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PRE AND POST-MONSOON ASSESSMENT OF HEAVY METAL POLLUTION IN WATER OF RIVER GOMATI, MIDDLE GANGA BASIN

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Research Paper

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ABSTRACT

Rivers are vital to human civilization but are increasingly threatened by pollution from industrial, agricultural, and domestic sources. The Gomati River, a major tributary of the Ganga in Uttar Pradesh, India, has experienced severe degradation due to rapid urbanization, industrial discharge, and poor wastewater management. This study evaluates heavy metal contamination and water quality variations along the Gomati River and its key tributaries during pre- and post-monsoon seasons of 2022. Water samples were analyzed for Fe, Ni, Cu, Zn, and Cd concentrations using Atomic Absorption Spectrophotometry, and multiple pollution indices: Metal Index (MI), Degree of Contamination (C_d), Heavy Metal Pollution Index (HPI), and Nemerow Pollution Index (NPI) were applied to assess contamination levels. Multivariate statistical tools, including Pearson correlation and Hierarchical Cluster Analysis (HCA), were used to identify inter-metal relationships and pollution sources. Results show that Cd, Ni, and Cu concentrations exceeded permissible limits at several sites, with contamination increasing downstream and peaking in the Sai tributary due to industrial and urban effluents. Pre-monsoon samples exhibited higher metal concentrations due to lower dilution and higher evaporation. Correlation and cluster analyses indicated a common anthropogenic origin of contaminants, while Caboi diagrams revealed near-neutral pH conditions favoring metal accumulation in sediments. Overall, the Gomati River system is classified as severely to critically polluted. Effective management strategies such as stricter regulation of effluent discharge, improved sewage treatment, sustainable agricultural practices, and continuous monitoring are essential to restore the ecological integrity and water quality of the Gomati River.

No. of Pages: 26 **References: 83**

Keywords: Gomati River, Heavy Metals, HPI, Caboi Diagram, Cluster Analysis, Monsoon.

INTRODUCTION

Throughout history, the growth of civilizations has largely occurred near rivers (Ahmad et al., 2010). However, rapid population expansion and the resulting dense settlements along riverbanks have led to the overuse of water resources and significant degradation of both water and sediment quality due to human activities. Surface water bodies have experienced substantial changes in both quantity and quality, driven by escalating anthropogenic pressures. These changes have disrupted aquatic ecosystems and fluvial processes, leading to the deterioration of aquatic habitats and a marked decline in biodiversity (Ugochukwu et al. 2019). The continuous discharges of untreated or

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partially treated industrial effluents and domestic sewage beside run-off from agricultural and mining areas into rivers have resulted in a steady increase in release of hazardous chemicals, particularly heavy metals, significantly deteriorating river water quality (Khadse et al., 2008; Sekabira et al., 2010; Lin et al. 2013).

Elements with a specific gravity greater than 5 g/cm^3 are categorized as 'Heavy metals'. Eco-toxicologists have identified approximately 20 elements e.g. mercury (Hg), lead (Pb), cadmium (Cd), chromium (Cr), zinc (Zn), arsenic (As), and nickel (Ni) along with others such as iron (Fe), copper (Cu), manganese (Mn), cobalt (Co), tin (Sn), thallium (Tl), silver (Ag), platinum (Pt), titanium (Ti), magnesium (Mg), molybdenum (Mo), selenium (Se), and bismuth (Bi) as environmental hazards due to their persistence and potential to cause harm across ecosystems (Nies, 1999; Kumar et al., 2019). Heavy metal ions exert both direct and indirect harmful effects on human health and aquatic ecosystems (Rai et al., 2015). In humans, exposure to these toxic metals can lead to a range of adverse outcomes, including physical discomfort, severe illnesses, birth defects, developmental abnormalities in fetuses, genetic mutations, cancer and irreversible damage to vital biological systems. In aquatic organisms, heavy metal contamination can result in reduced species diversity, stunted growth, and impaired reproductive capacity (Ahamad et al., 2024).

Heavy metal contamination in aquatic environments is a global concern due to the inherent toxicity of these elements, their widespread presence, persistence, and non-biodegradable nature. Their tendency to bioaccumulation in organisms and magnify through the food chain further exacerbates their ecological and health impacts (Yuan et al., 2011; Liao et al., 2017; Pushpraj and Babita., 2023). Thus, species at higher trophic levels like humans are more susceptible to harmful effects. Rivers serve as sensitive indicators of changes or disturbances in the natural state of a landscape (Schumm et al., 2000). Studies have shown that heavy metal pollution in rivers is closely linked to population growth, rapid urbanization, intensive domestic activities, expanding industrial and agricultural production as well as inadequate sanitation and wastewater treatment infrastructure (Akoto et al., 2008; Islam et al., 2014). As a result, the scarcity of clean drinkable water and declining water quality have become pressing challenges for both human sustenance and the health of aquatic ecosystems (Babiker et al., 2007). In countries like India, the uncontrolled and untreated discharge of residential/municipal and industrial wastewater and related pollutants into river catchments and urban water bodies from point sources and diffuse (non-point) sources (runoff from agricultural regions, urban areas, and homes, atmospheric deposition, construction sites, road traffic, small and large boats) further exacerbates the issue of maintaining water quality (Khadse et al., 2008; Ahmad and Khurshid, 2019; Gupta, 2020).

Heavy metals enter river systems in both dissolved (either as inorganic complexes or hydrated ions) and particulate forms. Within fluvial environments, these metals are primarily distributed among three key reservoirs: water, sediment, and biota (Maiti and Chowdhury, 2013). The concentrations of metals in each of these compartments are governed by a complex dynamic equilibrium influenced by various biological, physical and chemical processes (e.g. dissolution, precipitation, sorption, and complexion) (Saha et al., 2001). Heavy metals undergo speciation changes during their transportation. The constant interaction of heavy metals with different geochemical phases significantly affects their behavior and bioavailability and plays a critical role in determining their mobility and persistence in aquatic systems (Morillo et al., 2004; Nicolau et al., 2006). Metals are typically associated with silicates and occurring minerals, thus mineralogical composition of sediments significantly influences the natural distribution and mobility of these metals within river systems; however, anthropogenic activities can alter their chemical associations, leading to their binding with other forms such as carbonates, oxides, and sulphides (Paramasivam et al., 2015).

Given the critical role of clean water in sustaining all forms of life, it is essential to understand the sources and behavior of heavy metals within aquatic ecosystems. In regions where river water is extensively used for drinking, agriculture, and commercial activities and where rivers are subject to significant anthropogenic pressures, regular monitoring of metal concentrations in both water and sediments is vital. Equally important is the implementation of effective management systems to assess and ensure the suitability of river water for various uses (Xiao et al., 2011; Amadi, 2011; Djordjević et al., 2012). Abeysingha et al. (2020) further emphasize the importance of formulating long-term adaptation strategies that prioritize environmental flows and ecosystem services to safeguard the sustainability of riverine systems.

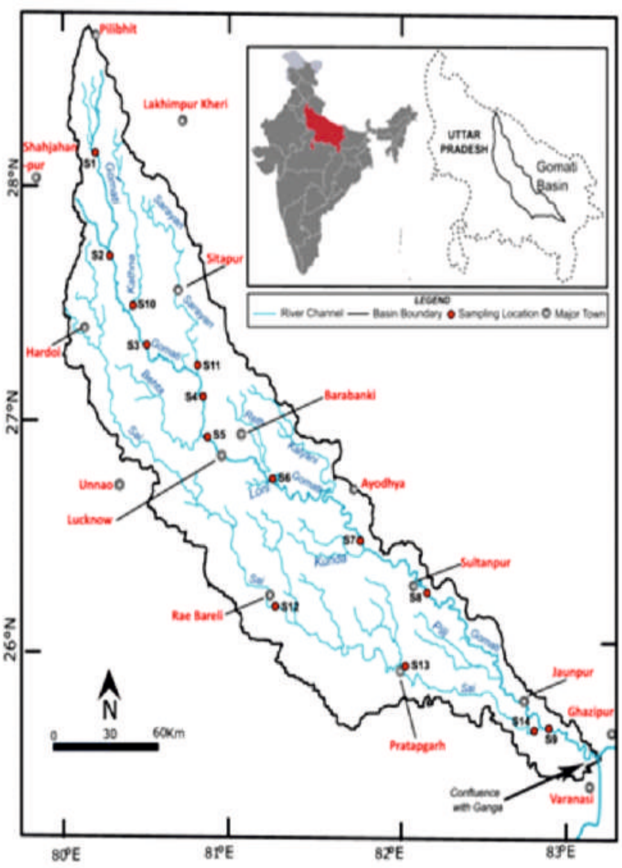

Fig. 1: Map of the Gomati River basin along with tributaries, major cities and sampling sites (modified from Kumari and Awasthi, 2025).

