. In the dry season, the pods are not yet ripe or unfilled. In addition, if there is high intensity rain during the growing season, it can cause the plants failure. With such situation, the concept and design of corn insurance could be a system of financing guarantees for planting and harvest failures as well as guarantees for part repayment of the farmer's capital, or as capital for the next planting activity. Further study for a more appropriate insurance scheme for corn is strongly encouraged.

Premium and coverage rates can be calculated based on the total cost of farming and or production which is equivalent to the results of optimal farming carried out by farmers. Basically, the farming costs incurred by corn farmers are almost similar to the costs of rice farming, so from the results of the study it is expected that the corn farming insurance scheme is the same as the rice insurance scheme.

3.2.3 Chili and Shallot

Chili and shallot are strategic commodity that can affect inflation. On cultivation aspect, chili and shallot are vulnerable to pests and climate change. For this reason, it is necessary to protect the production and harvest of chili and shallot through chili and shallot farming insurance scheme. The study revealed that farmers need to obtain insurance scheme even though the claims submitted later will not cover all production costs incurred by farmers. Chili and shallot insurance protects farmers from floods, droughts, and pests, such as yellow virus, sheath rot (attacks within 3 days of crop exhaustion), anthrax (fruit rot), stemborer (eaten fruit), trip, whitefly, *hapis* (sticky aphids), and fruit flies, white caterpillars, and crackles. Proper insurance scheme for chilies and shallots is protection for chili and shallot farming in the production process (cultivation) and selling price fluctuations (market).

The characteristics of these two commodities are different. The most prominent characteristic is that shallot can be harvested after plantations for about 65 days (2 months), while chili can provide a harvest period for about 6 months. Chili production costs reach IDR100 million/ha/planting season, while shallot is about IDR60–80 million/ha/planting season. In the event of a crop failure, insurance can compensate up to 50% of the total production cost. Farmers' ability to pay chili and shallot insurance premiums ranges from IDR 300 thousand to IDR6 million/ha/planting season. Insurance claim can be filed if plant damage reaches 70%.

There are potential for agricultural insurance schemes in the future. Many locations of agricultural land are included in the category of prone to flooding, drought or prone to pests and diseases. The government pays attention to protect against the risk of crop failure, so that the farming activities can be sustainable and have an impact on increasing the yields obtained by the farmers. Farmers' perception and understanding of agricultural insurance are still low. It is necessary to carry out intensive socialization with comprehensive information regarding the benefits of agricultural insurance.

3.3 Financial Support for Smallholding Farmers

The benefits of agricultural insurance schemes are numerous. They provide financial stability to farmers, enabling them to recover from unexpected losses, and continue to operate their businesses. By protecting farmers, agricultural insurance schemes also help ensure food security and stability in the global food supply chain. Despite their benefits, agricultural insurance schemes face several challenges and limitations. Some of these include inadequate knowledge and awareness of insurance schemes among farmers, high premiums, and the lack of insurance coverage for certain agricultural products.

In recent years, various initiatives have been introduced to increase the accessibility of agricultural insurance schemes to farmers worldwide. Governments and international organizations have launched policies and programs that aim to increase awareness of these schemes and to provide subsidies to reduce the cost of premiums. Agricultural insurance schemes play a vital role in mitigating the financial risks faced by farmers due to natural disasters, climate change, and other agricultural risks. By providing financial stability, these schemes help ensure food security, stability in the food supply chain, and the livelihoods of farmers around the world.

In conclusion, Indonesia's crop insurance experience provides a valuable lesson on the importance of agricultural insurance schemes in protecting small-scale farmers from the risks associated with natural disasters and other agricultural risks. While there is still room for improvement, the government's efforts to promote crop insurance and increase its accessibility have been an important step towards ensuring the stability and sustainability of Indonesia's agriculture sector.

4 Recommendations for Implementing Crop Insurance Schemes

Based on the findings of the study on agricultural insurance schemes, the following recommendations are suggested for the effective implementation of crop insurance schemes:

(1) Socialization, Promotion, and Advocacy: Before implementing any crop insurance scheme, it is crucial to conduct socialization programs among farmers to educate them about the importance and benefits of crop insurance. Promoting crop insurance and advocating for its implementation can also increase awareness among farmers.
(2) Use of Technology: The application of technology can be used to strengthen insurance schemes and make them more efficient. The use of mobile applications, satellite imagery, and drones can help in monitoring and assessing crop damages, and the use of online platforms can facilitate the insurance application and claim process.

(3) Capacity Building of Farmers: Farmers need to be trained and educated on the use of new technologies and modern farming practices to improve their productivity and reduce risks. Capacity building programs can also provide farmers with the knowledge and skills to manage and mitigate risks associated with climate change and natural disasters.
(4) Government Support: The government can provide support by offering subsidies and incentives to farmers to encourage them to participate in crop insurance schemes. The government can also play a vital role in regulating and monitoring insurance companies to ensure fair and transparent insurance services.
(5) Collaboration: Collaboration among stakeholders such as government, insurance companies, and farmers can help in developing and implementing effective crop insurance schemes. The involvement of non-governmental organizations and other development partners can also help in improving the reach and effectiveness of crop insurance schemes.

5 Concluding Remarks

Agricultural insurance schemes are essential for protecting farmers from the adverse impacts of climate change and natural disasters. Crop insurance is an effective tool for reducing risks and ensuring food security while improving the welfare of small-scale farmers. Indonesia's experience in crop insurance provides useful insights into policy alternatives that can enforce agricultural protection programs. The study recommends socialization, promotion, and advocacy, the use of technology, capacity building of farmers, government support, and collaboration among stakeholders for effective implementation of crop insurance schemes. These recommendations can be adopted by policymakers and other stakeholders to develop and implement effective crop insurance schemes that can mitigate risks and support sustainable agriculture. Overall, crop insurance can play a vital role in ensuring food security, improving the welfare of farmers, and promoting sustainable agricultural development.

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Land Use Change and Agro-Climatic Interactions

Sabir Khan, Shilpi Yadav, Vineesha Singh, and S. S. Khinchi

1 Introduction

One of the greatest concerns facing us today is climate change. India will be impacted by climate change in a variety of ways. The stark contrast between the drought-prone regions of Rajasthan, Andhra Pradesh, Gujarat, Orissa, and Uttar Pradesh and the nearly 40 million hectares of flood-prone terrain in the north and north-eastern belt demonstrates these disparities. According to Pradhan et al. (2015), the Indian summer monsoon (ISMR) considerably dominates the Asian Monsoon climate. India might experience more floods as a result of the Indian monsoon getting stronger. According to Lendrum et al. (2007), one of the most significant environmental issues confronting humanity today is climate change, which has implications for things like freshwater availability, health, natural ecosystems, and food production.

The largest contributor to the Indian economy in terms of income, jobs, and export earnings is agriculture. About 69% of the population relies on agriculture for their livelihood, and it accounts for close to 35% of the country's GDP. Agriculture is the backbone of the Indian economy. Every 3–7 years, a complicated weather phenomenon called EL NINO that brings drought, flooding, and other extreme

S. Khan
Department of Forest, Working Plan Office, Betul, Bhopal, Madhya Pradesh, India

S. Yadav
Sophia Girls' College (Autonomous), Ajmer, Rajasthan, India
e-mail: shilpi@sophiacollegeajmer.in

V. Singh (✉)
Department of Earth Sciences, Barkatullah University, Bhopal, Madhya Pradesh, India

S. S. Khinchi
Department of P.G. Studies in Geography, Dr. B. R. Ambedkar Government P.G. College, Sri Ganganagar, Rajasthan, India

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weather to different parts of the planet makes an appearance. The system affects weather in many countries, including India, and is made up of oceanic and atmospheric events caused by warm currents off the coast of Peru in the eastern Pacific. LA-LINA winds raise stronger across the pacific because the low pressure over the western Pacific Ocean and the high pressure all over the central-eastern Pacific Ocean. It is counter ocean current which becomes effective in the tropical western Pacific when EL-NINO becomes futile in the tropical eastern pacific. Cane and Arkin (2000) claim that some of the yearly fluctuations in climate are caused by arbitrary patterns of occurrence, much like a series of coin flips that will occasionally result in a long run of either heads or tails. Due to its repeated and synoptic coverage, remote sensing data can be used to monitor crop production and acreage at the district and regional levels. Crop type and yield evaluation before harvest are crucial for calculating crop production. By taking the findings from studies on land suitability mapping into account when allocating land uses, planners and administrators can achieve sustainability in land use (Cengiz et al., 2009). Traditional methods for providing this information are extremely tedious, time-consuming, and frequently subjective, but satellite remote sensing offers the crucial potential to give this information in a more consistent, comprehensive, timely, and objective way.

Northwest India experiences winter and pre-monsoon rains due to the Western disturbance. Winter season the development of the Rabi crops, which include the regional staple wheat, in the northern subcontinent is where rainfall is most crucial to agriculture. With adequate regard for the geographical variability of the terrain and other qualities for an efficient time and cost-effective evaluation, geographic information systems (GIS) are ideally suited for processing both spatial and non-spatial data (Ahamed, 2000).

Over the past few decades, research has focused on the effects of climate change on food production (Lobell, 2007; Adams et al., 1990; Parry et al., 2005; Kalra et al., 2008; Rosenzweig & Parry, 1994; Lobell et al., 2006; Cubasch et al., 2001; Mall et al., 2006). In general, all these studies have used average monthly and annual temperature and precipitation estimates from climate models. Fewer scientists have also considered additional aspects of climate change, such as variations in the daily and interannual variability of the climate (Mearns et al., 1997), an increase in the frequency of heat waves or other dangerous events changes (Rosenzweig et al., 2002). According to the Inter-Governmental Panel on Climate Change (IPCC, 2007a, b, c), desert ecosystems would likely be more affected by climate change by the end of the twenty-first century than semi-arid or subhumid parts of India. The 19.61 million acres of arid Rajasthan, which is spread across twelve western districts of the state, is particularly delicate and is under a lot of pressure because of the frequent droughts and scant rainfall. Northwest India has had a dry era for roughly 3000 years.

Using advanced very high-resolution radiometer (AVHRR) imagery, Doi (2001) illustrates the vegetation's response to rainfall in Rajasthan. A series of multitemporal georeferencing data into NDVI images with a spatial resolution of about 5.5 km are needed for the analysis, which is based on six maximum value composites. Each NDVI is checked pixel by pixel, with just the highest value being kept for each pixel. All pixels are examined before the MVC picture is created. The chosen six NDVI photos from the favorable and bad monsoons in June, September, and December are contrasted. Research on the sequential link between the NDVI and the frequency of rainfall in several districts has also been made. This demonstrates how rainfall and arable land have a favorable relationship. According to Manjunath et al. (2004), the current study deals with the use of AVHRR data for monitoring the wheat crop in Rajasthan State's 17 primary growing districts. Finally, because agricultural crops are dynamic, it is frequently helpful to look at how they have changed through time. Multitemporal data were thus employed for crop discrimination. Therefore, the study's goals are to estimate the area used for the Rabi, Kharif, and double cropping seasons in Rajasthan from the years 2011 through 2022 using moderate resolution imaging spectroradiometer (MODIS) data to ascertain the relationship between NDVI and rainfall. To ascertain the relationship between rainfall and crop yield, as well as the impact of western disturbances on the state of Rajasthan.

2 Study Region

The State of Rajasthan is in the western area of India, which is known due to its severe water scarcity, scant rainfall, and arid/semi-arid climate. A total of 33 districts, 39,753 populated villages, 249 Panchayat Samities, and 9168 Gram Panchayats make up the administrative structure of the state. Geographically, the state's landmass is largely made up of deserts. In comparison to the overall forest cover, the state's forests make up 4.19%. The Chambal, Banas, and Luni rivers are the three main rivers that flow in Rajasthan. The most crucial resource which is water is drastically lacking in the state. Rajasthan only has roughly 1% of the country's water resources despite having 10.4% of the country's area and 5.5% of its population. The state of Rajasthan has been split into nine agro-climatic zones (Fig. 1 and Table 1), from the flood-prone east to the desert west, based on weather patterns and agricultural methods. Rajasthan is the largest state of India, comprising 10.4 % of the country's total area. Nearly 76 % of the state's population resides in rural regions. Rajasthan produces 5.49% of the nation's total food grains production and 21.31 % of its oil seeds. The state has 49 million livestock mainly cows, buffaloes, and goats comprising 10.13 % of the country's livestock population.

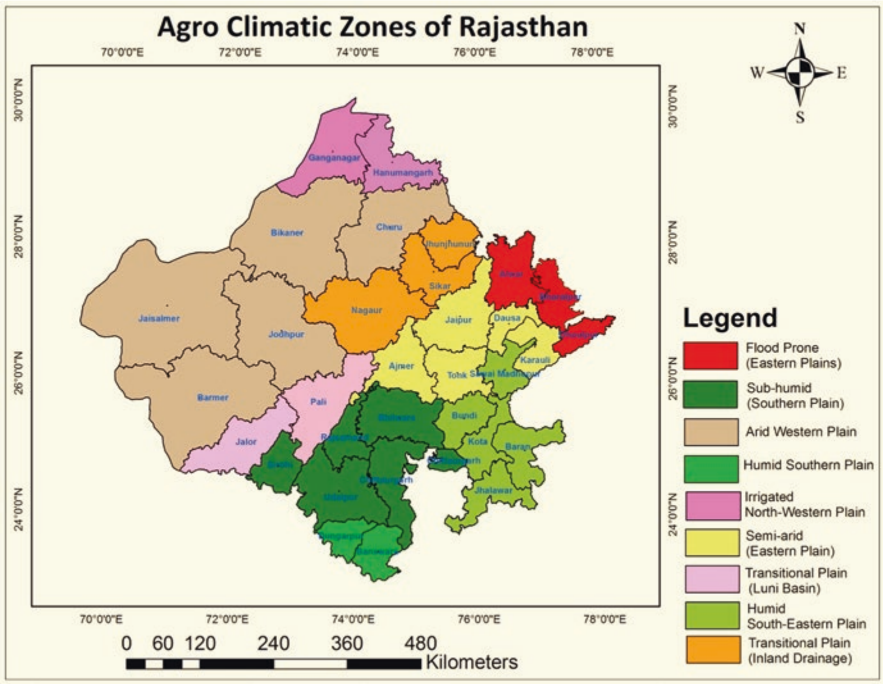

Fig. 1 Map showing agro-climatic zones of Rajasthan

Table 1 The nine agro-climatic zones in Rajasthan identified based on districts, rainfall, and type of crops

Agro-climatic zone	Districts	Rainfall (MM)	Type of crops Kharif	Rabi
Arid Western Plain	Bikaner, Jaisalmer, Barmer, Jodhpur, Churu	100–400	Bajra, gaur, and pulses	Wheat, mustard, rape-seed
Irrigated North-Western Plains	Ganganagar, Hanumangarh	300–400	Cotton, sugarcane and pulses	Wheat, mustard, gram, vegetables, and fruits
Transitional Plain of Inland Drainage	Nagaur, Sikar, Jhunjhunu, Churu	400–500	Bajra, sesamum	Wheat, barley, mustard, and gram
Transitional Plain of Luni Basin	Jalore, Pali, Sirohi, Jodhpur	300–500	Bajra, maize, guar, sesamum and pulses	Wheat, barley, and mustard
Semi-arid Eastern Plain	Jaipur, Dausa, Tonk, Ajmer	500–600	Bajra, sorghum and pulses	Wheat, barley, gram, mustard
Flood Prone Eastern Plains	Alwar, Bharatpur, Dholpur	650–750	Bajra, sorghum, maize, sugarcane, sesamum	Wheat, barley, gram, and mustard

(continued)

Table 1 (continued)

Agro-climatic zone	Districts	Rainfall (MM)	Type of crops: Kharif	Type of crops: Rabi
The Aravalli Hills and the sub-humid Southern Plains	Sirohi, Bhilwara, Udaipur, Chittorgarh	500–950	Maize, rice, cotton and opium	Wheat, gram, and oil seeds
Humid Southern Plains	Dungarpur, Banswara, Udaipur, Chittorgarh	750–900	Cotton and sugarcane, maize, sorghum, and paddy	Mustard, groundnut, sesamum, rapeseed, etc.
Humid South-Eastern Plains	Kota, Baran, Bundi, Jhalawar, Swai Madhopur	600–850	Paddy, sorghum, soybean	Wheat, barley, grain, mustard, etc.

Source: Directorate of Agriculture, Government of Rajasthan

2.1 *Extreme Climate*

Dry spells and floods observational data indicate that the likelihood of severe and extremely severe droughts occurring over the western Rajasthan region has increased during the past 100 years. The southern areas of Rajasthan have historically faced a significant number of severe droughts while having high average rainfall. Due to intense rainfall occurrences, flash floods have been seen in many locations in Rajasthan. A few examples are the floods that occurred over Barmer in 2006, Tonk, and Jaipur in July 1981. These recent floods have caused unprecedented loss of life and property. Twenty-seven river floodings have been seen around the state as a result of the intense rain. An example of flooding brought on by the Chambal River is the Dholpur Flood in August 1982. Variation in Temperature Rajasthan is the second state behind Jammu and Kashmir in terms of the number of cold waves that have happened historically (during the last 100 years), according to the examination of historical data for extreme weather occurrences. Historically, during the south-west monsoon season, a tendency of gradually declining mean annual temperature was seen throughout the Northwest region of India. All regions of India are expected to have an increase in annual mean surface temperature between 2071 and 2100, with the state of Rajasthan experiencing an increase of 2–4 °C (Fig. 1).

Geographic information systems (GIS), GPS, and satellite remote sensing are geospatial technologies that are now extensively employed in agriculture, forestry, watershed management, and natural resource management (Rizvi et al., 2009a). Applications of GIS and remote sensing in the field of agroforestry include estimating agroforestry areas (Rizvi et al., 2009b;Unruh et al.,1995), determining whether agroforestry systems are suitable (Ellis et al., 2004), and monitoring agroforestry parks (Bernard et al., 1997). However, the research on agroforestry must make considerable use of these technologies. In this aspect, remote sensing makes it possible to monitor vast regions in a short amount of time, but more crucially, it makes it possible to manage land over time. As a result, it is possible to study changes in land use and cover as well as examine temporal trends. In order to link climate change and human influence to sediment export and the potential effects that could result, remote sensing images can provide information about soil properties, land management, human activities, vegetation status, and cover modifications (Ge et al., 2011; Anwar et al., 2021; Wang et al., 2019). According to Lizaga et al. (2022) today, platforms like USGS and Copernicus may be used to immediately acquire numerous processed vegetation and water content indices. As an illustration, the US Geological Survey Earth Resources Observation and Science Center directly provides eight different surface reflectance-derived spectral indices, of which five are extensively utilized for monitoring soil humidity and vegetation state. It is unclear, however, whether these indices would best fit various research or if only one of them could be the best (Table 1).

3 Materials and Methodology

For the study satellite data is acquired from Land Processes Distributed Active Archive Centre (LP DAAC) which is Terra MODIS surface reflectance 8-day L3 global 250 m (Period: June to May from year 2011 to 2022 for the purpose of NDVI & Unsupervised Classification. Agricultural Data was obtained from the website of the Centre for Monitoring Indian Economy (CMIE) and the Directorate of Economics and Statistics (DES), India for the period of 12 years from 2011 to 2022 for the utilization to determine the area and production of Kharif crop, Rabi crop in Rajasthan state. Rainfall Data is obtained from the website of IMD for Average Annual Rainfall. Source of Ancillary Data like district/state, and vector coverage shape files are collected from Jaipur Development Authority (JDA). Software like ArcGIS, ERDAS IMAGINE and HANT Software are used for the Image Processing & Geo-Spatial Analysis.

Climate change and land use are tied to one another. At different temporal and spatial dimensions, these changes interact with one another; however, inappropriate land use is the main cause of climate change (Thapa, 2021). Eric et al. (2003) state that resource scarcity, which increases the demand for production on resources; shifting market possibilities; outside governmental intervention; loss of adaptive ability; and changes in social organization and attitudes are the synergistic factors that drive land-use change. Since they can influence the biophysical, biogeochemical, and biogeographical properties of the Earth system, changes in land use and land cover (LU/LC) are the primary focus of global change studies (Robinson et al., 2013; Jain et al. 2014). The goal of the current study is to make use of and assess MODIS time series for agricultural crop area monitoring across Rajasthan state. On a global, regional, and national level, climate change has an impact on every sector of the economy, including agriculture, construction, tourism, energy, health, and productivity (Ortiz-Bobea, 2021). A region's climate has an impact on the agricultural cropping pattern, and as a result, different regions produce different crops. The intergovernmental panel on climate change predicts that by the end of the twenty-first century, dry ecosystems would likely be more impacted by climate change than semi-arid or sub-humid areas of India, particularly the Thar Desert region (Hou et al., 2012) claims that the agroecosystem makes a sizable contribution to the global share of GHG emissions. Agriculture plays a significant role in both the Indian economy and the rural livelihood system of the nation. It contributes about 18% of the country's GDP and provides jobs for 50% of the population (Madhusudhan, 2015).

Numerous meteorological variables, including rainfall, temperature, humidity, wind speed, and length of daylight, have a considerable impact on the cropping pattern. The most significant factors impacting agriculture are, by far, the annual rainfall and its distribution throughout the year, as well as the patterns of diurnal and yearly temperatures. Vegetation indices obtained from remotely sensed satellite imageries are successfully utilized to monitor vegetation changes at various scales, claim Hamed et al. in 2023. The reflection of energy from the surface is substantially influenced by atmospheric dust as well as airborne particles, including gases and clouds, especially in the visible, short, and infrared spectrum. While vegetation change research requires integrated and comprehensive time series data, this leads to imageries with missing data (gaps) and outliers. Multi-temporal MODIS surface reflectance data from pre-sowing to the mature crop stage from years 2011 to 2022 were collected throughout the Kharif season (July to October) for the study. The downloaded MODIS data was in hdf format, thus it had to be converted to image data format and reprojected before the entire research region could be retrieved from the MODIS satellite images. Using ERDAS Imagine software, this conversion, reprojection, and extraction processes were carried out. Images using NDVI (Normalized Difference Vegetation Index) are created using Modis satellite data. HANTS (Harmonic Analysis of Time Series) algorithm was utilized for noise and cloud contamination screening and removal. A total of 552 MODIS pictures were managed and analyzed in this study, made up of 46 sets of 8-day composite data that were combined to create a time series data set for one Rabi season and one Kharif season. For the classification of the multidate NDVI data set, a hybrid technique was applied. Using a spectral profile matching method, the clusters were divided into spectral classes. For each station and the entire study region, rainfall and vegetation curves were created, and distinct patterns for the Normal, El Nino, and La Nina years were identified. Twelve years of average vegetation index values, from 2011 to 2022, were calculated. Agriculture, agricultural productivity, and the extent of water bodies decreased during El Nino years of rainfall while increasing during La-Nina years. Additionally, an effort has been made to look at the sequential relationships between rainfall and NDVI, rainfall and crop yield, and NDVI and crop yield in various state districts (Fig. 2).

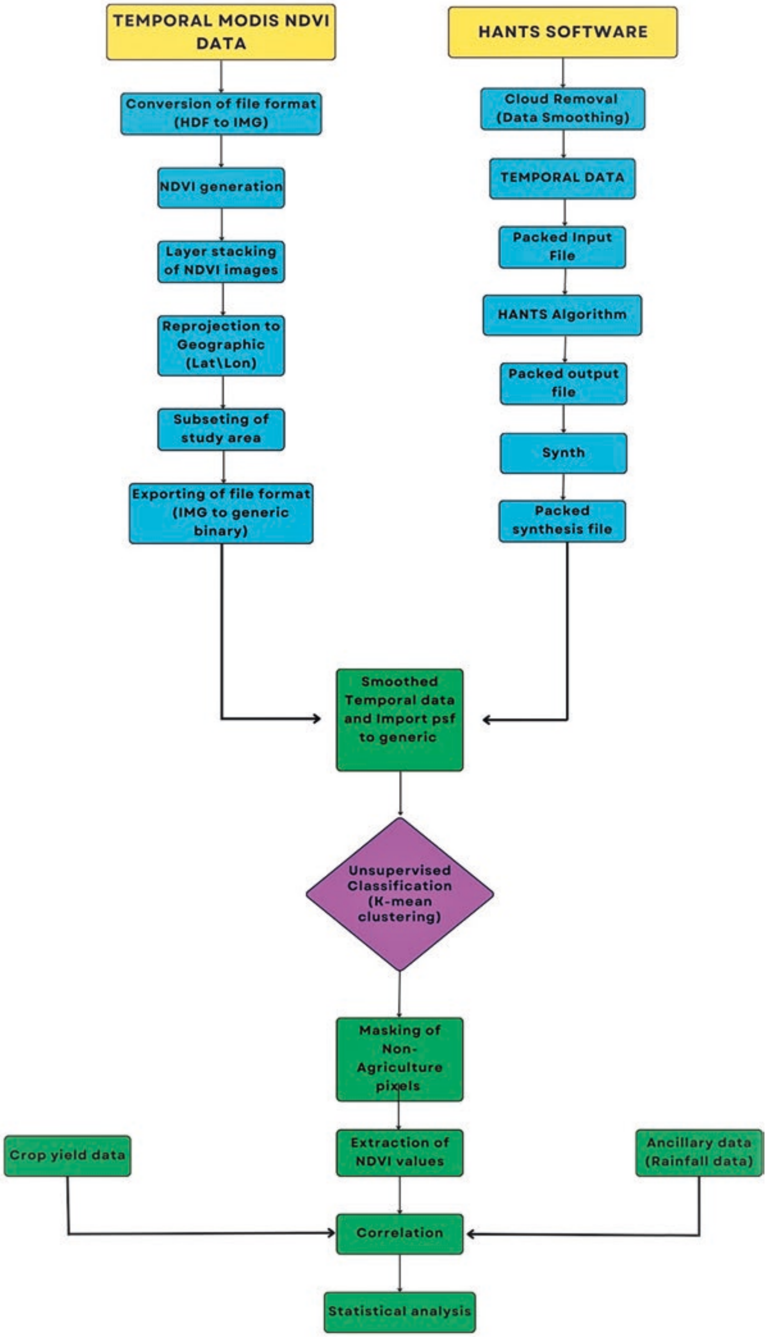

Fig. 2 Flowchart of methodology

4 Result and Discussion

The result section displays how we can attain the results, and the discussion section explores the significance of the results. In this section, you will find the relationship between rainfall, NDVI, and crop yield production district-wise for the Rabi crops and Kharif crops as well as unsupervised classification results too (Table 2).

Table 2 Relationship between rainfall and crop yield—Rabi crop and Kharif crop (district-wise)

District	Rainfall and crop yield (district–wise) (R) Rabi crop (hectare)	Rainfall and crop yield (district–wise) (R) Kharif crop (hectare)
Ganganagar	0.837	0.709
Hanumangarh	0.083	0.693
Bikaner	0.418	0.618
Churu	0.221	0.627
Jhunjhunu	0.328	0.563
Jaisalmer	0.094	0.350
Sikar	0.453	0.556
Alwar	0.266	0.652
Jaipur	0.525	0.752
Bharatpur	0.225	0.703
Jodhpur	0.341	0.723
Nagaur	0.341	0.75
Dausa	0.304	0.675
Ajmer	0.136	0.774
Karauli	0.165	0.655
Dhaulpur	0.134	0.353
Barmer	0.118	0.592
Sawai Madhopur	0.692	0.840
Tonk	0.368	0.943
Pali	0.140	0.714
Rajsamand	0.152	0.354
Bhilwara	0.161	0.383
Jalor	0.178	0.750
Bundi	0.104	0.555
Kota	0.281	0.583
Baran	0.457	0.170
Sirohi	0.161	0.506
Chittorgarh	0.094	0.589
Udaipur	0.215	0.214
Jhalawar	0.172	0.106
Dungarpur	0.206	0.094
Banswara	0.589	0.151

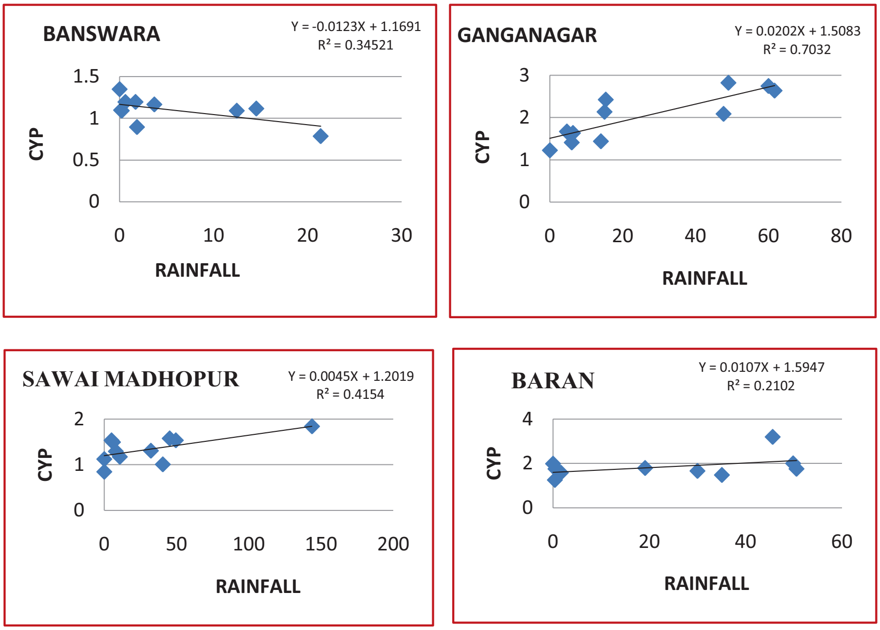

Fig. 3 Relationship in between rainfall and NDVI (district-wise) of Rabi crop

Figure 3 demonstrates unequivocally that there is a weekly correlation between rainfall and agricultural yield for the Rabi crop. Banswara (0.345), Ganganagar (0.703), Sawai Madhopur (0.415), Baran (0.21), etc. are among the districts with the strongest correlation between rainfall crop yield and NDVI according to regression research. Additionally, this regression analysis demonstrates that Rabi crop is not solely dependent on winter precipitation (Temperate Cyclonic Rainfall, Western disturbances, or Mahawat).

Figure 4 clearly shows that there is a significant relationship between rainfall and agricultural yield for the Kharif crop in districts like Tonk (0.89), Alwar (0.44), Pali (0.56), and Ganganagar (0.50). This regression study demonstrates how dependent the Kharif crop is on monsoon precipitation (Table 3).

Figure 5 illustrates year-wise relationship for Kharif crops, for example, 2011–2012 (0.167) and 2019–2020 (0.386). Rabi crop analysis results for 2011–2012 and 2019–2020 are 0.083 and 0.542, respectively. Rainfall and agricultural yield of the Rabi and Kharif crops are inversely correlated (Table 4).

Figure 6 eloquently shows that there is a negative correlation between rainfall and crop yield for the Kharif crop in districts like Junjhunu (0.188) and Ajmer (0.078). According to this analysis of regression, monsoon rainfall is a key factor in Kharif crop. This correlation illustrates unequivocally that there is a significant correlation between rainfall and crop output for the Rabi crop, district-wise, with Hanumangarh (0.007) and Jalor (0.562) being two good examples. The moderate relationship between rainfall and the agricultural yield of the Rabi crop is amply illustrated by this correlation (Table 5).

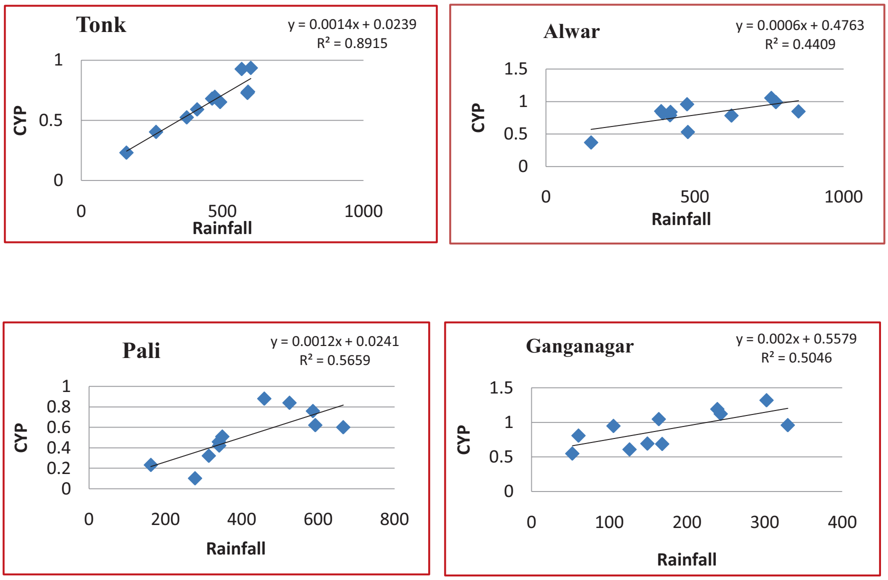

Fig. 4 Relationship between rainfall and NDVI (district-wise) of Kharif crop

Table 3 Relationship between rainfall and crop yield—Rabi and Kharif crop (year–wise)

Year	Rainfall and crop yield (R) Rabi crop (hectare)	Rainfall and crop yield (R) Kharif crop (hectare)
2011–2012	0.083	0.167
2012–2013	0.363	0.281
2013–2014	0.156	0.234
2014–2015	0.354	0.427
2015–2016	0.005	0.264
2016–2017	0.256	0.187
2017–2018	0.238	0.095
2018–2019	0.279	0.230
2019–2020	0.212	0.413
2020–2021	0.551	0.386
2021–2022	0.054	0.532

Figure 7 shows that for Kharif crops, year-wise values of 0.684 for 2011–2012 and 0.894 for 2021–2022 indicate a substantial connection. Rabi crop analysis results for 2011–2012 and 2021–2022 are 0.296 and 0.894, respectively. The amount of rainfall and the agricultural yield of the Rabi crop are moderately correlated.