The Gomati River, an alluvial river in the Ganga Plain, serves as a crucial water source for numerous urban and rural settlements along its course in central and eastern Uttar Pradesh, India (Gupta et al., 2014; Gupta and Subramanian, 1994) (Fig. 1). Once in a pristine state, the river has undergone severe degradation and is now recognized as one of the most polluted rivers in the country (Singh et al., 2005). Rapid population growth, urbanization and the expansion of agricultural, industrial activities have significantly altered the natural condition of its basin, increasing pressure on its ecological balance. Previous studies have reported elevated pollution levels in the Gomati River, identifying domestic and industrial wastewater as potential sources of heavy metal contamination (Singh et al., 2005, Gaur et al. 2005; Lohani et al. 2008). However, the majority of these investigations have been limited to the Lucknow region, leaving a gap in comprehensive, basin-wide assessments. To date, no detailed seasonal analysis has been conducted to evaluate the extent of heavy metal pollution across the entire Gomati River Basin. Various pollution indices offer valuable insight into the contributions from different contamination sources. The primary objective of this study is to assess the water quality of the Gomati River along its entire course using pollution indices and other environmetric tools. The study employs multivariate statistical techniques including Pearson Correlation Analysis (PCA) and Hierarchical Cluster Analysis (HCA) to identify potential sources of heavy metal contamination, examine correlations among different metals, and evaluate spatial variability across sampling sites.

2. Samples and Methodology

2.1 Study area

The River Gomati flows through the central part of the Gangetic basin (in Uttar Pradesh, India), traversing the Ganga Plain, which is predominantly composed of sandy-silty sediments deposited during the Quaternary Period, spanning the Pleistocene to Holocene epochs (Goel, 2018). It is an alluvial tributary of the River Ganga, originating from Fulhar Jheel, a lake located in Madhotanda village near Pilibhit, and merges with the Ganga near Varanasi, India covering a distance of approximately 940 km (Fig. 1). Unlike glacial-fed rivers, the Gomati is fed primarily by groundwater and rainfall, and originates in a marshy, forested region of the Tarai, about 50 km south of the Himalayan foothills (Kumar and Singh, 1978). Along its meandering course, the river gathers water and sediment loads from major urban centers including Lucknow (the state capital), Sultanpur, and Jaunpur, in addition to numerous smaller towns and villages spread across eight other districts: Pilibhit, Shahjahanpur, Lakhimpur, Sitapur, Barabanki, Ayodhya, Varanasi, and Ghazipur, through various small tributaries and drainage channels (Fig. 1). Among these, the River Sai is the major tributary, flowing roughly parallel and collecting runoff from Hardoi, Unnao, Raebareli, and Pratapgarh districts, before merging with Gomati at Jaunpur, just a few kilometers upstream from the Gomati's confluence with the Ganga. Other minor tributaries include Kathna, Sarayan, Behta, Reth, Luni, Kalyani, Kunda, and Pili. The River Sarayan joins Gomati near Sitapur, about 45 km upstream of Lucknow, while the Reth and Kalyani Rivers join it downstream of the city.

The River Gomati primarily redistributes Pleistocene-Holocene sediments comprising mainly sand, sandy clay, and varying amounts of calcareous nodules that were originally eroded from the Himalayas and deposited across the Ganga alluvial plain during the geological time (Singh et al., 2005). The Gomati Basin features a bas-relief landscape and gentle gradient, shaped by the combined effects of climatic fluctuations and base-level changes associated with tectonic activity (Srivastava et al., 2003). Spanning an approximate area of 30,437 km^2, the basin experiences relatively uniform climatological conditions, characterized by a semi-arid to sub-humid tropical climate with average annual rainfall ranging from 850 to 1100 mm (Dutta et al. 2011; 2015; Rai et al., 2010). The region receives nearly 75% of its total precipitation from the Indian Summer Monsoon (ISM), concentrated between June and September (Quamar et al., 2017). Seasonal temperature extremes are also notable, with summer highs reaching up to 46°C and winter lows dropping to around 2°C.

2.2 Sample collection and analysis

For this study, water samples were collected from pre-identified sites along the Gomati River and its major tributaries during two distinct seasons in 2022: pre-monsoon (May) and post-monsoon (October). Sampling was carried out at regular intervals from the river's origin to its downstream stretches, just before its confluence with the Ganga (Fig. 1). Site selection considered known discharge points for industrial effluents, domestic sewage, and solid waste, as well as the influences of major urban centers, based on insights from previous research and reconnaissance surveys (Fig. 1). The rationale for selecting these two seasons was to evaluate seasonal variation in water quality parameters and to understand how the river system either retains or flushes pollutants under contrasting hydrological conditions low flow during the summer (non-monsoon) and increased flow during the monsoon.

Water samples were collected in wide-mouth, pre-acid-washed, clean plastic bottles from nine locations along the main channel of the River Gomati: S1 (Gomat Tal/Fulhar Jheel, Pilibhit), S2 (Chapartala, Kheri), S3 (Neemsar, Sitapur), S4 (Bhatpur, Sitapur), S5 (Sitapur-Hardoi Bypass, Lucknow), S6 (Gangaganj, Lucknow), S7 (Aamghat, Amethi), S8 (Tatiyanagar, Sultanpur) and S9 (Kerakat, Jaunpur). In addition, samples were taken from five sites across major tributaries: S10 for River Kathna (Maholi, Sitapur), S11 for River Sarayan (Sidhauli, Sitapur), S12–S14 for River Sai at Raebareli, Pratapgarh, and Jaunpur, respectively, prior to its confluence with the Gomati. Sampling sites S5 and S6 represent upstream and downstream points of Lucknow city, respectively. Figure 1 illustrates the sampling locations, while Table 1 provides a brief description of each site. A handheld GPS device was used to accurately record the coordinates of each sampling location as given in Kumari and Awasthi, (2025). The study covered an approximate 900 km stretch of

Table 1: Sampling locations of the river water samples collected from the Gomati main channel and its tributaries with expected sources of heavy metal pollution.

Sample No.	**Sampling Locations**	**Distance from the origin (km)**	**Expected sources of pollution**
Gomati Main Channel			
S1.	Gomat Tal/Fulhar Jheel (Pilibhit)	0	Agricultural
S2.	Chapartala (Kheri)	206	Agricultural
S3.	Neemsar (Sitapur)	304	Agricultural
S4.	Bhatpur (Sitapur)	373	Agricultural, Industrial effluents & Domestic wastewater
S5.	Sitapur-Hardoi Bypass (Lucknow)	425	Agricultural, Industrial effluents & Domestic wastewater
S6.	Gangaganj (Lucknow)	496	Agricultural, Industrial effluents & Domestic wastewater
S7.	Aamghat, Jagdishpur (Amethi)	650	Agricultural, Industrial effluents & Domestic wastewater
S8.	Tatiyanagar (Sultanpur)	736	Agricultural, Industrial effluents & Domestic wastewater
S9.	Kerakat (Jaunpur)	915	Agricultural, Industrial effluents & Domestic wastewater
Tributary Kathna			
S10.	Maholi (Sitapur)	270	Agricultural, Industrial effluents & Domestic wastewater
Tributary Sarayan			
S11.	Sidhauli (Sitapur)	371	Agricultural, Industrial effluents & Domestic wastewater
Tributary Sai			
S12.	Dariyapur (Raebareli)	323 before confluence with Gomati	Agricultural, Industrial effluents & Domestic wastewater
S13.	Chilbila (Pratapgarh)	135 before confluence with Gomati	Agricultural, Industrial effluents & Domestic wastewater
S14.	Sarkoni (Jaunpur)	902	Agricultural, Industrial effluents & Domestic wastewater

the Gomati River, enabling an assessment of heavy metal (HM) pollution across upstream, midstream, and downstream zones.

A total of 28 water samples were collected during the study 14 samples, each in the pre-monsoon and post-monsoon seasons. Additionally, three duplicate samples were collected from sites S3, S6, and S9 to ensure analytical precision. Prior to collection, all pre-labeled 1-liter plastic bottles were thoroughly rinsed multiple times with the respective sample water. Sampling, transportation, preservation, and analysis followed standard protocols as recommended by the American Public Health Association (APHA, 2017), Bureau of Indian Standards (BIS, 2012), and World Health Organization (WHO, 2017) guidelines. For heavy metal analysis, water samples were first digested with concentrated nitric acid (HNO_3). The processed samples were then tested for six metals Fe, Ni, Zn, Cu, and Cd using a Flame Atomic Absorption Spectrophotometer, along with reagent blanks and standard solutions for accuracy. These metals were chosen based on findings from earlier studies on surface water pollution and the available laboratory facilities. All chemicals used were of analytical grade and sourced from Merck, India. Double-distilled water was used in all preparations, and all glassware was rigorously cleaned using deionized water and 2% HNO_3 to prevent contamination. To ensure data reliability, quality control and assurance protocols were implemented, including blank checks, standard verifications, and duplicate analyses. The accuracy and precision of the results were validated through repeated analyses of both samples and standards.