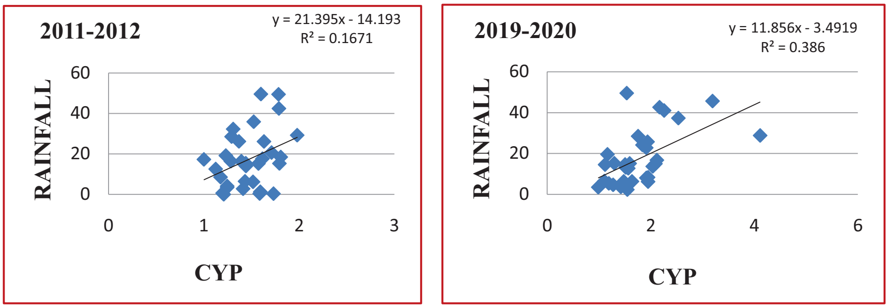

Fig. 5 Relationship between rainfall and crop yield (year-wise)

Table 4 Relationship between NDVI and rainfall—Rabi and Kharif crop

District	NDVI and rainfall (district-wise) (R) Rabi crop (hectare)	NDVI and rainfall (district–wise) (R) Kharif crop (hectare)
Ganganagar	0.320	0.694
Hanumangarh	0.007	0.750
Bikaner	0.141	0.489
Churu	0.070	0.563
Jhunjhunu	0.602	0.188
Jaisalmer	0.204	0.417
Sikar	0.485	0.796
Alwar	0.170	0.729
Jaipur	0.618	0.650
Bharatpur	0.459	0.563
Jodhpur	0.012	0.488
Nagaur	0.176	0.551
Dausa	0.621	0.621
Ajmer	0.637	0.708
Karauli	0.468	0.601
Dholpur	0.372	0.258
Barmer	0.031	0.470
Sawai Madhopur	0.536	0.479
Tonk	0.268	0.481
Pali	0.562	0.488
Rajsamand	0.454	0.450
Bhilwara	0.523	0.603
Jalor	0.562	0.821
Bundi	0.161	0.401
Kota	0.003	0.427
Baran	0.004	0.161
Sirohi	0.418	0.353
Chittorgarh	0.225	0.403
Udaipur	0.332	0.507
Jhalawar	0.126	0.145
Dungarpur	0.002	0.288
Banswara	0.054	0.1

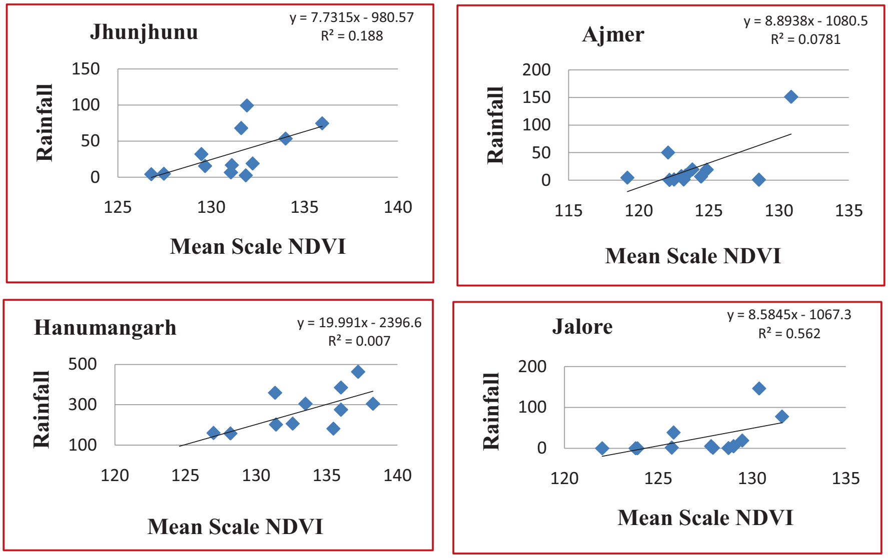

Fig. 6 Relationship between NDVI and rainfall (district-wise)

Table 5 Relationship between NDVI and rainfall—Rabi and Kharif crop

Year	NDVI and rainfall (R) Rabi crop (hectare)	NDVI and rainfall (R) Kharif crop (hectare)
2011–2012	0.296	0.684
2012–2013	0.530	0.648
2013–2014	0.041	0.976
2014–2015	0.353	0.618
2015–2016	0.184	0.708
2016–2017	0.342	0.618
2017–2018	0.202	0.619
2018–2019	0.242	0.666
2019–2020	0.313	0.680
2020–2021	0.781	0.738
2021–2022	0.079	0.894

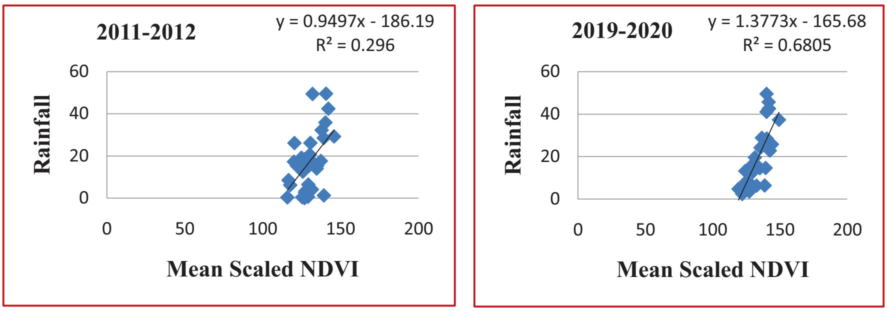

Fig. 7 Relationship between NDVI and rainfall (year-wise)

4.1 Unsupervised Classified Images from 2011 to 2022

It is a method of allocating pixels from related spectral classes. K-means clustering was used to classify a multidate stacked smoothened NDVI image. From 20 rounds, 80 clusters were created during the classification step, with a convergence threshold of 0.98. By comparing the spectral distance between the means of each spectral class, a spectral class will be assigned to each pixel. The following seven categories were created: double crop, Kharif, Rabi, forest, waste land, water body, and desert.

Minimum interaction with the analyst was necessary during an unsupervised categorization method. The training stage need not be the basis for categorization. This approach to classification uses algorithms to look at the unknown pixels in an image and classify them based on the inherent groupings or clusters in the picture data. The fundamental tenet is that data from the same class should be relatively closely spaced, but values from a particular cover type should be near together in the measurement space. K-means clustering and ISODATA clustering are only two examples of the many clustering techniques that may be used to identify the natural spectral groups that are present in the data collection.

One of the simplest unsupervised clustering algorithms is K-means clustering used to identify any natural spectral groupings that may exist in a batch of data. It accepts the analyst's estimate of how many clusters there should be in the data. After that, the multidimensional measurement space randomly "seeds" or locates the centers of that many clusters. The cluster with the closest arbitrary mean vector is then given credit for each pixel in the image. Afterward, iteratively moves them till it achieves the best spectral separability. The analyst then determines the identification of the land cover for each spectral class. We need to provide things like (i) the maximum number of clusters to take into account before we can do k-mean clustering. (ii) A convergence threshold, which is the proportion of pixels at most whose class values do not change during iterations, is used to measure convergence. The maximum number of iterations allowed.

Land use/land cover (LULC) classification (Fig. 8) shows that the influence of Kharif crop and double cropping dominates the major part of the study area especially the northeast, eastern, Southeast, and southwest parts of the area. Rabi crop covers fewer regions on the map. Besides this, we can see that in 2014–2015, 2015–2016 and 2016–2017 dominate the northeastern and central parts of the study area. This classification shows a beautiful agricultural dynamic from 2011 to 2022. Hence, Rajasthan State is very suitable for Kharif and double cropping.

According to the analysis and findings presented here, El Nino and La Nina events had an impact on rainfall, agriculture in the study area, and ultimately agricultural productivity. Shifting of the rain was a significant factor in El Nino years. The last 2 months of the rainy season (September and October) had more rain during the El Nino year. However, during the La Nina years, there was an increase in rainfall. Over northwest India during the season, there are often four to five western disturbances every month. While some of the western disturbances provide moderate to heavy rainfall that is evenly distributed, others pass with little to no

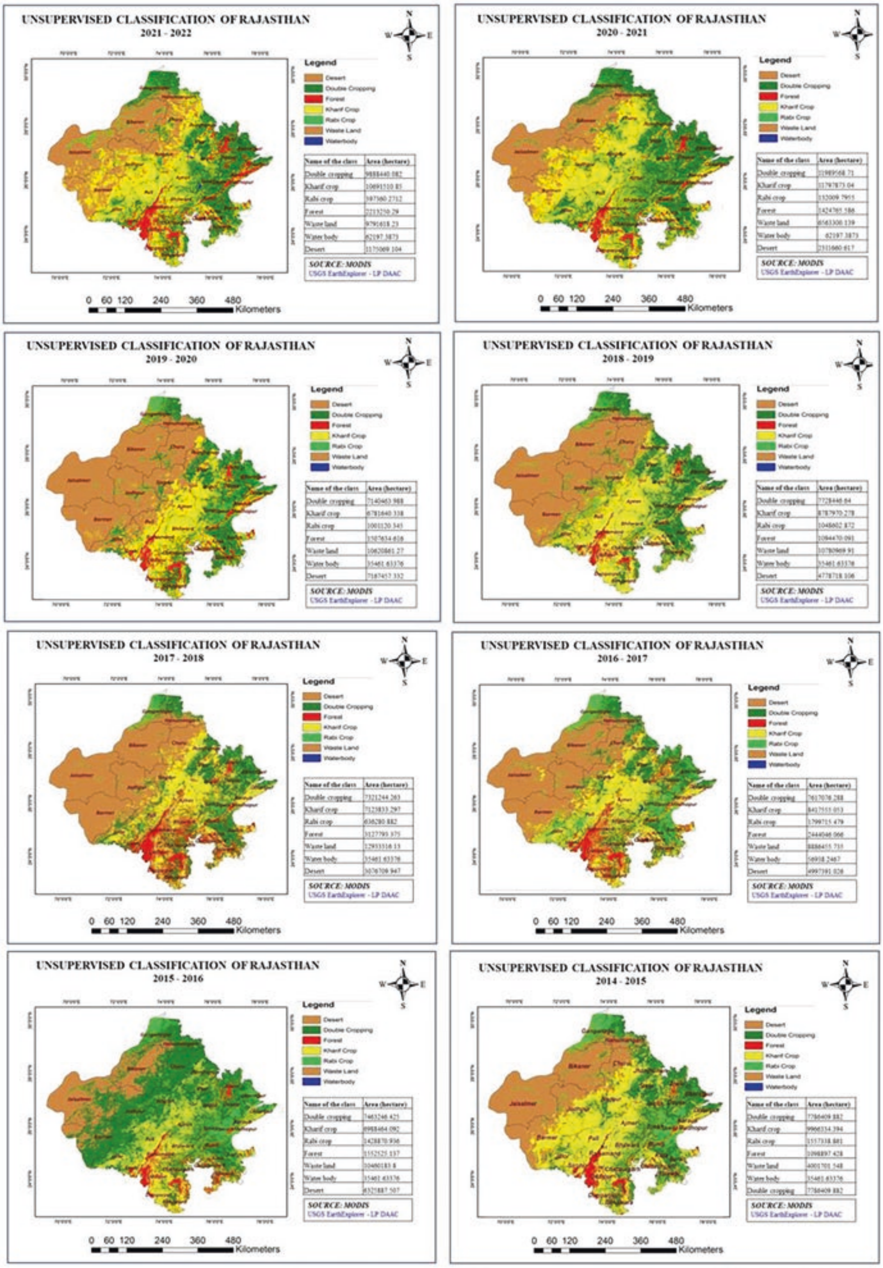

Fig. 8 (**a–k**) Land use/land cover of Rajasthan State using unsupervised classification method through K-Mean Clustering Algorithm from 2011 to 2022

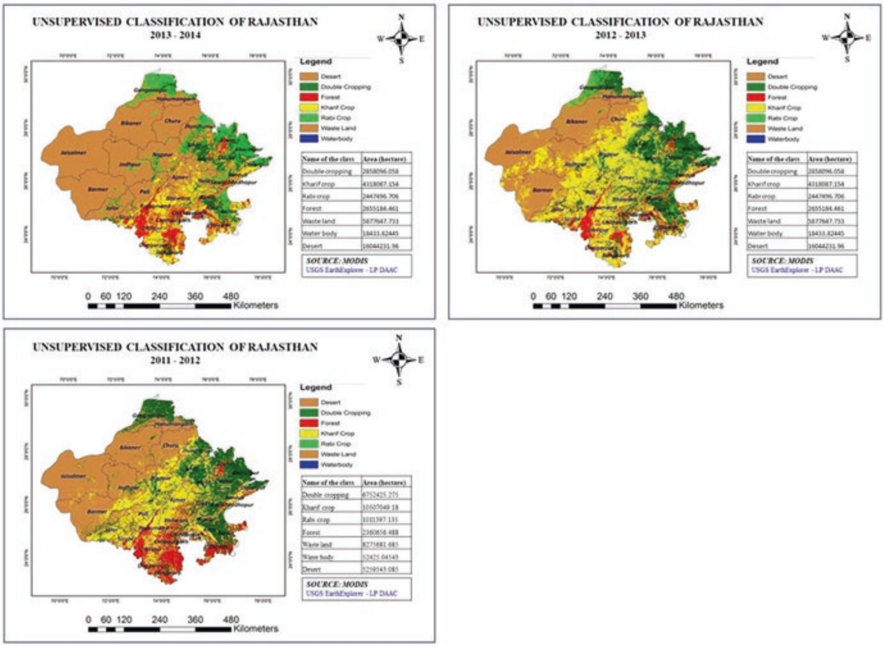

Fig. 8 (continued)

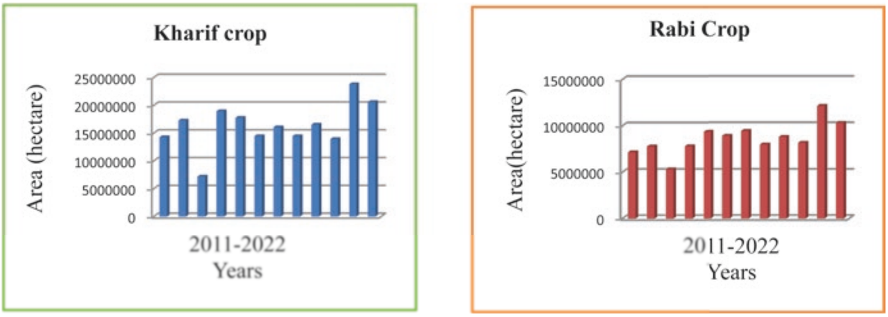

Fig. 9 Average productivity of Kharif and Rabi crop, 2011–2022

precipitation. The Indira Gandhi Nahar Project (IGNP) canal has altered the environment in Rajasthan's western districts (IGNP command region).

There is a strong association between rainfall and crop yield for the Kharif crop and a weak correlation between rainfall and crop yield for the Rabi crop. There is a moderate link between rainfall and NDVI of the Rabi crop and a good correlation between rainfall and NDVI of the Kharif crop. There is a moderate link between rainfall and NDVI of the Rabi crop and a good correlation between rainfall and NDVI of the Kharif crop.

Figure 9 demonstrates that in the study area, the Kharif crop predominates over the Rabi crop.

5 Conclusion

Crop yields and the kinds of crops that can be cultivated in Rajasthan regions can both be severely and positively impacted by climate change. Due to its repeated and synoptic coverage, remote sensing data offers a unique potential for assessing crop production and acreage at the district or regional levels. Forecasting agricultural production heavily relies on preharvest crop type and yield estimation. Changes in climate conditions, including quantity, quality, and production costs, have had a substantial impact on agriculture and will continue to do so. Temperatures and rainfall directly affect weather changes that are more unpredictable and severe circumstances.