2.3 Estimation of Pollution Indices

2.3.1 Metal index (MI) and Degree of contamination (C_d)

The metal index (MI) is estimated using the equation 1 as follows:

$$MI = \sum_{i=1}^{n} Ci / MACi \quad ......1$$

Where MI represents the Metal Index, Ci is the concentration of the i-th metal in the water sample, MACi is the maximum allowable concentration for that metal and i refer to each individual metal or sample component included in the calculation. This index provides a cumulative assessment of metal contamination by comparing observed concentrations to established safety thresholds. According to Caeiro et al (2005), MI< 0.3 is categorized as very pure (Class I), 0.3 to 1.0 is categorized as pure (Class II), 1.0 to 2.0 is slightly affected (Class III), 2.0 to 4.0 moderately affected (Class IV), 4.0 to 6.0 strongly affected (Class V) and > 6.0 is seriously affected (Class VI).

The impact of heavy metals on surface water quality can be measured using the degree of contamination (C_d) (Li *et al.*, 2015, 2016), calculated with the following equations:

$$C_d = \sum_{i=1}^{n} Cfi \quad ......2$$

$$Cfi = (Mi/Si) - 1 \quad ......3$$

Here, Cfi is the contamination factor of the ith heavy metal, Mi is its measured concentration, and Si is the standard permissible limit. According to Edet & Offiong, (2002) based on C_d values, water quality is classified as: Low pollution: $C_d < 1$, Moderate pollution: $1 < C_d < 3$, High pollution: $C_d > 3$.

2.3.2 Heavy metal pollution index (HPI)

The Heavy Metal Pollution Index (HPI) is a valuable tool for evaluating the overall water quality with respect to heavy metal contamination (Sheykhi and Moore, 2012). It functions as a weighted arithmetic index, similar in concept to the Water Quality Index (WQI) and is calculated in two primary steps: (1) by assigning relative weights to selected heavy metal that is typically inversely proportional to their permissible limit parameters and (2) quantify their combined impact on surface water quality by developing a rating scale based on those parameters (Mohan et al., 1996). The rating scale typically ranges from 0 to 1 and the selection of parameters is based on their significance in determining water quality. These rating values can also be determined by establishing an inverse proportional relationship with the standard permissible limits for each parameter (Horton, 1965). The unit weight (Wi) assigned to each parameter is inversely proportional to its respective standard value (Si), as described by equation (4):

$$HPI = \sum_{i=1}^{n} WiQi / \sum_{i=1}^{n} Wi \quad ....4$$

where n denotes the number of heavy metals used in the present study; Wi is unit weight of ith heavy metal. The subindex (Qi) is calculated from equation (5):

$$Qi = \sum_{i=1}^{n} ((Mi(-)Ii)/(Si - Ii)) \times 100 \quad ......5$$

In this context, Mi (μg/L) represents the measured concentration of the ith heavy metal, Si is its standard permissible limit, and Ii is the ideal value for that metal in drinking water, as specified by BIS (2012) and Prasad & Bose (2001). Earlier studies applied a single threshold value of HPI = 100 to categorize water as "Critically Polluted" (Prasad & Bose, 2001). However, a more refined classification system is now widely used, introduced by Edet and Offiong (2002), which categorizes HPI values into three levels of pollution: low (< 15), medium (15–30), and high (> 30). However, if HPI values go higher than 100, the sites are considered "critically polluted". In the present study, HPI has been computed to evaluate the extent of heavy metal pollution in the Gomati River, focusing on selected heavy metals across multiple sites.

2.3.3 Nemerow pollution index (NPI)

The Nemerow Pollution Index (NPI) is another widely used method for evaluating the overall pollution level at a given site, especially in the context of heavy metal contamination in water. It integrates both the maximum individual pollution index and the average pollution index across multiple pollutants to provide a more comprehensive assessment of environmental quality (Su et al., 2022). By accounting for the most severe as well as average of the single factor indices, which accurately represents the degree of water pollution, and the more polluting indicators, the NPI offers a balanced representation of site-wide pollution. This makes NPI more thorough when evaluating water quality than the single factor index method. This unitless numerical value is easy to interpret and effective in identifying polluted areas and prioritizing remediation strategies. The NPI is calculated using the following formula:

$$NPI=\sqrt{((Avg\ Pi)^2+(max\ Pi)^2)/2} \quad \ldots\ldots (6)$$

Where NPI is the overall pollution index for a sampling site, max Pi is the highest value among the individual pollution indices, Avg Pi = $1/n\sum n$ i=1Pi is the mean of the single-factor pollution indices, with n being the number of pollutants analyzed. Pollution severity based on NPI is typically categorized into four levels: Class I: NPI ≤ 0.7 — Clean or unpolluted, Class II: 0.7 < NPI ≤ 1 — Slight pollution, Class III: 1 < NPI ≤ 2 — Moderate pollution, Class IV: 2 < NPI > 3 — Heavy pollution, Class V: NPI > 3 — Serious pollution.

The NPI was used to analyze the level of pollution of a single water quality parameter in relation to standard values and to evaluate the effects of multiple pollutants on a specific water body. Each location index therefore reflects both the highest relative evaluated value and the average of all relative values. The NPI was used to assess pollution levels for individual water quality parameters compared to standard values and to evaluate the combined effect of multiple pollutants on the river. At each site, the index reflects both the highest pollutant value and the overall average, giving a balanced view between the worst and average conditions (Nemerow, 1991).

2.4 Pearson correlation matrix (PCA) and Hierarchical Cluster analysis (HCA)

The multivariate statistical methods such as PCA and HCA have proven to be effective tools in water quality assessment. To assess seasonal effects on water quality, Pearson's correlation coefficient (r) was calculated for heavy metals using Microsoft Excel software. This statistical method measures the strength and direction of linear relationships between variables, helping to identify interrelated water quality parameters that may influence overall water conditions. The correlation coefficient (r) ranges from +1 to -1 where +1 indicates a perfect positive linear relationship, -1 indicates a perfect negative linear relationship, and 0 suggests no linear correlation. A positive correlation implies that an increase in one metal is associated with an increase in another, while a negative correlation indicates the opposite. The strength of correlation either negative or positive was categorized as follows: very strong: 0.9–1.0, strong: 0.7–0.9, moderate: 0.5–0.7, weak: 0.5–0.3, negligible: 0.00–0.3 (Schober, et al., 2018). This analysis helps determine which metal concentrations tend to vary together, offering insights into possible common sources or environmental behaviors. Hierarchical Cluster Analysis (HCA) was carried out using PAST 4.0 software. The analysis used Ward's method with squared Euclidean distance to group samples by minimizing differences within each cluster. HCA, especially when applied using Ward's linkage method, efficiently groups water quality parameters based on internal similarities and external dissimilarities among

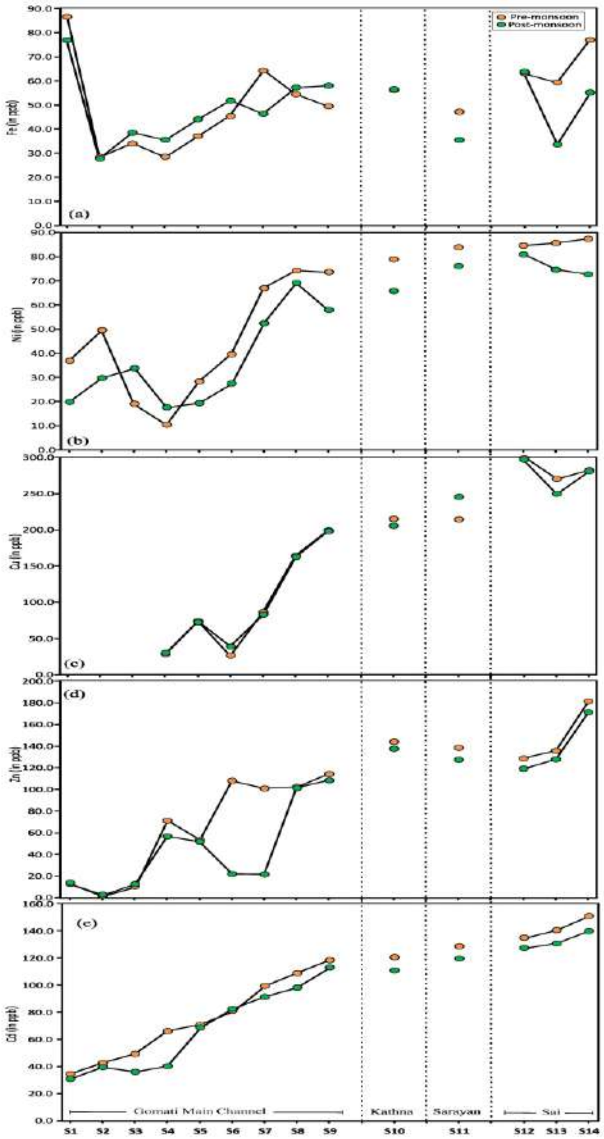

Fig. 2: Heavy metal concentrations (in μg/L) in the Gomati main channel (S1–S9) and tributaries [Kathna (S10), Sarayan (S11), Sai (S12-S14)] for (a) Fe (b) Ni (c) Cu (d) Zn (e) Cd. The pre- and post-monsoon data are represented in orange and green circles, respectively. Dashed vertical lines separate river sections and tributaries.

clusters (Gupta et al., 2014). As a result, the technique is widely used to identify patterns in water quality variation and analyze complex datasets as well as interpret the potential sources of heavy metal contamination in river systems (Mishra et al., 2015).