After using the HANTS (Harmonic Analysis of Time Series) algorithm, multiyear NDVI time series data from 2011 to 2022 produced from MODIS (MOD09Q1 reflectance) data were determined to be suitable for monitoring agricultural areas over Rajasthan. The HANTS algorithm has been found to be a useful tool for time series data smoothing and cloud-affected data analysis in NDVI temporal series. From the analysis, estimation, and result presented here, it can be inferred that better yields can be anticipated during the Rabi season in double cropping areas with rainfed conditions by implementing in situ moisture conservation practices and sparingly using fertilizers in terms of timing and quantity (Rao et al., 2011). Rainfall, agriculture in the study area, and ultimately agricultural productivity were all impacted by the El Nino and La Nina occurrences.

According to an analysis of rainfall, the Kharif crop is particularly affected by these occurrences. While the rainfall curve typically follows a bell-shaped pattern during the regular season, El Nino and La Nina years showed numerous variances. One notable characteristic of El Nino years was the shifting of the rainfall. Rainfall in El-Nino years was shifted to the final 2 months of the rainy season (September and October). While in La-Nina years, there was an increase in rainfall. The IGNP canal has altered the environment of Rajasthan's western districts (IGNP command area). Over the northwest part of India during the season, there are typically 4–5 western disturbances per month. While some of the western disturbances pass with little to no rain or infrequently no rain, others produce well-distributed and good rainfall. Months of winter Rainfall is crucial to agriculture, particularly for the growth of the Rabi crops in the northern subcontinent, which contains the regional grain wheat. Rabi crops do not entirely rely on winter rains, however, unlike kharif crops.

The study's results are as follows: Rainfall and crop yield for the Rabi crop have a weak association, while rainfall and crop yield for the Kharif crop have a strong link. Rainfall and NDVI of the Rabi crop showed a modest association, but the Kharif crop showed a good correlation between the two variables. A modest association between rainfall and NDVI was observed for Rabi crop showed a, while a good correlation between the two variables was observed for Kharif crop.

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Drone Technology in Perspective of Data Capturing

Ram Kumar Singh, Sanjay Singh, Manoj Kumar, Yogeshwer Singh, and Pavan Kumar

1 Introduction

The emergence of drone technology has significantly transformed diverse industries, introducing novel avenues for the acquisition, interpretation, and investigation of data (Faughnan et al., 2013; Idries et al., 2015). Unmanned aerial vehicles (UAVs), colloquially known as drones, have emerged as versatile apparatuses, equipped with an array of sensors and cameras capable of capturing high-fidelity imagery, video recordings, and assorted data from hitherto inaccessible or arduous vantage points (Cunliffe et al., 2020; Turner et al., 2012; Fudala & Bialik, 2020). A drone is an unmanned flying robot that can fly autonomously using software-planned flying path and it can be controlled remotely from the ground. It works with onboard sensors, global position systems (GPS), storage devices, etc., even if it is an unmanned aircraft. In 1951, Abraham Karem, a scientist from Iraq, pioneered the design of key components for both fixed and rotarywing unmanned aircraft, earning him the title of the father of Drone technology (Cajiao et al., 2021; Turner et al., 2018; Bollard-Breen et al., 2015).

This technological progression has ushered in promising prospects for the execution of research spanning across a spectrum of disciplines, encompassing but not limited to environmental science, agriculture, archaeology, wildlife surveillance, and disaster management (Jones et al., 2019). This preliminary discourse furnishes a comprehensive overview elucidating the pivotal role and significance of drone-centric research endeavors, accentuating its salient attributes, varied applications, and attendant advantages.

R. K. Singh (✉) · S. Singh · M. Kumar
Centre of Excellence on Sustainable Land Management, ICFRE, Dehradun, India

Y. Singh · P. Kumar
Rani Lakshmi Bai Central Agricultural University, Jhansi, India

P. Kumar, Aishwarya (eds.), *Technological Approaches for Climate Smart Agriculture*, https://doi.org/10.1007/978-3-031-52708-1_18

Drones have exerted a substantial influence on the realm of environmental research, furnishing researchers with a potent and adaptable instrument for data acquisition, ecological monitoring, and investigation into diverse environmental phenomena. These technological capacities have engendered novel prospects and heightened the caliber of research within the domain of environmental science. The subsequent elucidation delineates several avenues through which drones have engendered an impact on the landscape of environmental research (Korczak-Abshire et al., 2016; Leary, 2017; Adams et al., 2019; Al-Turjman et al., 2020).

Drone-based research encompasses the utilization of unmanned aerial vehicles (UAVs) to amass empirical data, conduct observational analyses, and execute experimental procedures across diverse environmental settings. These UAVs possess the capability to access geographically distant or perilous locales, affording researchers an exceptional vantage point and immediate access to real-time information (Bera et al., 2020; Xu et al., 2017). They are deployable for both qualitative and quantitative data acquisition, thereby augmenting the depth and precision of research outcomes (Jones et al., 2019; Patra et al., 2019; Mohamed et al., 2018). The involvement of drones in research extends beyond mere data collection, encompassing pivotal roles in cartography, topographical surveying, and the continuous monitoring of multifarious phenomena, thereby engendering an enriched comprehension and insights into the subject under study.

The drone is of four types based on built and flying techniques: multi-rotor, fixed-wing, single-wing, and fixed wing hybrid vertical take-off and landing (VTOL) drones as shown in Fig. 1. The major difference between all the drones is their flying capacity, uses, and data-capturing methods. In dense and highly rugged terrain, Multi-Rotor drones offer a distinct advantage in data capturing perspective over other drones. This advantage varies across different applications and sensor integration capabilities. The comparison between all the drones is listed in Table 1.

1.1 Classification of Drone Systems

With the rapid advancement of technology, drones have evolved into versatile systems with diverse capabilities and applications (Fotohi, 2020; Zhi et al., 2019; Manesh & Kaabouch, 2019; Volovelsky, 2014). This chapter presents a comprehensive classification framework for drone systems, aiming to categorize them based on their features, functionalities, and intended purposes. Understanding the various types of drone systems is essential for researchers, policymakers, and industry stakeholders to make informed decisions regarding their implementation and regulation.

The Indian Ministry of Civil Aviation, through gazette notifications CG-DL-E-26082021-229221 dated August 25, 2021, and CG-DL-E26012022–232917 dated January 26, 2022, respectively, released the Drone Rules and the Certification Scheme for Unmanned Aircraft Systems. These regulations also classify drones based on their weight, as various weight categories typically influence

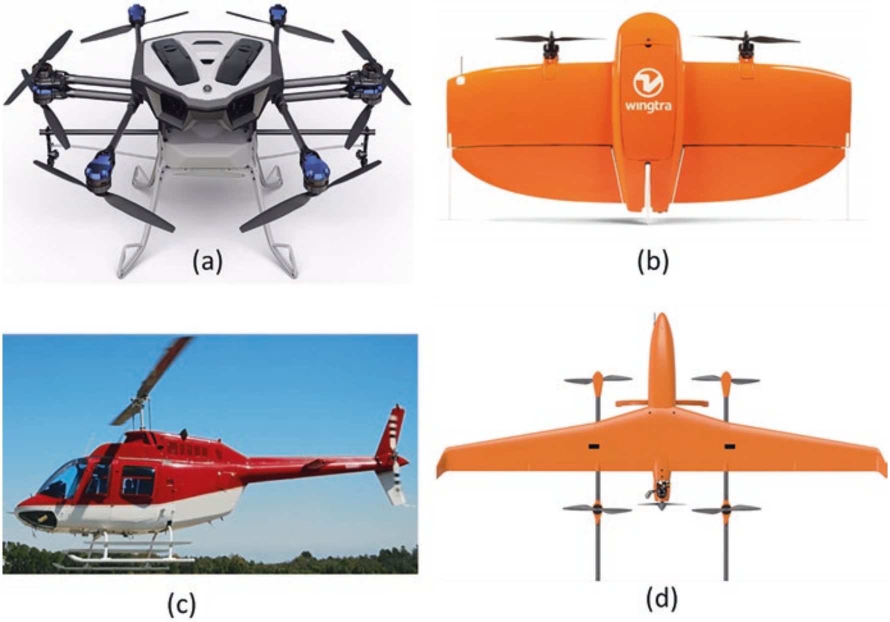

Fig. 1 Types of drone: (**a**) multi-rotor, (**b**) fixed-wing, (**c**) single -wing, and (**d**) fixed-wing hybrid vertical take-off and landing (VTOL) drones

their capabilities, flight characteristics, and regulatory considerations. The following outlines some general weight classifications for drones.

1.1.1 Nanodrones

These are the smallest and lightest drones, typically weighing less than 250 g (0.55 pounds). They are often used for indoor flying, simple tasks, and recreational purposes (Fig. 2). The nanodrone does not fly beyond 50 ft. (15 m) above ground level (AGL). Also, it needs permits, even if you fly in controlled airspaces like airports or other sensitive facilities.

1.1.2 Microdrones

Microdrones weigh between 250 g and 2 kg (0.55–4.4 pounds). They are slightly larger than nanodrones and can have more advanced features while still being suitable for indoor flying and some outdoor applications (Fig. 2). No permits are required for non-commercial usage only.

Table 1 Difference between multi-rotor, fixed-wing, single-wing, and fixed-wing hybrid vertical take-off and landing (VTOL) drones

Drone type	Advantages	Disadvantages	Applications	Finance/pricing
Multi-rotor	1. Ease to learning flying 2. Good sensor control 3. VTOL and hover flying 4. Operate in highly terrain areas.	1. Low endurance and flight time 2. Small payload capacity	1. Arial inspection 2. Arial photography and video making	1. Cheapest in drone range 2. Easy flying permission for remote sensing data capturing
Fixed-wing	1. Swift flying with high speed 2. Long flying capacity 3. High endurance	1. Launch and recovery need free open space 2. No function for VTOL/hover flying 3. Need extra training to operate	1. Aerial Lidar scanning	1. Expensive
Single-wing	1. Long flying capacity 2. Flying VTOL and hover 3. Heavier payload capacity	1. Harder to fly and more extensive training required 2. More dangerous	1. Drone-based delivery	1. Expensive
Fixed wing hybrid (VTOL)	1. Long flying capacity 2. Flying VTOL	1. Not perfect at either hovering or forward flight 2. In research and development phase	1. Drone delivery and data capturing	1. Moderate expensive

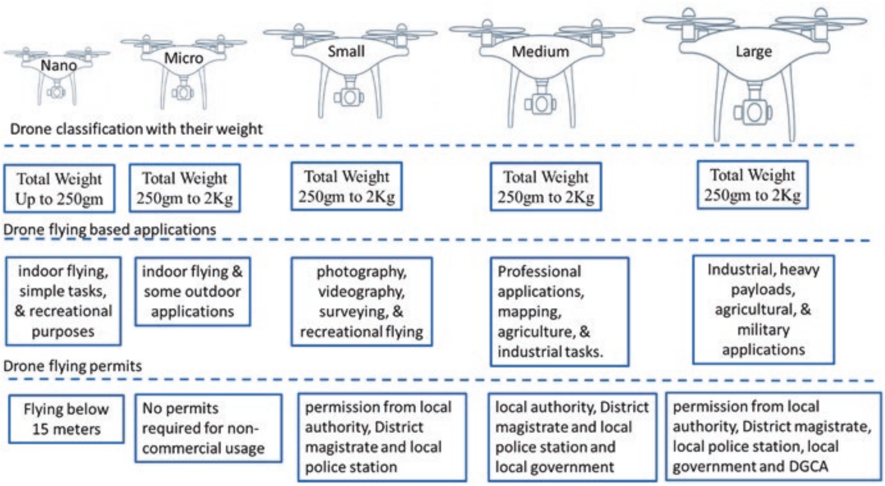

Fig. 2 Classification of drone based on DGCA, Ministry of Civil Aviation, Government of India (2021): left to right – nano, micro, small, medium, large drones, weight, flying applications, and permits requirements

1.1.3 Small Drones

Small drones fall within the weight range of 2–25 kg (4.4–55 pounds). They are commonly used for photography, videography, surveying, and recreational flying (Fig. 2). It needs permission from local authorities, the district magistrate, and the local police station for its usage.

1.1.4 Medium Drones

Medium drones weigh between 25 and 150 kg (55–330 pounds). They have higher payload capacities and longer flight endurance, making them suitable for various professional applications, including mapping, agriculture, and industrial tasks (Fig. 2). It needs permission from local authorities, the district magistrate, and local police station and local government for its usage.

1.1.5 Large Drones

Large drones weigh between 150 and 600 kg (330–1320 pounds). They are often used in industrial, agricultural, and military applications where heavy payloads or specialized equipment is required (Fig. 2). It needs permission from the local authority, district magistrate and local police station, local government, and DGCA for its usage.

It is important to note that these weight categories may have different classifications and regulations in various countries. The regulatory requirements for drone operation, such as registration, licensing, and flight restrictions, can vary based on the weight class and the intended use of the drone (Condomines et al., 2019; Amanullah et al., 2020; Besada et al., 2019). Additionally, as drone technology continues to advance, the boundaries between these weight categories may evolve over time. Always be sure to check with local aviation authorities to understand the specific rules and regulations that apply to drones in your area.

Modern drones are equipped with a variety of cutting-edge technologies that enhance their research capabilities. The major components of the drones are:

1. *Cameras and Sensors*—Drones can carry different types of cameras (RGB, multispectral, thermal) and sensors (LiDAR, gas detectors, radiation detectors) to capture a wide range of data relevant to the research objectives.
2. Integrated micro global positioning system (GPS) receiver devices enable geolocation and accurate mapping of data collected by drones. It has the capability to get the precise locations using real time kinematics (RTK) and inertial measurement unit (IMU) to accelerometers and gyroscopes to measure acceleration and rotation, which can be used to provide position data.

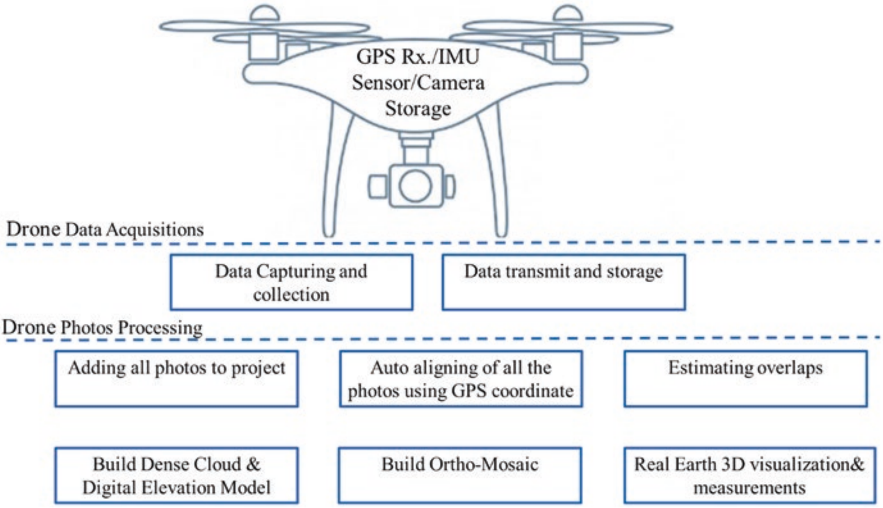

Fig. 3 Drone data acquisition and their processing to get remote sensing data

3. *Autonomous Flight*—Drones can be programmed to follow predefined flight paths autonomously, ensuring consistent data collection and minimizing human intervention.
4. *Remote sensing* drones enable remote sensing by capturing data from the air, providing researchers with a comprehensive view of large areas or inaccessible terrain.

The drone has the ability to store captured information and key data directly onto its onboard storage chip. Despite technological advancements, the drone can also transmit real-time data to the ground system unit, facilitating swift communication. This proves highly beneficial for rapid incident reporting, analysis, and decision-making (Fig. 3). The drone captured data are collectively processed to derive useful analytical outcomes. The data are processed using drone processing software, an advanced software tool that assists in processing the collected data, creating maps, 3D models, and other visualizations for analysis (Nikolic et al., 2013; Birtchnell & Gibson, 2015; Mathews & Wikle, 2019; Williams et al., 2017) (Fig. 4).

1.2 Drone Processing Software

Drone processing software plays a crucial role in transforming raw data captured by drones into valuable insights, maps, models, and visualizations. The process involves several steps that leverage advanced algorithms and computational techniques to extract meaningful information from the collected data. Here is an overview of how drone processing software works:

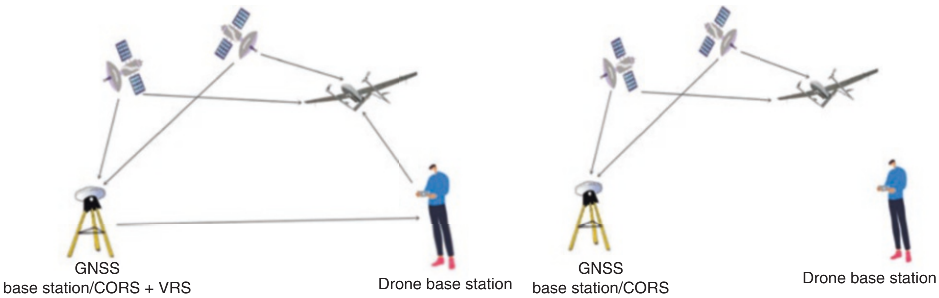

Fig. 4 Drone flying in real-time kinematics (RTK) and post-processing kinematics (PPK) mode of data collection. (Source:ref.: https://www.jouav.com/blog/rtk-drone.html)

1.2.1 Data Collection

The process begins with a drone equipped with various sensors, cameras, and other data-capturing devices. Drones are flown over the target area, and they capture a multitude of images, videos, or sensor readings. These data points serve as the raw material for further analysis. Data Import and Management: The captured data are then uploaded to the processing software. The software organizes and manages the data, often allowing users to select the specific datasets they want to process.

1.2.2 Image Stitching and Alignment

If images were captured, the software first stitches these images together to create a seamless and georeferenced mosaic. This involves identifying common features in overlapping images and aligning them accurately.

1.2.3 Feature Extraction

The software identifies key features in the imagery, such as points, lines, and areas of interest. This step is crucial for generating accurate maps and models.

1.2.4 Photogrammetry

Photogrammetry is a technique used to measure distances and create detailed 3D models from 2D images. Drone processing software uses photogrammetric algorithms to triangulate points and calculate distances, enabling the creation of 3D point clouds.

1.2.5 Point Cloud Generation

The software constructs a point cloud—a collection of data points in a three-dimensional coordinate system. This point cloud represents the surface of the surveyed area and can be used to create 3D models and maps.

1.2.6 Digital Surface Model (DSM) and Digital Terrain Model (DTM) Generation

The software differentiates between ground-level surfaces (DTM) and above-ground features (DSM) to create accurate elevation models. These models are crucial for applications such as land surveying and construction planning.

1.2.7 Orthomosaic Generation

An orthomosaic is a georeferenced, orthorectified image that removes distortions caused by terrain and camera angles. Drone processing software aligns and merges images to generate high-resolution orthomosaics, which are often used for detailed visual inspections and accurate measurements.

1.2.8 Analysis and Visualization

Once the basic models and maps are generated, the software offers various tools for analysis and visualization. Users can perform measurements, compare data over time, and extract insights to make informed decisions.

1.2.9 Export and Sharing

The final outputs, such as 3D models, maps, and reports, can be exported in various formats compatible with geographic information systems (GIS), computer-aided design (CAD) software, or other tools. These outputs can be shared with stakeholders for collaboration and decision-making.

1.2.10 Advanced Analysis (Optional)

Some drone processing software may offer more advanced analysis options, such as vegetation health assessment using multispectral or thermal imagery, volumetric measurements of stockpiles, and more.

1.3 Applications of Drone-Based Research

Drone technology has found applications in a wide range of research fields:

- *Environmental Monitoring*: Drones are used to monitor ecosystems, track deforestation, assess pollution levels, and study changes in land cover and vegetation (Ayamga et. al., 2021; Kevin et al., 2021).
- *Agriculture*: Drones assist in crop monitoring, pest detection, precision agriculture, and yield estimation through high-resolution imaging and multispectral analysis (Alsamhi et al., 2019; Rahman et. al., 2017; Yang et al., 2018).
- *Archaeology*: Drones aid in the identification and documentation of archaeological sites, enabling researchers to create detailed maps and models of historical landscapes.
- *Wildlife Conservation*: Drones are utilized for wildlife tracking, population estimation, and behavior observation, reducing disturbance to sensitive species (Sharma et. al., 2020).
- *Geological Surveys*: Drones provide valuable data for geological mapping, landslide detection, and assessing seismic activity in remote or rugged areas (Lin et. al., 2018).
- *Disaster Response*: Drones play a crucial role in disaster assessment, search and rescue operations, and damage evaluation following natural or man-made disasters (Bagloee et al., 2016).

1.4 Benefits and Future Prospects

The integration of drone technology in research offers several benefits, including increased efficiency, cost-effectiveness, and reduced risk to researchers. Drones enable data collection from multiple angles and perspectives, enhancing the quality and depth of research outcomes. As technology continues to advance, drones are becoming more sophisticated, with longer flight times, improved sensor capabilities, and enhanced autonomy (Holloway et al., 2019; Morrison et al., 2013; Hodgson & Piovan, 2021; West et al., 2019; Tsiamis et al., 2019; Ayamga et al., 2021; Alamouri et al., 2021). However, challenges related to regulatory frameworks, data privacy, and operational limitations still need to be addressed for the full realization of drone-based research's potential.

In conclusion, drone-based research has transformed the way researchers collect and analyze data across various disciplines. The versatility, accessibility, and technological capabilities of drones have opened up new frontiers in research, leading to deeper insights and innovative solutions to complex challenges. As the field continues to evolve, drone technology is poised to play an increasingly pivotal role in advancing scientific knowledge and driving progress across diverse research domains.

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Renovating Conservation Agriculture: Management and Future Prospects

Dipti Grover, Bhawna Dahiya, Ajay Kumar Mishra, Neha Kalonia, Pinki Rani, and Sheetal Sharma

1 Introduction

The Indo-Gangetic plain (IGP), being the breadbasket of the world, is a 630 million acres (255 million-hectare) fertile land encircling the most populous parts of Pakistan, Nepal, Bangladesh and most of northern and eastern India (Naresh et al., 2018). Punjab, Haryana, Uttar Pradesh, Himachal Pradesh, Bihar and West Bengal are the states that make up the Indian IGP region; there are 10.5 million hectares of rice-based cropping systems there. Rice-based cropping system may be designated rice as a significant crop or followed by succeeding cultivation of other crops. The rotation of crops involving grains, pulses, oilseeds, cotton, sugarcane, green manures, and vegetable crops is one of the main cropping systems used in India.

Due to implementing a Green Revolution technology that caused yield growth, followed by area growth, agricultural output in this region has kept up with food demand during the past three decades. Nevertheless, it is necessary to increase rice productivity further as the land area under rice cultivation is declining. The most fertile land of IGP has degraded because of faulty agricultural practices such as intensive tillage, straw burning, excessive use of agrochemicals, flooded irrigation and mono-cropping. However, new difficulties for rice-based cropping systems include climate change, fuel price increases, agriculture costs, socioeconomic shifts like labour migration, urbanization, and worries about environmental contamination (Mahajan et al., 2017). To maintain the rice-based cropping system, conservation

D. Grover · B. Dahiya · N. Kalonia · P. Rani
Institute of Environmental Studies, Kurukshetra University, Kurukshetra, Haryana, India

A. K. Mishra (✉) · S. Sharma
International Rice Research Institute South Asia Regional Centre (ISARC), Varanasi, Uttar Pradesh, India
e-mail: a.k.mishra@irri.org

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agriculture (CA) must be used instead of traditional management techniques, and CA must be renovated.

Three interconnected principles serve as the foundation of CA: (i) no-till/minimal tillage (no or minimal mechanical soil disturbance); (ii) cover cropping (permanent preservation of soil mulch cover); and (iii) crop diversity. FAO describes CA as a resource-efficient agricultural crop production paradigm focused on strengthening the natural and biological processes above and below the ground (http://www.fao.org.ag/ca). It leads to the enhancement of carbon(C) sequestration (Kumar et al., 2022), improvement in the structure and stability of the soil, enrichment in retaining soil moisture, creating microclimate at residue–soil interface, restoring habitat, and maintaining the ecosystem, and enhancement in microbial diversity. CA was practised over 205 million ha of land spread across 102 nations, growing by about 10.5 million ha annually. The results of the multiple parameter study of CA in South Asia showed that system productivity increased by 5–12%, water use efficiency by 10–30%, energy by 46–62%, labour by 26–44%, profitability by 20–27% and greenhouse gas (GHG) emissions by 12–33%. Much improvement has been observed in soil health. However, further sustainable crop intensification with conservation strategies for food security and environmental issues is necessary. So, renovation in conservation agriculture is the future of agriculture and food security could be protected; nevertheless, farmers cannot achieve this alone. Governments with multiple stakeholders share the responsibility and disseminate awareness of conservation agriculture through schemes and policies encouraging farmers to adopt the initiative.

2 Concept of Renovating Conservation Agriculture

To keep pace with global food demand, two contrasting approaches to agriculture future are required: resource conservation and sustainable intensification. Renovating conservation agriculture is the modification and improvement of conventional conservation agriculture. The major challenges in renovating conservation agriculture can be changing farmers' strategy (Mishra et al., 2022a) and their behaviour toward transitioning from conventional to renovating conservation agriculture (RCA).

RCA includes various agricultural techniques to boost soil biodiversity, rebuild soil organic matter, improve water retention and nutrient uptake and mitigate climate change (CC) by halting soil organic carbon (SOC). RCA assists the farmer in preserving farm income and productivity while regenerating the soil and ecosystem (Table 1) (Mishra et al., 2022a, b, c). Several agricultural practices focus on topsoil restoration by soil biodiversity enhancement, rebuilding soil organic matter, improving water retention and nutrient uptake and climate change (CC) mitigation by arresting soil organic carbon (SOC). RCA assists the farmer in preserving farm income and productivity while regenerating the soil and ecosystem (Mishra et al., 2022a, b, c).

Table 1 Differences between conventional, conservation and renovating conversation agriculture

	Conventional agriculture	Conservation agriculture	RCA
Tillage	Intensive Tillage	No tillage /minimum tillage	Single pass no-tillage/low tillage and mulching/ strategic tillage (once in 5 years)
Cropping system	Mono cropping /less efficient crop rotation	Diversified and more efficient crop rotation	Need-based (nutrient)/ diversified crop rotation
Residue management	Residue burning	Surface retention of residue/permanent cover	Surface retention with required residue and the rest of it is sent to market for further utilization
Agrochemicals	Excessive use of agrochemicals (ex-situ)	Use of in-situ organic fertilizers / compost	Soil test-based organic amendments /fertilizers / supplements as and when needed
Water use / irrigation	Flooded irrigation	Conservative irrigation practice (sprinkler irrigation, drip irrigation)	Conservation irrigation strategies with other strategies: precipitation storage, moderating soil temperature, reducing run-off and evaporation
Soil degradation	A lot of soil degradation	Improved soil structure and stability	Degradation reversed and restored
Priority /major concern	Crops are a major concern	Crops are a major concern	Integration of crops, trees and livestock
Yield	Higher yield on a short-term basis but declining on long-term basis	Higher yield on long-term basis	Higher yield in a sustainable way
Environmental quality	Degraded	Considerable managed /improved	Integral part of restoring and enhance the environmental quality
Greenhouse gas emission	Maximum	Reduced	Minimise
Economy	Input—higher Output—higher for short term	Input—lower Output—higher for long term	Enhanced on the basis of insectivization and market-based/sustained profitability

3 Issues Related to Rice-Based Agriculture in the Indo-Gangetic Plains

RWCS, or the rice-wheat cropping system, is the foundation of Indian agriculture, especially in the northwest. However, on-going RWCS adoption in northwest India has led to significant problems and stagnation in this system's productivity (Dhanda et al., 2022). Due to technological intervention, the country's food grain output increased significantly despite the arrival of Green Revolution, the RWCS's existing farming methods are compromising the viability of this system by depleting its soil and water resources (Chauhan et al., 2012; Kumar et al., 2018). Crop productivity doubled over the past 10 years but at the cost of improper input management, which had a detrimental effect on the environment, biodiversity, soil quality, and air quality (Godfray & Garnett, 2014; Tilman et al., 2011).

3.1 Deteriorating Soil Health

The amount of mineral nutrients that are taken out from the soil by tillage and crop production depends on the soil's ability to produce crops and supply nutrients, which is in turn affected by the type of soil, its organic matter content, the quantity of nutrients applied and the removal or recycling of crop residues from the soil. A major source of nutrition is rice. Puddling used in rice farming destroys the soil's structure, which results in unacceptable soil aeration and compaction (Kumar et al., 2008; Pathak et al., 2011). Because of this, the continued use of the RWCS has caused a hardpan at shallow depths that prevents root proliferation and penetration into the soil, impacting the development of the subsequent wheat crop. When wheat was planted after puddled transplanted rice rather than directly seeded rice, a decrease in wheat production (8% lower) was observed. (Yadav et al., 2021; Chaudhary et al., 2023). In the surface layers, constantly changing properties, such as soil water transmission, aggregation, bulk density, and aeration, significantly affect the soil's physical quality (Cavalieri et al., 2009). In the process of preparing the seedbed, the organic matter that was once concealed is oxidized and the macro-aggregates are broken down into micro-aggregates, which negatively affects the soil's properties. Various methods of tillage have an impact on soil aggregation both directly by destroying macro-aggregates and indirectly by affecting biological and chemical variables (Barto et al., 2010). Different physical properties and soil organic matter (SOM) are indicators of soil quality and are crucial to the production efficacy of soil (Shukla et al., 2006). The mechanical disintegration of macro-aggregates during conventional tillage typically destroys the mycelium network (Borie et al., 2006) and decreases the amount of SOC and microbial biomass (Mikha & Rice, 2004). Puddling breaks up soil aggregates, which causes surface crusts and cracks to develop when the soil dries, delaying the preparation of a seedbed for subsequent crops. The large clods created when tillage breaks the soil provide inadequate contact with the seed, limiting germination. Late-appearing seedlings may become trapped under the surface if crusts form after rain shortly after sowing. Burning residue destroys soil microflora and fauna, which reduces biodiversity. Additionally, repetitive burning incidents in a field wipe out the soil's microbial population, which has a long-term negative impact on the biological properties of the soil (Grover & Chaudhry, 2023; IARI, 2012; Li et al., 2013; Mehta et al., 2013).

3.2 Groundwater Depletion

Groundwater (GW) is crucial in establishing global water and food security. India abstracts a significant amount of GW globally, using almost 90% of it to irrigate almost 60% of its irrigated land (CGWB, 2021). Following the Green Revolution, there was a major shift to cereal cultivation, multiple cropping seasons and a hike in irrigated areas. This led to increased yield, higher profits, and greater food security, but at the cost of depleted water supplies (Barik et al., 2017; Davis et al., 2019; Zaveri & Lobell, 2019). Due to its whacking at the desired quantity and frequency throughout the year, GW-fed irrigation subsequently spread (Shah, 2009), Making the country less impressionable to famines. The RWCS is widespread in northwest India, particularly in Punjab, Haryana and Uttar Pradesh, and most of these areas rely on groundwater for cultivation. (Ambast et al., 2006). It requires an enormous amount of water to keep rice paddies from flooding. Rice produced using conventional methods during a season needs about 1500 mm of water. Additionally, seedlings need about 50 millimetres of water to reach the transplanting growth stage. However, where rice is produced on light-textured soils in India and Pakistan, farmers use much more water than is necessary (Timsina & Connor, 2001). In some areas of the IGP, the water table has declined by 0.1–1.0 m year^{-1} due to inadequate irrigation systems and more dependence on groundwater, creating a shortage and raising water costs (Harrington et al., 1993; Sharma et al., 1994; Sondhi et al., 1994).

The groundwater level drastically decreased due to excessive use and poor groundwater management (Humphreys & Gaydon, 2015). In the Indian states of central Punjab and some of Haryana, the rise in groundwater depth has hastened, going from about 0.2 m per year between 1973 and 2001 to about 1.0 m between 2000 and 2006. In 2009, overexploitation occurred in 108 out of 138 administrative blocks in Haryana and 103 out of 138 administrative blocks in Indian Punjab. The mean water-table level in the Indian Punjab of the NW-IGP, which was 22.8 m in 2006, is predicted to rise to 34.2 m by 2016 and 42.5 m by 2023 (Hira, 2009). The traditional method of puddled transplanted rice (PTR) production in the NW IGP of India faces a severe threat from overexploitation of groundwater resources caused by high water input and poor water productivity (WP). In the current agricultural scenario in India, rice cultivation typically requires a significant amount of water, ranging from 2500 to 3500 l for every kilogram of rice produced. To mitigate the ongoing degradation of water resources, it is crucial to enhance the water productivity of rice farming. The goal is to reduce the water requirement to about 2000 l/kg, thus making rice cultivation more sustainable and less taxing on the water resource base (Mohapatra et al., 2013).