25 Caboi diagram

Water samples were also classified using the method by Caboi et al. (1999), which is based on pH and metal load (µg/L). The various metal load categories expressed in the Caboi diagram are "near neutral-low metal," "acid-high metal," "near neutral high metal," "near neutral-extreme metal," and "high acid-extreme metal". A lower pH corresponds to a higher metal load, increasing the mobility of heavy metals in water under acidic conditions (Singh et al., 2017).

3. Results

3.1 Distribution of heavy metals

Table 2 presents the summary of heavy metal minimum, maximum, average and standard deviation values in water samples from all sites. Of the nine metals analyzed, five (Fe, Ni, Cu, Zn, Cd) were detected, while Mn, Cr, Co, and As were either absent in our samples or below detection limit. The results of heavy metal concentrations in the river water samples analyzed are plotted in Figure 2. Except at some sites, the data for Ni, Cu, Zn and Cd shows increasing trend with downstream locations. Fe behaved differently and show fluctuations in its concentrations at different sites and during different seasons. However, in each case the concentrations of metals in tributaries were higher than the main channel. The measured values ranged as follows: pH from 7.8 to 8.4 (Average: 8.0) for pre-monsoon and 7.2 to 8.4 (Average: 7.9) for post-monsoon, Fe from 28.5 to 86.6 μg/L (Average: 50.6 μg/L) for pre-monsoon and from 27.9 to 76.9 μg/L (Average: 48.8 μg/L) for post-monsoon, Ni from 10.6 to 87.6 μg/L (Average: 56.1 μg/L) for pre-monsoon and from 13.0 to 81.1 μg/L (Average: 48.2 μg/L) for post-monsoon, Cu from 24.4 to 299.3 μg/L (Average: 160.8 μg/L) for pre-monsoon and from 28.9 to 297.3 μg/L (Average: 162.2 μg/L) for post-monsoon, Zn from 2.0 to 181.6 μg/L (Average: 90.6 μg/L) for pre-monsoon and from 3.1 to 71.9 μg/L (Average: 171.6 μg/L) for post-monsoon. Cd from 34.8 to 151.3 μg/L (Average: 94.1 μg/L) for pre-monsoon and from 26.1 to 140.2 μg/L (Average: 86.4 μg/L) for post-monsoon.

3.2 Pollution Indices

Figure 3 shows the classification and water quality distribution in the Gomati and its

Table 2: Statistical summary of analytical results of heavy metals measured in this work, compared to values acceptable by Bureau of Indian Standards (BIS) in surface waters for drinking purpose.

Parameters	Pre-Monsoon			Post-Monsoon			Standard values
	Max	Min	Average ± sd	Max	Min	Average ± sd	
pH	8.4	7.8	8.0 ± 0.2	8.4	7.2	7.9 ± 1.0	6.5–8.5$
Fe	86.6	28.5	50.6 ± 16.3	76.9	27.9	48.8 ± 12.8	300$
Ni	87.6	10.6	56.1 ± 26.9	81.1	13	48.2 ± 24.1	20$
Cu	299.3	24.4	160.8 ± 100.5	297.3	28.9	162.2 ± 97.5	1500$
Zn	181.6	2.0	90.6 ± 54.4	171.6	3.1	71.9 ± 55.7	15000$
Cd	151.3	34.8	94.1 ± 37.3	140.2	26.1	86.1 ± 37.8	3$

All concentrations are expressed in (μg/L); sd: standard deviation, $BIS (2012)

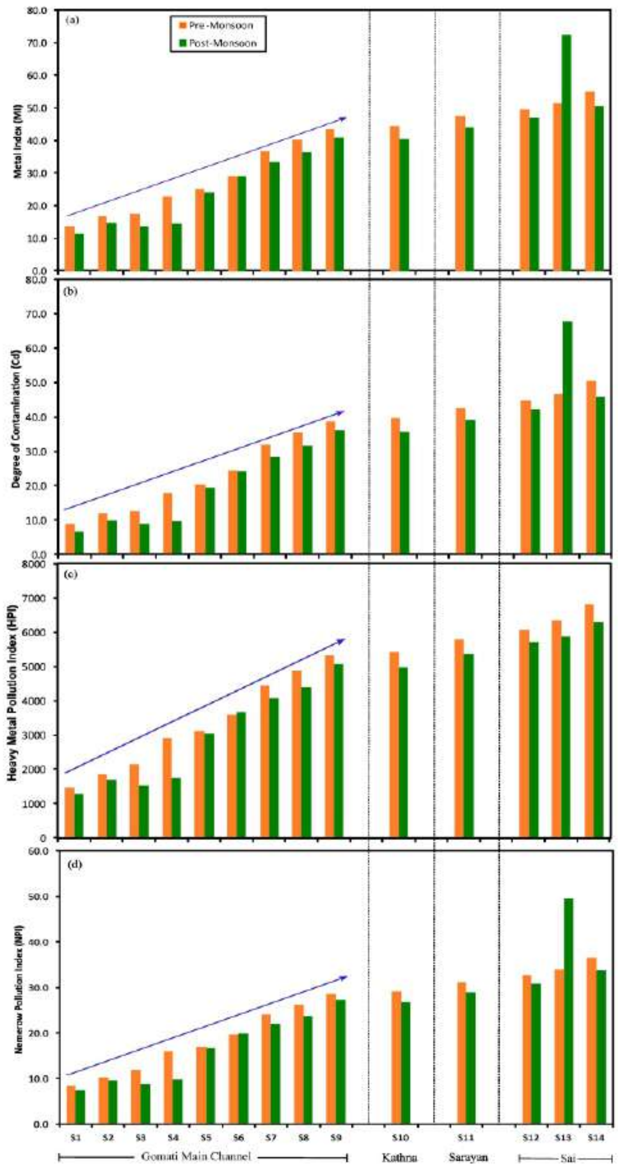

Fig. 3 Variations of different metal indices calculated using heavy metal concentrations in the Gomati main channel and tributaries (a) Metal Index (b) Degree of contamination (c) Heavy Metal Pollution Index (d) Nemerow Pollution Index.

tributaries based on MI, C_d, HPI, and NPI, the calculation and values for which are shown in Supplementary Tables S1 and S2. The MI values ranged from 13.7 to 55.3 in the pre-monsoon and from 11.6 to 72.6 in the post-monsoon (Fig. 3a). The lowest value was recorded at site S1 in both seasons, while the highest was at S14 (pre-monsoon) and S13 (post-monsoon). For C_d, values ranged from 8.7 to 50.3 in the pre-monsoon and 6.6 to 67.6 in the post-monsoon, with mean values of 30.3 and 28.9, respectively (Fig. 3b). HPI increased along the Gomati River from upstream locations to downstream, mainly due to pollution received from midstream tributaries and drains (Fig. 3c). During the pre-monsoon, HPI followed the order S1 < S2 < S3 < S4 < S5 < S6 < S7 < S8 < S9 < S10 < S11 < S12 < S13 < S14, with the lowest pollution at S1 and the highest at S14. The post-monsoon pattern was similar, except for a slight change between S2 and S3. Like HPI, the NPI method proved effective in showing the overall condition of the river (Fig. 3d).

3.3 Correlation and Cluster Analysis

Table 3 presents Pearson correlation matrices for six water quality parameters (pH, Fe, Ni, Cu, Zn, and Cd) and metal indices calculated using heavy metal concentrations during pre- and post-monsoon seasons. In the pre-monsoon period, Fe shows moderate positive correlation with Ni (r = 0.52) and strong positive correlation with Cu (r = 0.71). Ni is strongly positively correlated with Cu (r = 0.88), Zn (r = 0.77), and Cd (r = 0.87). Cu also has strong positive correlations with Zn (r =

Table 3: Heat map of Pearson's correlation matrix between various heavy metals measured in Gomati River during pre- and post-monsoon periods and estimated pollution indices.

PRE-MONSOON	pH	Fe	Ni	Cu	Zn	Cd	MI	NPI	HPI	C_d
pH	1.00									
Fe	-0.41	1.00								
Ni	-0.46	0.52	1.00							
Cu	-0.46	0.71	0.88	1.00						
Zn	-0.42	0.39	0.77	0.79	1.00					
Cd	-0.51	0.37	0.87	0.96	0.95	1.00				
MI	-0.51	0.40	0.89	0.95	0.95	1.00	1.00			
NPI	-0.51	0.37	0.87	0.96	0.95	1.00	1.00	1.00		
HPI	-0.51	0.37	0.87	0.96	0.95	1.00	1.00	1.00	1.00	
C_d	-0.51	0.40	0.89	0.95	0.95	1.00	1.00	1.00	1.00	1.00
POST-MONSOON	**pH**	**Fe**	**Ni**	**Cu**	**Zn**	**Cd**	**MI**	**NPI**	**HPI**	**C_d**
pH	1.00									
Fe	0.01	1.00								
Ni	-0.21	0.11	1.00							
Cu	-0.14	0.29	0.92	1.00						
Zn	-0.06	0.15	0.83	0.90	1.00					
Cd	-0.31	0.14	0.90	0.93	0.87	1.00				
MI	-0.43	-0.01	0.85	0.81	0.81	0.93	1.00			
NPI	-0.44	-0.02	0.83	0.79	0.80	0.92	1.00	1.00		
HPI	-0.31	0.14	0.90	0.93	0.87	1.00	0.93	0.92	1.00	
C_d	-0.43	-0.01	0.85	0.81	0.81	0.93	1.00	1.00	0.93	1.00

*The values range from -1 to +1 and are color-coded where dark green signifies very strong positive correlations, dark red signifies very strong negative correlations, intermediate shades of yellow and orange show strong, moderate to weak correlations).

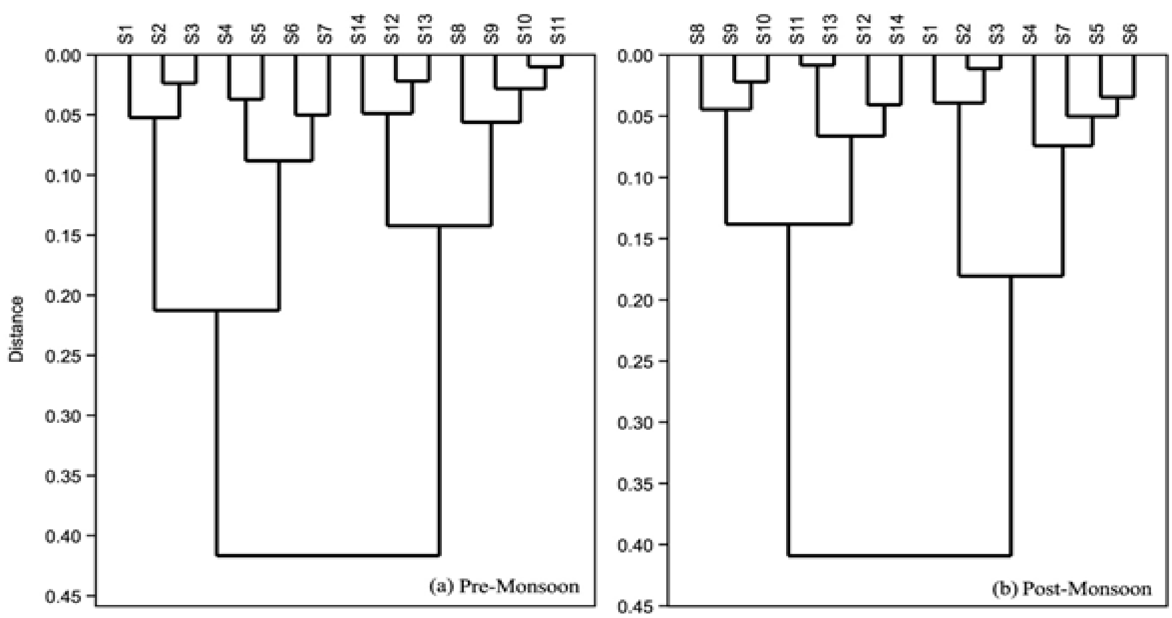

Fig. 4: The dendrogram obtained from hierarchical clustering analysis for sampling sites during (a) pre-monsoon (b) post-monsoon.

0.79) and an extremely strong one with Cd (r = 0.96); Cd and Zn are similarly vary strongly positively correlated (r = 0.95). In the post-monsoon season, very strong positive correlations are observed between Cu and Ni (r = 0.92), Cu and Cd (r = 0.93), and Ni and Cd (r = 0.90). Zn also shows strong positive correlations with Ni (r = 0.83) and Cd (r = 0.87). Metal indices like MI, C_d, HPI, and NPI also show very strong to strong positive correlations with Cd, Zn, Cu and Ni suggesting their decisive roles in estimation of these pollution indices and degradation of the water quality.

HCA was performed to understand the similarity among the parameters that contribute largely in contaminating water with heavy metals. HCA grouped the sampling sites into three major clusters in both pre- and post-monsoon seasons, though the site composition within clusters varied. HCA using Ward's method on the pre-monsoon data, group sampling sites into three clusters based on similarities in water quality within these groups (Fig. 4a): HCA1: sites S1–S7 formed one large cluster; HCA2: S12–S14 grouped together and forms another cluster; HCA3: S8–S11 clustered separately. In contrast, during the post-monsoon (Fig. 4b), sites HCA1: S8–S14 merged into a single larger cluster, while upstream sites HCA2: (S1–S4, S7) and midstream sites HCA3: S5–S6 formed two distinct groups. During both the seasons, heavy metals were grouped into two clusters: Cluster 1: Zn, Cd, Fe, Ni; Cluster 2: Cu (not shown).

3.4 Caboi diagram

Water samples were categorized using the Caboi diagram (Caboi et al., 1999; Ficklin et al., 1992) based on pH and total dissolved metal load (Fe + Ni + Cd + Zn + Cu). Since metal precipitation and release depends on pH, the near-neutral to alkaline nature suggests heavy metals likely should settle in sediments as carbonates or oxides (Singh et al., 2005). In this study, water pH for the Gomati main channel and tributaries ranged from 7.6 to 8.3 (pre-monsoon) and 6.1 to 10.6 (post-

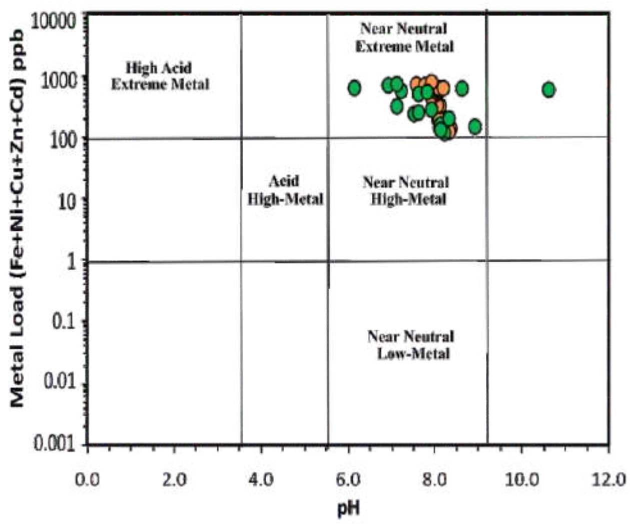

Fig. 5: Caboi diagram representing the mobility of heavy metals in the Gomati main channel and tributaries with the variation in pH. Orange circles are for pre-monsoon data and green circles for post-monsoon data.

monsoon), generally indicating neutral to alkaline conditions, within WHO limits (Fig. 5). However, extreme pH values were observed post-monsoon in tributaries Kathna (high: 10.6) and Sai at Pratapgarh (low: 6.1).

4. Discussion

Although sampling seasons differed, some of our locations overlapped with study by Singh et al. (2005). Comparing our data with that study, we observed that except Fe, the concentrations of all heavy metals were much higher in pre- and post-monsoon seasons of 2022. Fe was previously reported as 79–319 μg/L (Singh et al., 2005), 102–339 μg/L (Khan et al., 2020), and 92–270 μg/L (Khan et al., 2021). However, in 2022, Fe levels were lower during both the seasons (28–87 μg/L, pre-monsoon and 28–77 μg/L, post-monsoon). Fe concentration is highest at the origin of the Gomati River (S1, Madho Tanda) during both seasons, but it decreases at S2 and then shows fluctuating values with a general increase downstream (Fig. 2a). Higher Fe levels are found at downstream stations (S7–S9) and again in the Sai tributary (S12–S14). Post-monsoon Fe values are slightly lower than pre-monsoon ones at most sites, indicating dilution caused by rainfall and surface runoff. The concentrations in tributaries such as Kathna (S10) and Sarayan (S11) are

Table 4: Estimation of Metal index (MI) and Degree of contamination (C_d) for different sampling sites of the Gomati River main channel and tributaries.