3.3 Exhausting Nutrient Pools

The high intensity in crops, low or non-accessibility of organics, and excessive reliance on chemical fertilizers, which results in a lack of several micronutrients, are the main causes of the intensive rice-based cropping system in IGP (Singh et al., 2007, 2015). High-scale deficiencies of cationic micronutrients like copper (Cu), zinc (Zn), iron (Fe) and manganese (Mn) in various soils have been documented globally (Shukla et al., 2014; Sillanpaa, 1990). Recent Indian studies describe widespread micronutrient deficiencies in fields due to the routine removal of these nutrients by crop uptake (Shukla et al., 2014; Shukla et al., 2015). Molecular oxygen is lost during flooding, and NO_3, Fe (III), Mn (IV) and SO_4 undergo chemical reduction. These changes result in a decrease in the accessibility of nitrogen (N), sulphur (S), and zinc (Zn) and a rise in the availability of phosphorus (P), potassium (K), silicon (Si), molybdenum (Mo), copper (Cu), and cobalt (Co) and (Zn) (De Datta, 1986; Patrick Jr., 1982; Sanyal & De Datta, 1991). Microorganisms that break down organic substrates under anaerobic circumstances are also more likely to produce toxic byproducts like organic acids, hydrogen sulphide, and methane (Ponnamperuma, 1972). The RW system has caused a nutrient imbalance and the removal of significant minerals (N, P, K, and S) from the soil, which has led to a decline in soil quality. The most severe deficiencies are those in N, P, and K. One tonne of rice requires the removal of 20.1 kg N, 4.9 kg P, and 25.0 kg K during production (Tandon & Sekhon, 1988). Crops continuously use up the limited amount of nutrients in the soils of IGP, which have minimal levels of organic matter (Bijay-Singh & Yadvinder-Singh, 2004). Excessive nutrient mining of the soils is one of the major factors contributing to the soils' exhaustion under the RW system. For N, N, 25% for P and 40% for K, the efficacy of applied nutrients has been about 50% (Witt et al., 1999). Significant nitrogen losses through leaching, runoff, gaseous release, and soil fixation cause lower efficiencies. Nevertheless, only fertilizer macronutrients are added to the earth, while some crucial micro- and secondary nutrients are ignored. As a result, a long-term microelement deficiency has been developing, which harms grain yield by disrupting the equilibrium of nutrients in the soil. These losses may result in the deterioration of soil and water quality and the degradation of the ecosystem (Prasad, 2005).

3.4 Residue Burning

Burning agricultural waste can have several negative consequences, such as localized air pollution, a rise in black carbon, and local and global climate change contributions (Ahmed et al., 2015). Farmers typically prefer to burn the leftover rice residue because it is challenging with tillage and sowing procedures for the next wheat harvest. Harvest residue removal through open-field burning is a human-initiated practice to make way for the following harvest (Gadde et al., 2009). Punjab generates approximately 23 and 17 million tonnes of paddy and wheat straw annually, of which more than 80% of paddy straw (18.4 million tonnes) and nearly 50% of wheat straw (8.5 million tonnes) are burned in fields (Kumar et al., 2015). Paddy residue is burned primarily as a result of the inability of the workforce to collect stubble manually, the costly process of residue removal and the poor market rates of residues (Grover et al., 2015). Because an intensive rice-wheat crop cycle does not permit crop residues to be kept on the field for long periods, they are frequently open-burned (Gadde et al., 2009) to quicken the preparation of the field for the next season's crop. Every year, residue burning goes on for over 3 weeks, covering the Indo-Gangetic plain in smog from west to east (Badarinath et al., 2009; Mishra & Shibata, 2012). Black carbon, the second-largest greenhouse gas after carbon dioxide, is produced when agricultural leftovers are not completely burned (Chung et al., 2005; Forster et al., 2007; Ramanathan & Carmichael, 2008; UNEP, 2009). In Haryana, during the rice and wheat crop seasons, both burning and non-burning times, the air quality index (AQI) and concentration of primary pollutants (SOx, NOx, and PM2.5) were measured. During crop residue burning, AQI is discovered in extremely polluted groups, and SOx, NOx, and PM2.5 concentrations were 78, 71 and 53% higher than the NAAQS values (Grover & Chaudhry, 2019). An estimated 23 million tonnes of rice residue are burned annually by about two million cultivators in the northwest and some areas of eastern India (NAAS, 2017). In total, 516 million tonnes and 116 million tonnes, respectively, were estimated to be the total quantity of crop residues produced and burned in 2017–18. Air pollution from burning agricultural residue is a significant contributor to early (human) mortality. A survey in a village in Haryana revealed that the primary motivation for burning was to rapidly prepare the land for the following crop and get rid of weeds and pests. The inability to harvest stubble manually, the high cost of removing residues and the poor market prices of residues were other factors that were noted as contributing to residual burning (Grover et al., 2015). However, according to the literature on burning, burning straw after the rice has been harvested can have both short- and long-term positive and negative impacts on the soil's quality. In the short term, burning improves the availability of some nutrients like phosphorus and potassium (Erenstein, 2002). According to a recent study, it might boost the crop's productivity in the following growing season (Haider, 2012). However, it can also lead to the loss of plant nutrients like nitrogen, potash and sulphur and adversely impact the local microbial population, community structure, and biological properties like organic carbon and glomalin content (Grover & Chaudhry, 2023). In addition to the significant loss of soil fertility brought on by residue burning (Prasad et al., 1999), the ensuing air pollution affects millions of people in cities and villages downwind due to seasonal meteorological conditions that allow smoke to blanket a large area (Mishra & Shibata, 2012; Vijayakumar et al., 2016). In some northwest Indian cities, particulate air pollution in 2017 exceeded the safe daily threshold levels by more than five times, leading to serious health issues in rural and urban regions. (Central Pollution Control Board of India, 2017). As a result, it is difficult to handle the RWCS leftovers in a timely and cost-effective manner, particularly the rice straw (Fig. 1).

Fig. 1 Drivers of crop residue burning in North-western IGP of India

3.5 Greenhouse Gas Emissions

Agricultural soils increase the atmospheric CH_4 and N_2O (Mosier, 1998). Two of the most significant greenhouse gases causing global warming are methane (CH_4) and nitrous oxide (Fig. 2) (IPCC, 1996). CH_4 emission is caused by methanogenesis, a biogeochemical process required in all anaerobic settings where organic matter is decomposed (Oremland, 1988). Due to the submerged soil, anaerobic conditions develop in wetland rice paddies, one of the most significant sources of atmospheric CH_4 (Neue et al., 1997).

Climate change harms the productivity of the main staple food crops (wheat, maize, rice and soybean) in many parts of the globe. And agriculture is the main driver of this change. About one-fourth (10–12 Gt CO_2 eq. yr1) of net anthropogenic greenhouse gas (GHG) emissions are contributed by agriculture, forestry, and other land-use industries. About 16% of India's greenhouse gas pollution comes from agriculture. Cattle (38.9%) and rice (36.9%) methane emissions account for 74% of agricultural greenhouse gas emissions (Vetter et al., 2017). Nitrous gas emissions from fertilizers make up the remaining 26%.

Most rice is transplanted on land repeatedly prepared using wet tillage and is saturated with water (puddling). The field is flooded in water for the crop's development, and the seeds of wheat are sown thoroughly on tilled soil with adequate air circulation (Gupta et al., 2015). Anaerobic fields of rice are a major source of CH_4,

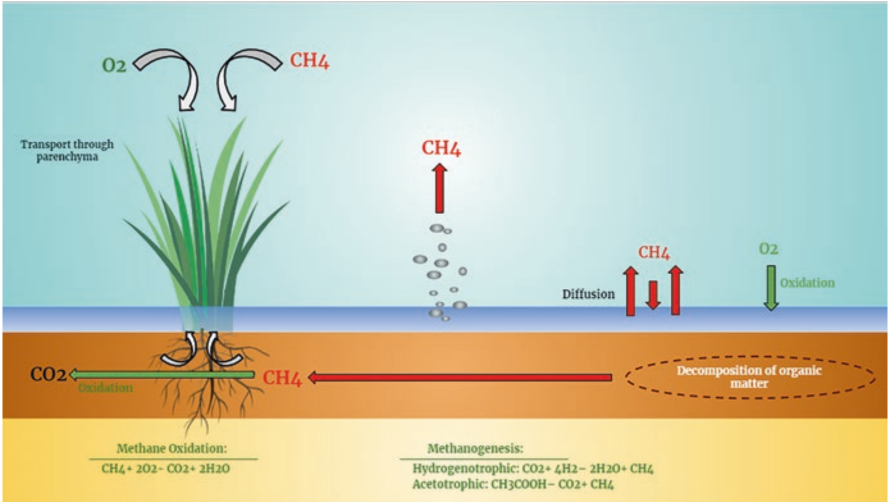

Fig. 2 Diagram showing the process by which methane in a rice crop is produced and released. (Adapted from Tivet & Boulakia, 2017)

and both crops (rice and wheat) emit N_2O when nitrogen fertilizer is applied (Wassmann et al., 2004). Intensive tillage and regular irrigation use much energy and contribute significantly to CO_2 emissions (Gupta et al., 2015).

Puddled rice in India emits 3.37 million tonnes of methane, of which 1.84 million tonnes come from irrigated rice paddies. This accounts for about 24% of all agricultural CH_4 emissions. As a result of the application of nitrogenous fertilizer to rice, wheat, and other products, however, approximately 0.14 million tonnes of N_2O are released into the atmosphere (Bhatia et al., 2013). Future food grain demand will necessitate more excellent fertilizer application, which will increase N_2O emissions. Numerous studies show that climate change will raise N_2O emissions by disturbing the rates of N cycling and plant N demand by affecting growth rates (Del Grosso & Parton, 2012; Xu-Ri et al., 2012).

3.6 *Abiotic Stress Challenges*

Rice production is affected by many abiotic factors, including temperature, rainfall, moisture content, radiations, soil type, etc. The two key elements essential for developing rainfed rice in eastern India are temperature and radiation. The possible yield of wet-season rice in eastern India is severely constrained by the high minimum temperature and radiation during the monsoon unless harvested later in the year (Garrity et al., 1986). In upland and lowland farming regions, soil moisture needs to be more conservation. Rainwater quickly dissipates in upland areas, whereas droughts are a significant worry in lowland areas.

Most of the country's rice is grown in the eastern area, which deals with the problem of heavy rainfall and severe flooding almost every year. The upland ecology's output is reduced by drought or heavy rainfall. Cold weather during anthesis has a significant impact on rice output. Most rice-growing regions in eastern India experience extreme cold during the winter, which causes the late-planted rice to experience cold at the time of anthesis. According to Huke (1982), temperature becomes one of the significant output constraints from high altitudes in north-eastern India, where low temperature is a limitation, to low altitudes, where the high night-time temperature restricts production.

In Assam, North Bihar, Orissa, and West Bengal, the bulk of the rainfed rice regions experience either floods or droughts, sometimes both, every year. Flash floods and water logging impact nearly ten million hectares of plains in Bihar, Orissa and West Bengal (Prasad et al., 1986). On the other hand, in these states, highland rainfed rice is severely constrained by drought and moisture stress. Studies on constraints on rice production in Bihar reveal significant crop loss as a result of flooding and drought (Jha, 1998; Thakur, 1994). In Bihar, nearly 95–100 thousand tonnes of lowland rice produced with rain are wasted each year. About 12–27% of the actual production in Bihar is lost annually due to floods in the lowlands and rainfed areas. One of the main challenges is managing the water in rainfed areas with poorly drained soil (Hossain, 1996; Prasad et al., 1986).

A rice-wheat cropping system's intensive water use boosted salinization in many areas of a semi-arid ecosystem. There are signs of declining yields in areas where balanced nutrient applications have not yet been applied. Micronutrients are lacking. Due to delayed wheat sowing, low plant stands, and ineffective nutrient management, the subhumid ecosystem's wheat output is lower after rice. Excess soil moisture during rice harvest is linked to delayed wheat sowing. Higher seed rates and nutrients can occasionally offset wheat yield declines (Tiwari et al., 2013). It was discovered that about one-third of the rice produced in the eastern states is rainfed, cultivated in low-lying areas, and has poor drainage (Shenoi & Mandal, 1986). In rainfed uplands, where lateritic soils limit yields with low nitrogen content and high iron and a pH that occasionally falls under five, poor soil fertility is a frequent problem. Salinity, alkalinity and/or zinc insufficiency are soil issues in other rainfed regions. Apart from the coastal saline soils of West Bengal and Orissa, the majority of rainfed areas in Bihar and Assam are plagued by the issue of soil salinity (Singh et al., 2012). Because floodwater contains a partial pressure of CO_2 that buffers carbonate and reduces pH, flooded soils differ from other soils in regulating acidity and alkalinity. When flooded, soils that are initially acidic tend to counterbalance with the floodwater and become less acidic quickly (Table 2). In contrast, alkaline and sodic soils initially take longer to move towards neutrality. These pH shifts affect chemical balance, impacting nutrient supply.

Table 2 Abiotic challenges in different regions of India (source-CRRI VISION 2030)

Issues	States
Small and marginal farmers who lack the means to use suggested or optimal inputs	India's eastern regions predominate
Irregular rains and poor soil quality	Odisha, Madhya Pradesh, and a portion of Uttar Pradesh
Water logging caused by inadequate draining, flash floods	East Uttar Pradesh, Assam, West Bengal, North Bihar, and
Using conventional types	Primarily Eastern states
Low and inconsistent fertilizer use	Eastern and North-eastern States
Due to the monsoon postponement, transplantation was delayed and prolonged	Predominantly rain-fed regions
Inadequate use of technology	Production mainly in uplands and lowlands
Alkali and saline soils	Kerala, West Bengal, Odisha, Haryana, Tamil Nadu, Karnataka, Maharashtra, Andhra Pradesh, Gujarat, Western Uttar Pradesh, Punjab

3.7 Labour Intensive

In India, the most traditional technique for establishing rice involves hand transplanting the germinated seeds onto the fields after young seedlings have been transplanted into puddled soil (wet tillage). However, because this method of production requires a lot of water, labour, and energy, and these resources are getting harder to come by, it is becoming less lucrative (Kumar & Ladha, 2011). Also, the COVID-19 crisis-induced lockdown and the mass labour migration resulted in a substantial labour scarcity that harmed rice cultivation in the granary states.

3.8 Declining Crop Yield

India is still ranked among the nations with the lowest rice production, despite having its place in the globe for rice production and area. About 70% of the 414 rice-growing districts in the country have recorded rice yields lower than the national average yield (Srivastava & Mahapatra, 2012). India's yields in irrigated fields—4.2 tonnes of rice per hectare—are too low compared to China and Egypt, where yields are 6.1 and 8.3 tonnes per hectare, respectively (Tiwari, 2002). The yield gap analysis has shown that we produce between 30% and 40% less yield than what could be produced using the high-production cultivars currently accessible on productive irrigated land. Unbalanced soil yield and land degradation are also associated with unsustainable intensification in the area (Singh et al., 2007). However, since the 1990s, the rice-wheat system has started to exhibit symptoms of stress, including production fatigue and a decline in soil fertility (Yadav et al., 1998). This is particularly true in regions where a continuous rotation of rice and wheat prevails and system diversity is minimal (Fujisaka et al., 1994; Singh & Singh, 1995).

After the Green Revolution era, the rate of growth of rice productivity in IGP was impressive, hovering around 3.2% until 1980. However, after the 1980s, there was a slowdown in rice productivity growth, which became significantly more pronounced in the 1990s (0.37%). In the IGP area, long-term continuous dependability over the W-R system shows indications of yield plateau and declining productivity (0.02 t ha^{-1} $year^{-1}$) (Duxbury et al., 2000). Singh et al. (2010) opined that the system's monotony, the repetitiveness of cereal-to-cereal crop cycles, and the overuse of natural resources are to blame for the stagnation of wheat and rice yields. Due to insufficient nutrients and improper water management brought about by the combination of competing and complementary practices, the wheat-rice system produces poor yields (Timsina & Connor, 2001).