		Pre-Monsoon					Post-Monsoon				
Samples/ Symbols	Maximum Allowable conc. (MAC) in ppb	Mean conc. (Ci) in ppb	Ci/MAC	Metal Index	Cfi	Degree of contamination C_d	Mean conc. (Ci)	Ci/MAC	Metal Index	Cfi	Degree of contamination C_d
S1											
Fe	300	86.60	0.29	**13.73**	-0.711	**8.73**	76.91	0.26	**11.59**	-0.744	**6.59**
Ni	20	37.07	1.85		0.853		20.00	1.00		0.000	
Cu	1500	0.00	0.00		-1.000		0.00	0.00		-1.000	
Zn	15000	13.17	0.00		-0.999		13.73	0.00		-0.999	
Cd	3	34.75	11.58		10.584		30.99	10.33		9.329	
S2											
Fe	300	28.50	0.10	**16.83**	-0.91	**11.83**	27.90	0.09	**14.84**	-0.91	**9.84**
Ni	20	49.70	2.49		1.49		29.93	1.50		0.50	
Cu	1500	0.00	0.00		-1.00		0.00	0.00		-1.00	
Zn	15000	2.03	0.00		-1.00		3.06	0.00		-1.00	
Cd	3	42.76	14.25		13.25		39.75	13.25		12.25	
S3											
Fe	300	34.08	0.11	**17.64**	-0.89	**12.64**	38.56	0.13	**13.92**	-0.87	**8.92**
Ni	20	19.26	0.96		-0.04		33.95	1.70		0.70	
Cu	1500	0.00	0.00		-1.00		0.00	0.00		-1.00	
Zn	15000	10.77	0.00		-1.00		12.81	0.00		-1.00	
Cd	3	49.69	16.56		15.56		36.27	12.09		11.09	
S4											
Fe	300	28.60	0.10	**22.78**	-0.90	**17.78**	35.63	0.12	**14.55**	-0.88	**9.55**
Ni	20	10.58	0.53		-0.47		17.73	0.89		-0.11	
Cu	1500	29.01	0.02		-0.98		29.47	0.02		-0.98	
Zn	15000	71.33	0.00		-1.00		56.80	0.00		-1.00	
Cd	3	66.40	22.13		21.13		40.57	13.52		12.52	
S5											
Fe	300	37.17	0.12	**25.20**	-0.88	**20.20**	44.13	0.15	**24.19**	-0.85	**19.19**
Ni	20	28.51	1.43		0.43		19.50	0.98		-0.03	
Cu	1500	74.37	0.05		-0.95		74.03	0.05		-0.95	
Zn	15000	53.67	0.00		-1.00		52.14	0.00		-1.00	
Cd	3	70.79	23.60		22.60		69.03	23.01		22.01	
S6											
Fe	300	45.52	0.15	**29.30**	-0.85	**24.30**	51.88	0.17	**29.08**	-0.83	**24.08**
Ni	20	39.78	1.99		0.99		27.63	1.38		0.38	
Cu	1500	26.94	0.02		-0.98		0.00	0.00		-1.00	
Zn	15000	108.37	0.01		-0.99		22.25	0.00		-1.00	
Cd	3	81.40	27.13		26.13		82.59	27.53		26.53	
S7											
Fe	300	64.26	0.21	**36.84**	-0.79	**31.84**	46.39	0.15	**33.39**	-0.85	**28.39**
Ni	20	67.10	3.36		2.36		52.60	2.63		1.63	
Cu	1500	86.93	0.06		-0.94		83.40	0.06		-0.94	
Zn	15000	101.23	0.01		-0.99		21.77	0.00		-1.00	
Cd	3	99.63	33.21		32.21		91.63	30.54		29.54	

S8											
Fe	300	54.43	0.18	**40.39**	-0.82	**35.39**	57.27	0.19	**36.57**	-0.81	**31.57**
Ni	20	74.37	3.72		2.72		69.20	3.46		2.46	
Cu	1500	164.60	0.11		-0.89		163.00	0.11		-0.89	
Zn	15000	102.56	0.01		-0.99		102.00	0.01		-0.99	
Cd	3	109.11	36.37		35.37		98.40	32.80		31.80	
S9											
Fe	300	49.52	0.17	**43.54**	-0.83	**38.54**	58.08	0.19	**40.87**	-0.81	**35.87**
Ni	20	73.76	3.69		2.69		58.03	2.90		1.90	
Cu	1500	199.62	0.13		-0.87		0.00	0.00		-1.00	
Zn	15000	114.60	0.01		-0.99		108.68	0.01		-0.99	
Cd	3	118.65	39.55		38.55		113.30	37.77		36.77	
S10											
Fe	300	56.23	0.19	**44.57**	-0.81	**39.57**	56.41	0.19	**40.65**	-0.81	**35.65**
Ni	20	79.03	3.95		2.95		65.90	3.30		2.30	
Cu	1500	215.50	0.14		-0.86		205.90	0.14		-0.86	
Zn	15000	144.29	0.01		-0.99		137.80	0.01		-0.99	
Cd	3	120.83	40.28		39.28		111.07	37.02		36.02	
S11											
Fe	300	47.27	0.16	**47.50**	-0.84	**42.50**	35.57	0.12	**44.06**	-0.88	**39.06**
Ni	20	84.06	4.20		3.20		76.30	3.82		2.82	
Cu	1500	214.87	0.14		-0.86		246.00	0.16		-0.84	
Zn	15000	138.67	0.01		-0.99		127.63	0.01		-0.99	
Cd	3	128.96	42.99		41.99		119.87	39.96		38.96	
S12											
Fe	300	63.27	0.21	**49.73**	-0.79	**44.73**	63.50	0.21	**47.02**	-0.79	**42.02**
Ni	20	84.73	4.24		3.24		81.13	4.06		3.06	
Cu	1500	299.33	0.20		-0.80		297.33	0.20		-0.80	
Zn	15000	128.88	0.01		-0.99		119.43	0.01		-0.99	
Cd	3	135.23	45.08		44.08		127.63	42.54		41.54	
S13											
Fe	300	59.40	0.20	**51.62**	-0.80	**46.62**	33.67	0.11	**72.58**	-0.89	**67.58**
Ni	20	85.80	4.29		3.29		74.77	3.74		2.74	
Cu	1500	270.47	0.18		-0.82		250.00	0.17		-0.83	
Zn	15000	135.98	0.01		-0.99		128.03	0.01		-0.99	
Cd	3	140.84	46.95		45.95		205.67	68.56		67.56	
S14											
Fe	300	77.00	0.26	**55.27**	-0.74	**50.27**	55.27	0.18	**50.75**	-0.82	**45.75**
Ni	20	87.57	4.38		3.38		72.83	3.64		2.64	
Cu	1500	282.80	0.19		-0.81		281.30	0.19		-0.81	
Zn	15000	181.58	0.01		-0.99		171.63	0.01		-0.99	
Cd	3	151.30	50.43		49.43		140.17	46.72		45.72	

nearly similar to those in the main channel. For Ni, earlier studies reported 7–10 μg/L (Singh et al., 2005), 8–105 μg/L (Gaur et al., 2005), and 30–69 μg/L (Gupta et al., 2014). However, in our study, Ni ranged from 10–88 μg/L (pre-monsoon) and 17–81 μg/L (post-monsoon). Ni concentrations are lowest near the headwaters (S1–S3) and increase sharply downstream, reaching to about 80 μg/L (Fig. 2b). Both seasons show a similar trend, but pre-monsoon Ni values are generally higher, likely due to lower water discharge and higher evaporation before the monsoon.

Cu concentrations in Lucknow water varied from 1–4 μg/L (Singh et al., 2005) and 0–35 μg/L (Gaur et al., 2005). Gupta et al. (2014) reported 14–42 μg/L Cu at Lucknow while, Singh et al. (2010) found 11–80 μg/L Cu in Jaunpur. In our data of 2022, Cu levels were much higher, ranging from 26–299 μg/L (pre-monsoon) and 29–297 μg/L (post-monsoon). Cu concentrations gradually increase downstream, reaching the highest level in the Sai tributary (~250 μg/L) (Fig. 2c). Post-monsoon Cu values are slightly lower, reflecting dilution by rainfall. Zn concentrations were

14–29 μg/L (Singh et al., 2005), 30–91 μg/L (Gaur et al., 2005), and 56–74 μg/L (Gupta et al., 2014). In 2022, they were broader, ranging from 2–182 μg/L (pre-monsoon) and 3–172 μg/L (post-monsoon). Zn also shows a gradual rise from S1 to S9 (up to ~180 μg/L) (Fig. 2d). The tributaries have similar or slightly lower Zn levels, except the Sai tributary, which remains relatively high. Zn concentrations vary little between the two seasons.

Cd showed exceptionally high levels (30.9–151.3 μg/L) in 2022, far above values reported earlier. It was below detection limits in Gaur et al., (2005) and 0.1–0.5 μg/L in Singh et al., (2005); both studies were done in Lucknow. However, elevated Cd levels were also noted in later studies: 40–96 μg/L at Jaunpur (Singh et al., 2010), 13–55 μg/L (Gupta et al., 2014) and 50–54 μg/L (Khan et al., 2020, 2021) in Lucknow. All these suggest increasing levels of heavy metal pollution for elements like Ni, Cu, Zn and Pb with time in the Gomati and its tributaries. Cd exhibits a steady downstream increase from ~20 μg/L to more than 140 μg/L, with slightly lower values after the monsoon, again suggesting dilution by rainwater (Fig. 2e). The clear downstream rise in Cd indicates continuous accumulation of contaminants along the river.

Based on classification and distribution using MI, C_d, HPI, and NPI indices, the overall water quality in the Gomati and its tributaries is found to be extremely poor. Table S3 summarizes the water quality of the sampling locations based on various pollution indices. The spatial trend (Fig. 3) confirmed a progressive decline in water quality downstream, consistent across all indices. MI, with all values >6 during both the pre- and post-monsoon seasons fall under *seriously affected* (Class VI) category. C_d values all >3, classifying the sites as *highly polluted*. HPI values exceeded 100 at all sites, increasing from upstream to downstream, classifying the entire river stretch as *critically polluted*. NPI results also categorized the river as *severely polluted* (Class VI). Thus, the Gomati River shows a consistent deterioration of water quality from upstream (S1) to downstream (S9). The combined results of MI, Cd, HPI, and NPI classify the river and its tributaries as severely to critically polluted. The declining pattern of water quality along the river matches the trend of increasing Cd pollution suggesting Cd concentrations in river are at critical values. All the indices showed higher contamination in the river, however such contamination affects are severe in the midstream tributaries like Kathna, Sarayan, and Sai (especially at S13 in Pratapgarh during the post-monsoon) and minimal in the Gomati main channel as concentrations from tributaries get diluted downstream after merging with the river.

Pearson correlation analyses indicate strong associations among metals (Table 3) and suggest that these metals likely originate from common sources or exhibit similar chemical behavior, particularly Cd, Cu, and Ni. The post-monsoon data suggest towards pollutant remobilization due to runoff. Additionally, all metals show negative to negligible correlations with pH in both seasons, indicating that metal concentrations are either unaffected or tend to increase as the water becomes more acidic. This may be due to release of heavy metals by sediments into water as acidity increases. However, the Caboi's diagram suggest most of our samples fell into the "near neutral-extreme metal" category suggesting although our samples are close to neutral in pH (6.5–8.5) but the water carries very high metal loads. This reflects severe contamination, as neutral pH typically favors better water quality but here high metal concentrations override the buffering capacity of the system. None of the samples fall in other fields, suggesting that metal enrichment is the primary issue, not acidification. This pattern implies that the Gomati River and its tributaries are under serious heavy metal stress. Thus, Caboi's Diagram discards the possibility of release of metals by natural geochemical acidification processes, rather it suggests to be driven by anthropogenic inputs (Fig. 5). HCA during both the seasons grouped the heavy metals into two clusters: Cluster 1 including Zn, Cd, Fe, Ni suggesting a common source to these and Cluster 2 having Cu alone.

Table 5: Estimation of Heavy metal pollution index (HPI) and Nemerow pollution index (NPI) for different sampling sites of the Gomati River main channel and tributaries.

				Pre-Monsoon						**Post-Monsoon**					
Samples/ Symbols	**Standard Permissible Limit (Si) in ppb**	**Ideal Value (Ii) in ppb**	**Unit Weight Value (Wi)**	**Monitor Value (Mi) in ppb**	**Qi= |Mi-Ii|/(Si-Ii)*100**	**WiQi**	**HPI = ΣWiQi/ΣWi**	**Pi**	**NPI**	**Monitor Value (Mi) in ppb**	**Qi= |Mi-Ii|/(Si-Ii)*100**	**WiQi**	**HPI = ΣWiQi/ΣWi**	**Pi**	**NPI**
S1															
Fe	300	0	0.00	86.60	28.87	0.10	**1457.2**	0.29	**8.4**	76.91	25.64	0.09	**1282.1**	0.26	**7.5**
Ni	70	20	0.01	37.07	34.13	0.49		1.85		20.00	0.00	0.00		1.00	
Cu	1500	50	0.00	0.00	3.45	0.00		0.00		0.00	3.45	0.00		0.00	
Zn	15000	5000	0.00	13.17	49.87	0.00		0.00		13.73	49.86	0.00		0.00	
Cd	5	3	0.20	34.75	1587.56	317.51		11.58		30.99	1399.33	279.87		10.33	
S2															
Fe	300	0	0.00	28.50	9.50	0.03	**1825.4**	0.10	**10.4**	27.90	9.30	0.03	**1684.5**	0.09	
Ni	70	20	0.01	49.70	59.40	0.85		2.49		29.93	19.87	0.28		1.50	
Cu	1500	50	0.00	0.00	3.45	0.00		0.00		0.00	3.45	0.00		0.00	
Zn	15000	5000	0.00	2.03	49.98	0.00		0.00		3.06	49.97	0.00		0.00	
Cd	5	3	0.20	42.76	1987.97	397.59		14.25		39.75	1837.50	367.50		13.25	**9.6**
S3															
Fe	300	0	0.00	34.08	11.36	0.04	**2139.1**	0.11	**12.0**	38.56	12.85	0.04	**1525.7**	0.13	**8.8**
Ni	70	20	0.01	19.26	1.49	0.02		0.96		33.95	27.90	0.40		1.70	
Cu	1500	50	0.00	0.00	3.45	0.00		0.00		0.00	3.45	0.00		0.00	
Zn	15000	5000	0.00	10.77	49.89	0.00		0.00		12.81	49.87	0.00		0.00	
Cd	5	3	0.20	49.69	2334.48	466.90		16.56		36.27	1663.50	332.70		12.09	
S4															
Fe	300	0	0.00	28.60	9.53	0.03	**2905.6**	0.10	**16.0**	35.63	11.88	0.04	**1721.0**	0.12	**9.8**
Ni	70	20	0.01	10.58	18.85	0.27		0.53		17.73	4.53	0.06		0.89	
Cu	1500	50	0.00	29.01	1.45	0.00		0.02		29.47	1.42	0.00		0.02	
Zn	15000	5000	0.00	71.33	49.29	0.00		0.00		56.80	49.43	0.00		0.00	
Cd	5	3	0.20	66.40	3169.83	633.97		22.13		40.57	1878.33	375.67		13.52	

S5															
Fe	300	0	0.00	37.17	12.39	0.04	**3106.6**	0.12	**17.1**	44.13	14.71	0.05	**3024.5**	0.15	
Ni	70	20	0.01	28.51	17.03	0.24		1.43		19.50	1.00	0.01		0.98	
Cu	1500	50	0.00	74.37	1.68	0.00		0.05		74.03	1.66	0.00		0.05	
Zn	15000	5000	0.00	53.67	49.46	0.00		0.00		52.14	49.48	0.00		0.00	
Cd	5	3	0.20	70.79	3389.33	677.87		23.60		69.03	3301.67	660.33		23.01	**16.6**
S6															
Fe	300	0	0.00	45.52	15.17	0.05	**3594.2**	0.15	**19.6**	51.88	17.29	0.06	**3646.2**	0.17	**19.9**
Ni	70	20	0.01	39.78	39.56	0.57		1.99		27.63	15.27	0.22		1.38	
Cu	1500	50	0.00	26.94	1.59	0.00		0.02		0.00	3.45	0.00		0.00	
Zn	15000	5000	0.00	108.37	48.92	0.00		0.01		22.25	49.78	0.00		0.00	
Cd	5	3	0.20	81.40	3919.83	783.97		27.13		82.59	3979.33	795.87		27.53	
S7															
Fe	300	0	0.00	64.26	21.42	0.07	**4433.0**	0.21	**24.1**	46.39	15.46	0.05	**4063.7**	0.15	**22.1**
Ni	70	20	0.01	67.10	94.20	1.35		3.36		52.60	65.20	0.93		2.63	
Cu	1500	50	0.00	86.93	2.55	0.00		0.06		83.40	2.30	0.00		0.06	
Zn	15000	5000	0.00	101.23	48.99	0.00		0.01		21.77	49.78	0.00		0.00	
Cd	5	3	0.20	99.63	4831.33	966.27		33.21		91.63	4431.67	886.33		30.54	
S8															
Fe	300	0	0.00	54.43	18.14	0.06	**4868.4**	0.18	**26.3**	57.27	19.09	0.06	**4375.9**	0.19	
Ni	70	20	0.01	74.37	108.73	1.55		3.72		69.20	98.40	1.41		3.46	
Cu	1500	50	0.00	164.60	7.90	0.01		0.11		163.00	7.79	0.01		0.11	
Zn	15000	5000	0.00	102.56	48.97	0.00		0.01		102.00	48.98	0.00		0.01	
Cd	5	3	0.20	109.11	5305.57	1061.11		36.37		98.40	4770.00	954.00		32.80	**23.8**
S9															
Fe	300	0	0.00	49.52	16.51	0.06	**5305.2**	0.17	**28.6**	58.08	19.36	0.06	**5056.8**	0.19	**27.3**
Ni	70	20	0.01	73.76	107.52	1.54		3.69		58.03	76.07	1.09		2.90	
Cu	1500	50	0.00	199.62	10.32	0.01		0.13		0.00	3.45	0.00		0.00	
Zn	15000	5000	0.00	114.60	48.85	0.00		0.01		108.68	48.91	0.00		0.01	
Cd	5	3	0.20	118.65	5782.42	1156.48		39.55		113.30	5515.00	1103.00		37.77	