Additionally, the repeated transition of anaerobic to aerobic and back to anaerobic growing conditions impacts crop development, soil structure and nutrient relationships. The rapid slowdown in yield growth since the early 1980s may have been caused by several variables. The middle of the 1960s saw significant technological advances. The technologies that emerged in the 1980s and afterward stabilized yields rather than providing a quantum leap in output, which slowed production growth (Sekar & Pal, 2012). Due to a drop in factor productivity, yields have declined in many of these areas. Farmers have turned to using chemical fertilizers at levels higher than advised to maintain current yield levels. These are the regions where fertilizer use has risen significantly, and further growth is highly improbable due to economic factors (Yadav et al., 2000). Depletion of the soil's ability to give nutrients, a delay in planting, an increase in pest activity, and changes in climatic variables like a drop in solar radiation and an increase in temperature are some potential reasons for yield decline. Climate has various effects on plant life, which can hinder, stimulate, change, or modify crop output. Temperature, solar radiation, rainfall, relative humidity and wind speed are constituents that can act alone or in concert to affect crop development and productivity (Pathak et al., 2003).

4 Conservation Agriculture Practices as a Solution to Rice-Based Cropping in Indo- Gangetic Plains

4.1 Conservation Tillage

According to several studies (Chauhan et al., 2012; Timsina & Connor, 2001), conventional tillage practices have harmed the sustainability of the Indo-Gangetic plains, primarily because of the shortage of labour, high production costs, an increase in weed incidences, unpredictable weather patterns and a lack of crop-producing machinery. In the traditional R-W method, wheat is cultivated following the rice harvest in well-drained, dry soil after repeated ploughing. In contrast, rice is replanted in puddled soils and grown under ponded conditions. In addition to the expense of irrigation, fuel, and labour, this frequent tillage disrupts the soil structure and decreases the availability of nutrients (Timsina & Connor, 2001). Because of these negative effects, the R-W system needs alternative solutions with low water, energy, and labour requirements (Timsina & Connor, 2001). To address these difficulties, alternative tillage techniques and other crop establishment techniques, such as dry-direct seeded rice (DSR) and unpuddled transplanted rice, have been adopted throughout IGP. Due to the scale of the farms, the proper environment, and the accompanying infrastructures, conservation agriculture practices have been promoted in the northwest IGP. However, due to inadequate infrastructure, small farm size, and unfavourable environmental conditions like rainfall fluctuation, the implementation of such techniques has been less favoured, especially in the Terai region of Nepal. The CA-based rehearses, principally with zero culturing, have been embraced in around 180 million ha of worldwide cropland.

4.2 Crop Diversification

It is all around perceived that cereal arrangements are profoundly impractical and comprehensive and place high strain on the current soil assets contrasted with vegetables or grain oilseed. Crop broadening with crop replacement, blending, or intercropping can be a significant instrument for relieving the issues related to different environmental changes. India's agro-ecosystem is ideal for developing various oilseeds and restorative harvests.

In order to achieve expected yields from the crops such as rice, concentrated culturing is done, which consumes much energy as work and fuel (Banjara et al., 2019). Additionally, the expansion sought after for oilseeds (Mishra et al., 2022a, b, c) can be met through enhancement in the rice-wheat editing framework, where rice is developed in turn with the upland harvests like oilseeds and vegetables. This example might give a reasonable answer to eliminate the rice-wheat trimming framework issues and satisfy the fundamental requirements of oilseeds and vegetables. Rice is a significant cereal in the Indo-Gangetic plain that cannot be supplanted in the blustery season because of high precipitation, bringing about continuous flooding. Hence, the most feasible choice is to utilize good harvests post-stormy and summer seasons as yield enhancement, including harvests, for example, oilseeds and vegetables throughout the colder and summer seasons. It additionally guarantees a decrease in compound composts and pesticide load, giving more significant business potential open doors (Gill & Ahlawat, 2006).

Utilization of vegetable yields in the current framework fixes the environmental N consideration of vegetable harvests in the framework fixes Barometrical N as well as enhances soil fruitfulness, increments supplement accessibility, further develops soil structure, and advances mycorrhizal colonization (Wani et al., 1995), and eventually help to support the drawn out efficiency of cereal-based trimming frameworks. Taking on rice-berseem-cowpea feed or rice-potato-green gram arrangement improved rice development, yield, supplement take-up and quality, contrasted and rice-wheat trimming framework. In addition, rice-berseem-cowpea feed or rice-potato-green gram arrangement likewise expanded rice's financial matters and energetics. It is additionally expressed that as wheat is a staple food yield of the area, replacing wheat with berseem is suggested a single time or two times in a 3-year pattern of the rice-wheat editing framework. Counting the vegetable part briefly might defeat the issues that emerge because of the ceaseless reception of the grain oat (rice-wheat) editing framework.

4.3 Crop Residue Management/Mulching

Universally rice creates a billion tons of straw deposits consistently. Extra rice buildups slow down the cultivating exercises, expanding the expense of activity and unfortunate seed germination. Because of this, 70% of the rice straw delivered chiefly in Asian nations is scorched. Farmers often opt for stubble burning despite having access to various alternatives, primarily due to the limited time available before planting the next crop. Consuming is more available and less expensive and decreases weeds in succeeding yields. As indicated by gauges, China consumed 44% of all yield junk, trailed by India (33.6%), Bangladesh (4.4%), Pakistan (4%), Thailand (3.1%) and the Philippines (3.1%) (Jain et al., 2014; Singh et al., 2008, 2014). Thus, to forestall biomass misfortune, brown haze creation and carbon dioxide outflows, consuming straw transparently has been restricted universally and broadly. Consuming rice straw is normal in IGP, bringing about loss of nourishment and extreme air quality that unfavourably influences human well-being and the climate; consuming of buildup discharges particulate matter, dark carbon, NOx, SO_2, N_2O and unstable natural mixtures (Lohan et al., 2018). The consumption of 23 MT of rice deposits in NW India brought about a yearly deficiency of 9.2 MT of carbon (CO_2-likeness around 34 MT) and 1.4105 lots of nitrogen (like INR 200 crores). Buildup age from rice is one of the primary difficulties in the north-western Indo-Gangetic fields, where Haryana, Punjab and Uttar Pradesh produce 27.13 and 57.66% of the nation's rice and wheat, separately. Dark carbon, the second-biggest supporter of an unnatural weather change after CO_2, warms the lower air. Consequently, it is important to use in situ buildup executives procedures that consolidate paddy straw or cutting straw and blend it into the dirt (Singh et al., 2018).

4.3.1 In–Situ Crop Residue Management

Consolidation of yield buildup maintenance is a supplement moderating measure that increments soil fruitfulness and N accessibility, influencing succeeding harvest development by immobilizing accessible soil supplements through a microbially intervened process. Rice straw expansion can increment microbially intervened immobilization and adjustment of N, diminishing misfortunes related to receptive overflow. During rice tillering, proteobacteria advancement discovered the prominent role of microorganisms in N immobilization. Rice buildup consolidation upgraded microbial action and, when joined with natural compost, further developed actual soil conditions, increasing the succeeding wheat crop yield. Rice stubble consolidation expanded SOC and microbial biomass carbon. Straw fuse enhanced soil C capacity by 12%, inclining toward soil C sequestration. In any case, straw fuse for extensive stretches fundamentally expanded CH_4 productions and SOC thickness in the dirt. Rice deposits contain high measures of silica, which can adjust the substance properties of acidic soils, diminishing P fixation, increasing soil pH and improving base maintenance. Buildup fuse fortifies soil supplement reusing and further develops soil well-being by expanding the soil's natural matter. Rice buildup consolidation upgrades the next wheat crop's grain yield and net returns (Kumar et al., 2021).

Mulching of Crop Residues

Mulching of harvest deposits or spreading on the dirt surface further develops nitrogen and water use efficiencies and lessens weed spreading. This approach likewise keeps up with soil temperature, controls soil disintegration and further develops soil well-being, further developing by and large yield efficiency (Bhatt et al., 2016). Rice straw mulching further improves carbon sequestration (Singh et al., 2008). NT with buildup maintenance can sequestrate 6.8–13.7 Mg C ha^{-1} north of 15–30 years in rice-rapeseed editing framework in the bumpy agro-ecosystem of the Eastern Himalayas, India. Rice straw mulching lessens the most extreme soil temperature by 2.0–3.3 °C and increases weed dry matter by 12.5–15.7%, increasing wheat development and yield. Rice buildup mulching expanded wheat crop yields by 19.4 and 11.1% contrasted and rice buildup held on the dirt surface and consolidated buildup, individually, primarily by decreasing weed thickness and dry weight.

Technologies for In Situ Crop Residue Management
Happy Seeder

The Happy Seeder empowers farmers to plant seeds of the ensuing yield. Of the farmers utilizing happy seeder innovation, 90.6% left crop residue in the field, while just 3.9% burned it. The Happy Seeder is one of the most productive advances for rice residue management by decreasing GHG outflows and thus bringing down GWP. In north-western India, the happy seeder decreased particulate matter contamination by >98% (1 kg ha^{-1} year^{-1}), GHGs by ~80% (933 CO_2 eq. kg ha^{-1} year^{-1}), and groundwater withdrawals by ~20% (1412 m^3 ha^{-1} year^{-1}) in a rice-wheat framework in comparison to other systems. Subsequently, embracing the happy seeder is an ecologically and financially reasonable option for residue burning.

Straw Management System and Super (SMS) The straw management system (SMS) connects existing combined harvesters to spread straw inside for in-situ straw administration. The connection is mounted to the back of the consolidated reaper underneath the straw walkers and behind the chaffer sieves. Spinning disks spread the residue from the straw walker. A Super SMS for straw spreading saves

US$4 ha^{-1} compared with manual straw spreading. Combining a combined harvester with Super SMS saves time and energy in managing rice residue. It also saves water for irrigation due to moisture retention. It allows turbo Happy Seeder to work more effortlessly by improving its capacity by 20–25% with the least harm to the cutting flails and improving crop establishment and yield.

Straw Chopper cum Spreader

Generally, two types of straw chopper cum spreaders are available commercially. The first one has flail blades attached to the drum that cut, chop and spread the paddy straw in the field. The second one consists of a cutter bar, reel and auger that transfers the cut straw to the chopper consisting of an additional unit that reduces straw size. Combine harvester-type blades are fixed on the combined header-type chopper unit. Paddy straw choppers combined with a Happy Seeder promote mulching with an investment cost of US$ 5776. A straw chopper cum spreader improves the dispersion of chopped straw for mulching or incorporates straw into the, promoting soil health.

4.3.2 Ex Situ Crop Residue Management

Biofuel A Rice straw is a superb material for bioethanol production because of its lignocellulosic nature. Its cellulose and hemicellulose content can be promptly hydrolyzed into fermentable sugars. Rice straw is utilized for (i) electricity generation through direct combustion, (ii) converting to bioethanol and biogas biochemically (iii) mixing in the soil as fertilizer and (iv) thermochemical conversion to bio-DME (dimethyl ether). However, the bioethanol pathway is the most sustainable approach to reducing global warming. Due to the presence of high silica and ash content in the rice straw, it is not much suitable alternative for ethanol production as silica affects the enzymatic activity, thereby lowering the production—the monetary worth of bioethanol generation from rice straw changes between nations. For instance, bioethanol creation from rice straw in Vietnam has negative ecological impacts utilizing the ongoing innovation. In India, converting rice straw into bioethanol has assessed financial gains. Biogas production from rice straw is a harmless process for the environment compared to residue burning. The excess processed digested sludge can be added to the field as a source of nutrients.

Biochar

Pyrolyzing rice straws get ready biochar. It tends to be utilized as a dirt correction but relies upon the natural substance's qualities. The pyrolysis temperature influences the home time, substance creation and biochar structure. Biochar produced at 400° C exhibits high solubility and an impressive cation exchange capacity, making it an ideal choice for use in fertilizer and soil amendment applications. Biochar can modify dirt's physicochemical properties, local microbial area and enzymatic exercises. Urease, soluble phosphatase and microbial exercises expanded in soil altered with 10 mg kg^{-1} biochar.

Nonetheless, invertase and soluble phosphatase exercises diminished in soil corrected with 50 mg kg^{-1} biochar. Biochar application further develops carbon sequestration, upgrades crop development and diminishes N_2O and CH_4 discharges. Biochar expansion to a rice creation framework for a considerable length of time expanded rice's present net worth (NPV) by 12%. It decreased nonsustainable power by 27%. Adding 41.5 t ha^{-1} of rice husk scorch (dry weight premise) expanded rice grain yield by 33% under watered conditions. Biochar diminished the carbon impression of spring rice by 26% and summer rice by 14% in the application's primary year when contrasted with the open consumption of rice buildups in northern Vietnam. Following 8 years of biochar application, these qualities expanded to 49% in spring rice and 38% in summer rice. The transformation of rice straw to biochar acknowledged net advantages of US$183 ha^{-1} in India. Biochar further developed soil fruitfulness, upgraded carbon capacity, diminished GHG outflows and could be an option in contrast to buildup consumption if monetarily reasonable.

Baling

Rice straw utilization can reduce the gap between the demand and supply of fodder. Fulfilling the demand for livestock products with India's ever-increasing cattle population requires more feed and fodder from shrinking land resources. Rice straws can bridge the gap between fodder demand and supply. Characteristics of rice residue, such as low heating values and low bulk density, can interfere with its storage and transportation, reducing its commercial utilization. However, bailing resolves many of such issues by changing its characteristics. In Pusa Basmati 1509, bailing enhanced income by US$ 14.60 and US$ 37.16 when used with a hay rake.

Electricity Generation

Production of rice and power generation involves several steps to minimize energy losses, such as superheated steam drying, husking, polishing, torrefaction, steam gasification and power generation. About 200 t rice grain processing day^{-1} could generate 3.4 MW of electricity, with a production efficiency of 32%. In Ghana, energy requirements can be fulfilled by 7% in non-electrified communities through rice husk gasification. Similarly, in India, rice straw can enhance electricity generation in integration with economical and efficient technologies.

4.4 Fertilizer Management

The executives of supplements in the harvests impact the efficiency of the yields. Various reasons are liable for manure loss and low efficiencies, like filtering, immobilization, volatilization and denitrification. However, productivity can be improved by suggesting a legitimate technique for compost application with suitable and time. Compost use in IGP in RWS is an important factor, with the mean application of $N + P_2O_5 + K_2O$ going from 258 kg ha^{-1} in the LGP to 444 kg ha^{-1} in the

TGP. Different reviews have shown that farmers apply manures in rice more than the suggested paces of N and P composts. This overutilization of supplements has prompted multi-supplement deficiencies in the soil in RWS. Various composts, for example, Homestead yard fertilizer (Mishra et al., 2019), vermicompost, and poultry excrement can increase rice-wheat-based crop systems. The use of poultry excrement (PM) and vermicompost (VC) at the pace of 2.5 t ha^{-1}, alongside 75% of the suggested inorganic composts (RD), enhanced grain yield (6.16 and 6.27 t ha^{-1}, respectively) considerably over the suggested dosages of N, P, and K (5.33 t ha^{-1}). Different types of materials as a source of fertilizer, such as Panchagavya, an age-old traditional organic source of plant nutrients used in India, were applied in rice fields. Various sorts of materials such as Panchagavya, a deep-rooted organic source of plant nutrients in India, when applied in rice fields, enhanced grain productivity with RDF (suggested dose of RDF (recommended dose of fertilizers).

4.5 Irrigation Management

The irrigation management must be optimized to prevent unnecessary water waste. The amount of water supplied for irrigation during the growing season must not surpass the effective crop water requirements to increase water use efficiency in agriculture.

A crop's ideal quantity of water to grow without experiencing water stress is known as the crop water requirement (CWR). A crop's water needs must be met to produce the highest output. The net irrigation requirement, the differential between the crop's water needs and effective precipitation, is the volume of water needed to replenish the soil's water content in the root zone. The local climate conditions, the hydraulic characteristics of the soil, and the crop characteristics will be used to calculate the daily crop water requirement (Saccon, 2018). Construction of field channels to regulate water flow to and from your field, land preparation to reduce water loss, and other sound water management practices can all be done to successfully and efficiently use water and maximize rice yields (Table 3).

Field Channels

Paddy fields have breaches in the bunds that allow water to move from one field to the next. If channels are built to transport water to and from each field or group of fields, water irrigation and drainage are significantly improved. Under such circumstances, water in a single field cannot be controlled, making field-specific water management impossible.

Land Levelling

The basis for effective water management is an area that has been levelled out. If a field is not levelled correctly, water will pool in the lower areas while receding water dries out the higher areas. Consequently, there are issues with weed development, uneven fertilizer distribution, uneven crop emergence, and uneven early growth.

Table 3 Various water management techniques for rice cultivation

Continuous flowing irrigation	Rice grain production is increased by water flowing from field to field by avoiding the buildup of harmful salts in the soil. With irrigation water flowing continuously, nitrogen loss will be more significant
Rotational irrigation	In order to prevent standing water in the area between irrigations, the necessary amount of water is applied at regular intervals. The irrigation interval is changed so the product won't ever experience a water shortage. The advantage of rotational irrigation may be the better utilization of rainwater. During the crop's crucial time, shallow submersion is advantageous
Continuous submergence	Practiced due to the main benefits of increased nutrient availability and decreased weed management issues. For a high yield, shallow water submergence is ideal throughout the crop time
Intermittent submergence	Under conditions of high relative humidity and low evaporative demand, this practice involves submerging the crop during its critical phases and maintaining saturation or drying it until hair cracks

Tillage

Up to one-third of the water for paddy rice production goes towards wet soil preparation. Water consumption can be decreased in large-scale irrigation systems by synchronizing activities and shortening the time spent on land preparation. When there are big and deep cracks, much water can be lost during soaking before puddling. This water loss can be significantly decreased by using shallow tillage to fill the gaps before soaking.

Bund

Effective bunds reduce water losses from seepage and under-bund flows. At the start of the crop season, bunds should be tightly packed and gaps filled with mud. Bunds can be repaired using plastic sheets, particularly in permeable areas.

Due to the strategic and economic importance of the northern Iranian area for rice production, traditional irrigation techniques must be changed (flood irrigation). Flood irrigation is a popular and traditional method of irrigation used by farmers in Iran to manage weeds, but it does not always produce the highest yield and Water Productivity. In order to determine the impact of various irrigation management strategies on water consumption, rice yield, and water productivity in the paddy fields of Babolsar, Mazandaran, Iran, research was carried out during the 2017–2018 growing season. The study's findings showed that applying irrigation water alternately has little effect on rice grain production. This reduction is ineffective until the soil moisture is comparable to the amount of water the rice can easily access. The best irrigation practices in paddy fields, which save a significant quantity of water and benefit the rice crop, are, therefore, alternate irrigation 5 days after the disappearance of surface water. Compared to the control treatment, water productivity among the various irrigation management techniques significantly improved grain yield (Pourgholam-Amiji et al., 2021).

Fig. 3 The 4R's of nutrient management

4.6 Precision Nutrient Management

One of the key elements of precision agriculture is precision nutrient management, which uses cutting-edge, innovative, and site-specific technologies to manage the spatial and temporal variability in the inherent nutrient supply from soil and to improve productivity, sustainability, profitability and the turbulence of agricultural production systems related to climate change. Crops receive nutrients as and when needed using this science-based approach. Rice development, like the production of all crops, benefits significantly from careful nutrient management. N, P and K are three essential nutrients for rice's improved growth (Tripathi et al., 2021). Applying it requires knowledge of regional agricultural yields, tillage practices, residue management, fertilizer use, external inputs, and the soil's ability to give nutrients.

The 4R's of Nutrient Management

For farmers to follow the 4Rs of nutrient management, an improved nutrient management recommendation guideline that is user-friendly and supported by science is required. The 4Rs' implementation aids in balancing the nutrient management process's fiscal, environmental, and social aspects (Fig. 3).

Tools of Nutrient Management

The main advantages of using nutrient management tools include decreased production costs and waste, increased crop yield, and decreased greenhouse gas emissions from rice production.

Yield Monitoring (YM)

To assess grain yield and moisture content, yield monitors are fastened to conveyors or combines. Data can be mapped when combined with a GPS logging position. It identifies in-field yield differences and enables precise seeding and fertilizer application adjustments for the following year (Mishra et al., 2021a, b).

Chlorophyll Meter

One of the most popular diagnostic instruments for determining the nitrogen status of crops is the soil plant analysis development (SPAD) chlorophyll meter. It came out in 1984 (Minolta Co. Ltd., Japan). When the SPAD number dropped to between 29 and 32, it was clear that more fertilizer was required.

Crop Manager

It is a tool that small farmers and extension agents use, and it can quickly provide nutrient suggestions for specific farmers' fields with or without data from soil tests. The farmers share details about how they handle their fields and crops, including planting techniques, rice varieties, typical yields, fertilizer preferences and harvesting techniques. This tool suggests the appropriate amounts of nitrogen, phosphorus and potassium to apply at key phases of the plant's development to increase yield and profit based on the provided inputs.

Green Seeker

Through an innovative mobile application, this tool makes it simple to calculate the nitrogen needs of a standing crop. This practical tool optimizes fertilizer intake and yield by determining the ideal quantity, location, and timing for nitrogen application.

Leaf Colour Chart The high-quality plastic strip used for the foliage colour chart comes in various shades of green, from light yellowish to dark green. Every 7–10 days, from 15 to 20 days after transplanting or sowing until blooming starts, the LCC score of the first fully exposed leaf is assessed. If it is below the critical LCC score, a specific quantity of fertiliser-N is applied. (Patel et al., 2022).

Soil Health Cards

To enhance the soil health of individual farmers' fields, the Indian government introduced soil health cards. According to the plan, soil samples were examined in several soil testing labs for clay content, macro- and micronutrient presence, pH, and salinity levels. The findings are provided to the producers as a soil health card, which they can reference when applying fertilizer to different crops.

Nutrient Management Models: For precise nutrient control in crop production, computer-based decision support systems like nutrient expert (NE) and the QUEFTS model are frequently used. In order to guarantee need-based nutrient treatments, the models are designed to account for regional and temporal variations in nutrient availability (Patel et al., 2022).

4.7 Integrated Pest Management

Non-judicious use of synthetic pesticides caused a severe threat to sustainable agriculture (Mishra et al., 2021a, b). 'Integrated pest management' (IPM) combines the use of biological, cultural, and chemical practises to control populations of harmful organisms in crop production systems, prevent the development in a number of harmful organisms in agricultural production, keep the use of plant protection products and other forms of intervention at levels that are economically and ecologically justified, and reduce or minimize risks to human health (Steiro et al., 2020). It has developed in reaction to issues brought on by a reliance on chemical pesticides that are too great. These issues include the emergence of pesticide resistance, eradicating pests' natural enemies, outbreaks of pests that had previously been controlled, risks to unintended species, and environmental contamination (Fig. 4).

Fig. 4 Elements of integrated pest management

Role of IPM in Sustainable Agriculture

IPM increases farm yields and the availability of food by reducing pre- and post-harvest crop losses, contributes to food and water safety and raises income levels by reducing the amount of pesticides, which in turn reduces residues in food, feed, and fibre, and environment, maintains & conserves natural resource (i.e. soil, water and biodiversity) and enhances ecosystem services. IPM also protects other ecosystem services, such as pollination, while fostering others, such as pest predation.

Principles of IPM

A logical chain of occurrences led to the development of the eight principles and their numbering. Since it includes the initial planning and steps done at the level of the cropping system to lessen the severity and frequency of pest outbreaks, Principle 1 (Prevention and Suppression) comes first. Once the cropping system is in place, principles 2 (Monitoring) and 3 (Decision-making), based on the concept that in-season control measures result from a good decision-making process that considers actual or anticipated pest incidence, come into play. A list of control choices is provided in Principles 4–7 (Table 4); they can be investigated in order of least pre-occupying to most preoccupied. Principle 8 (Evaluation), which ensures that users reflect on and evaluate their actions to improve the entire process, closes the circle (Barzman et al., 2015).

Three factors are necessary for IPM to be effective: knowledge of and understanding of the interactions between the rice production system's component species; tools to ensure that the results of natural regulation support yield; and prevention of the succession of crop health syndromes that can be harmful to crops (Horgan, 2017). Such tools comprise field flooding to prevent weeds, traps or barriers from keeping out snails or rodents, biological control and host plant resilience. It also calls for adequate knowledge dissemination and the guiding of farmers toward best management practices (Table 5).

Table 4 Key principles and descriptions of IPM

	Key principles	IPM descriptions
1.	Prevention and suppression	Reduce the likelihood of pest incidence and its effects. (e.g. stale seedbed technique, under-sowing, conservation tillage)
2.	Monitoring	Monitoring must be carried out using appropriate techniques or tools for early diagnosis, forecasting, and warning that are based on science
3.	Decision making	Based on the findings of the surveillance. IPM concentrates on intervention with a threshold. The threshold is the specified pest density, or population number, above which management should be implemented
4.	Nonchemical methods	Biological (live natural foes), physical, and ecological techniques are acceptable. Examples include biological management or soil solarization
5.	Pesticide selection	The pesticides applied must be as targeted-specific as feasible
6.	Reduced pesticide use	A decrease in herbicide usage rates and dosages
7.	Antiresistant strategies	Use a mixture of various pesticides; each applied at a different time and with a distinct mode of action
8.	Evaluation	Considering the data on pesticide use, its results, and a host of other factors

Table 5 Management of pest populations by using different inputs

Inputs	Practices
Biological inputs	Biological control through the release of predators, parasites, or pathogens Biological control through fish, ducks, geese, goats, etc. Release of sterile male insects Bio-pesticides Biological preparations (e.g. natural plant extracts)
Chemical inputs	Chemicals that disrupt insect behaviour (e.g. pheromones) Induced resistance-activating compounds Growth-regulators Conventional pesticides
Other inputs	Pest-resistant or highly competitive crop varieties Field sanitation, use of quality seeds and seed bed sanitation Crop rotation Inter-cropping Management of sowing, planting, or harvesting dates Water/irrigation management Soil and nutrient management (including mulching, zero/low tillage, fertilizer management, and proper irrigation) Hand-picking of pests or hand-weeding Traps or trap crops Mechanical/physical controls (including barriers, crushing devices and use of heat), post-harvest loss prevention

Fig. 5 Key principles of conservation agriculture

4.8 Awareness Related to Conservation Agriculture to Stakeholders

A powerful option is offered by Conservation agriculture for meeting the future food demands while contributing to sustainable agriculture and rural development. CA methods improve input efficiency, increase farm income, and improve or sustain crop yields, soil, biodiversity and the natural resource base (Fig. 5).

Strategies to promote CA will call for moving away from the conventional approach and to involve all stakeholders like farmers, scientists, government and civil society organizations for end-end solutions. To make them aware of conservation agriculture, we should tell them about the benefits of conservation agriculture. CA improves soil productivity, increases organic matter, conserves soil and water, improves soil structure, reduces soil erosion, improves water and air quality, increases biodiversity and carbon sequestration.

4.8.1 Government Initiatives for Developing Agriculture

National Agriculture Market (eNAM)

It is a pan-India electronic trading portal that networks the existing APMC (Agricultural Produce & Livestock *Market* Committee) mandis to create a unified national market for agricultural commodities. Small Farmers Agribusiness Consortium (SFAC) is the lead agency for the implementing eNAM. They promote uniformity in agriculture marketing by streamlining procedures across the integrated markets and removing information asymmetry between buyers and sellers, promoting real-time price discovery based on actual demand and supply.

National Mission for Sustainable Agriculture (NMSA)
NMSA has been developed to enhance agricultural productivity, especially in heavy rainfall areas focusing on integrated farming, water use efficiency, soil health management and synergizing resource conservation.

Programs of NMSA

1. **Rainfed Area Development (RAD)**

   - For the development and conservation of natural resources along with farming systems, area-based approach is developed. It combines various aspects of agriculture, such as crops, fishery, livestock, horticulture, forestry and other agro-based activities that generate revenue.
   - Implemented practices will regulate the nutrients of soil based on soil health card, develop farming lands and new property resources like a bank for grains, fodder, shredders for biomass and combined marketing initiative.

2. **On-Farm Water Management (OFWM)**

   - Promotes advanced on-farm water conservation equipment and technologies, emphasizing efficient harvesting and management of rainwater for the utilization of water.
   - Water conservation on the farm by digging farm ponds utilizing funds from the MGNREGA mission.

3. **Soil Health Management**

   Various sustainable practices have been promoted by the governments for the preservation of soil health on the basis of type of crop and on those specific locations where that crop could be grown with the help of various techniques like residue management, organic farming by making new maps with details on soil fertility and linking them with macro- & micromanagement of nutrients, optimum land use, proper utilization of fertilizers and reducing degradation & erosion of soil.

4. **Climate Change and Sustainable Agriculture: Monitoring, Modelling and Networking (CCSAMMN)**

   - Create and disseminate knowledge and updated information on climate change.
   - Support pilot blocks for spreading rainfed technologies and coordinate with other schemes or missions like MGNREGS, NFSM, RKVY, IWMP, Accelerated Irrigation Benefit Program (AIBP) NMAET.

Strategies Associated with NMSA

1. Covers all the varieties of crops including livestock farming and fisheries. It focuses on pasture-based composite farming and plantations and also mitigates the risks related with the failure of crops through residual production systems.
2. To help and protect resources during dry seasons, droughts, or heavy floods NMSA consider adopting technologies.
3. Promote water management techniques that will help in the practical and optimum utilization of water resources, promotes techniques for water management.
4. Promotes better agronomic techniques for higher yields in farms, better soil conservation, better water holding capacity of soils, optimum utilization of energy and chemicals, higher soil carbon storage, database on soil through, survey of land use pattern.
5. Promotion of better nutrient practices based on location and crop type for enhancing the health of the soil and yield of crops, increasing the quality and protecting the land resources and water resources.
6. To develop climate change mitigation techniques for specific agro-climatic conditions. Collaborate with institutions and domain experts.
7. Co-ordination, converging and utilizing investments from other schemes like MGNREGS, mission for integrated development of horticulture (MIDH), RKVY, National Food Security Mission, IWMP, National Mission for Agriculture Extension and Technology (NMAE&T).

5 Conclusion

A rice-based cropping system majorly covers the most fertile lands of IGP. However, continuous rice cultivation resulted in the exhaustion of soil nutrients, emission of GHGs, groundwater depletion and loss of soil microbiota. To mitigate the damage, the adoption of renovating conservation agriculture is a promising approach. It includes agricultural practices such as crop diversification, residue management, bio-fertilizer usage, precision nutrient management, integrated pest management, and water conservation practices, which help conserve resources and restore soil health and ecological balance. RCA has resulted in a significant increase in productivity and achieved better resource management. As farmers are reluctant to adopt RCA, they need to be educated and encouraged by extension officers about the benefits and impact of renovating conservation agriculture to change conventional agriculture. The government should also take the initiative to promote and help farmers practice RCA through various schemes and policies.

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THE PHENOMENON OF PERSONALITY

Dr. Neha Mathur
Dr. Fehmeena Bakht
Pakhi Mathur

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About the Book

Personality refers to the enduring characteristics and behaviour that comprise a person's unique adjustment to life, including major traits, interests, drives, values, self-concept, abilities, and emotional patterns.

Personality development is the process by which the organized thought and behaviour patterns that make up a person's unique personality emerge over time. Many factors influence personality, including genetics and environment, how we were parented, and societal variables. It helps you to live your life in a better way. It builds confidence in you, help you to look your life in a positive way, creates positive energy within you, improves your health, improves your skills, decreases your stress, and make you a more pleasing personality. The book covers aspects of Personality development and helps the reader to shine their personality.

About The Authors

Dr. Neha Mathur is M. Com; MBA and Ph.D. She is a Certified Trainer of 21st Century Employability Skills from Wadhwani Foundation, besides being a topper in "Enhancing Soft Skills and Personality" by NPTEL – AICTE and of Content Writing Course. She has been taking PG and UG classes of the Management stream for the last more than 25 years. She has also been teaching Soft Skills, Communication Skills & Management Subjects. She has taught at various institutions and is presently engaged as a Professor in AISECT Group of Universities. She has authored 40+ books on various topics covered under Soft Skills and Management. She has, to her credit, a number of research papers published in various journals of repute. She has also been guiding scholars for their Ph.D. Degrees.

Dr. Fehmeena Bakht is an Assistant Professor in Department of Psychology, Sophia Girls' College Ajmer, Rajasthan. She has 5 years of teaching experience in various Colleges and University. She has obtained her B.Ed (Education) from Barkatullah University, M.A.(Psychology) from IIS University, Rajasthan and Ph.D (Psychology) from IIS University. She has guided students in M.A. Her research areas of specializations are Organizational Psychology & Behavioral Psychology. She has presented many Research papers in International, National and state level Conferences and Seminars. She has published research articles in journals and contributed Chapters in several edited books and also attended several workshops, webinars and Faculty Development Programs as a Resource Person. She is a member of several academic boards/bodies and also the editorial Board member of several journals and books. She has also organized various academic programs and webinars.

Pakhi Mathur is an aspiring Forensic Psychologist. Pakhi has written many articles and research papers in the field of Psychology and plans on researching the areas of Psychopathology, and Criminology. The budding writer has co-authored 6 books till date.

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