S10															
Fe	300	0	0.00	56.23	18.74	0.06	**5405.7**	0.19	**29.2**	56.41	18.80	0.06	**4955.5**	0.19	**26.8**
Ni	70	20	0.01	79.03	118.07	1.69		3.95		65.90	91.80	1.31		3.30	
Cu	1500	50	0.00	215.50	11.41	0.01		0.14		205.90	10.75	0.01		0.14	
Zn	15000	5000	0.00	144.29	48.56	0.00		0.01		137.80	48.62	0.00		0.01	
Cd	5	3	0.20	120.83	5891.33	1178.27		40.28		111.07	5403.33	1080.67		37.02	
S11															
Fe	300	0	0.00	47.27	15.76	0.05	**5778.8**	0.16	**31.1**	35.57	11.86	0.04	**5359.8**	0.12	**28.9**
Ni	70	20	0.01	84.06	128.12	1.83		4.20		76.30	112.60	1.61		3.82	
Cu	1500	50	0.00	214.87	11.37	0.01		0.14		246.00	13.52	0.01		0.16	
Zn	15000	5000	0.00	138.67	48.61	0.00		0.01		127.63	48.72	0.00		0.01	
Cd	5	3	0.20	128.96	6297.90	1259.58		42.99		119.87	5843.33	1168.67		39.96	
S12															
Fe	300	0	0.00	63.27	21.09	0.07	**6066.5**	0.21	**32.6**	63.50	21.17	0.07	**5716.3**	0.21	**30.8**
Ni	70	20	0.01	84.73	129.47	1.85		4.24		81.13	122.27	1.75		4.06	
Cu	1500	50	0.00	299.33	17.20	0.01		0.20		297.33	17.06	0.01		0.20	
Zn	15000	5000	0.00	128.88	48.71	0.00		0.01		119.43	48.81	0.00		0.01	
Cd	5	3	0.20	135.23	6611.70	1322.34		45.08		127.63	6231.67	1246.33		42.54	
S13															
Fe	300	0	0.00	59.40	19.80	0.07	**6323.4**	0.20	**34.0**	33.67	11.22	0.04	**5869.5**	0.11	**49.6**
Ni	70	20	0.01	85.80	131.60	1.88		4.29		74.77	109.53	1.56		3.74	
Cu	1500	50	0.00	270.47	15.20	0.01		0.18		250.00	13.79	0.01		0.17	
Zn	15000	5000	0.00	135.98	48.64	0.00		0.01		128.03	48.72	0.00		0.01	
Cd	5	3	0.20	140.84	6892.00	1378.40		46.95		205.67	6400.00	1280.00		68.56	
S14															
Fe	300	0	0.00	77.00	25.67	0.09	**6803.0**	0.26	**36.5**	55.27	18.42	0.06	**6289.2**	0.18	**33.8**
Ni	70	20	0.01	87.57	135.13	1.93		4.38		72.83	105.67	1.51		3.64	
Cu	1500	50	0.00	282.80	16.06	0.01		0.19		281.30	15.95	0.01		0.19	
Zn	15000	5000	0.00	181.58	48.18	0.00		0.01		171.63	48.28	0.00		0.01	
Cd	5	3	0.20	151.30	7415.02	1483.00		50.43		140.17	6858.33	1371.67		46.72	

* For NPI calculation Maximum Allowable conc. (MAC) is same as given in Table 3.

Table 6: The level of heavy metal pollution at different sampling sites of the Gomati River main channel and tributaries based on the estimated MI, C_d, HPI, NPI values.

Sampling sites	Seasons	MI	Rating of water quality	Cd	Rating of water quality	HPI	Rating of water quality	NPI	Rating of water quality
S1	Pre- Monsoon	13.7	Seriously affected	8.7	High pollution	1457	Critically polluted	8.4	Seriously polluted
	Post- Monsoon	11.6	Seriously affected	6.6	High pollution	1282	Critically polluted	7.5	Seriously polluted
S2	Pre- Monsoon	16.8	Seriously affected	11.8	High pollution	1825	Critically polluted	10.4	Seriously polluted
	Post- Monsoon	14.8	Seriously affected	9.8	High pollution	1685	Critically polluted	9.6	Seriously polluted
S3	Pre- Monsoon	17.6	Seriously affected	12.6	High pollution	2139	Critically polluted	12.0	Seriously polluted
	Post- Monsoon	13.9	Seriously affected	8.9	High pollution	1527	Critically polluted	8.8	Seriously polluted
S4	Pre- Monsoon	22.8	Seriously affected	17.8	High pollution	2906	Critically polluted	16.0	Seriously polluted
	Post- Monsoon	14.6	Seriously affected	9.6	High pollution	1721	Critically polluted	9.8	Seriously polluted
S5	Pre- Monsoon	25.2	Seriously affected	20.2	High pollution	3107	Critically polluted	17.1	Seriously polluted
	Post- Monsoon	24.2	Seriously affected	19.2	High pollution	3024	Critically polluted	16.6	Seriously polluted
S6	Pre- Monsoon	29.3	Seriously affected	24.3	High pollution	3594	Critically polluted	19.6	Seriously polluted
	Post- Monsoon	29.1	Seriously affected	24.1	High pollution	3646	Critically polluted	19.9	Seriously polluted
S7	Pre- Monsoon	36.8	Seriously affected	31.8	High pollution	4433	Critically polluted	24.1	Seriously polluted
	Post- Monsoon	33.4	Seriously affected	28.4	High pollution	4064	Critically polluted	22.1	Seriously polluted
S8	Pre- Monsoon	40.4	Seriously affected	35.4	High pollution	4868	Critically polluted	26.3	Seriously polluted
	Post- Monsoon	36.6	Seriously affected	31.6	High pollution	4376	Critically polluted	23.8	Seriously polluted
S9	Pre- Monsoon	43.5	Seriously affected	38.5	High pollution	5305	Critically polluted	28.6	Seriously polluted
	Post- Monsoon	41.0	Seriously affected	36.0	High pollution	5057	Critically polluted	27.3	Seriously polluted
S10	Pre- Monsoon	44.6	Seriously affected	39.6	High pollution	5406	Critically polluted	29.2	Seriously polluted
	Post- Monsoon	40.7	Seriously affected	35.7	High pollution	4956	Critically polluted	26.8	Seriously polluted
S11	Pre- Monsoon	47.5	Seriously affected	42.5	High pollution	5779	Critically polluted	31.1	Seriously polluted
	Post- Monsoon	44.1	Seriously affected	39.1	High pollution	5360	Critically polluted	28.9	Seriously polluted
S12	Pre- Monsoon	49.7	Seriously affected	44.7	High pollution	6067	Critically polluted	32.6	Seriously polluted
	Post- Monsoon	47.0	Seriously affected	42.0	High pollution	5716	Critically polluted	30.8	Seriously polluted
S13	Pre- Monsoon	51.6	Seriously affected	46.6	High pollution	6323	Critically polluted	34.0	Seriously polluted
	Post- Monsoon	72.6	Seriously affected	67.6	High pollution	5869	Critically polluted	49.6	Seriously polluted
S14	Pre- Monsoon	55.3	Seriously affected	50.3	High pollution	6803	Critically polluted	36.5	Seriously polluted
	Post-Monsoon	50.7	Seriously affected	45.7	High pollution	6289	Critically polluted	33.8	Seriously polluted

HCA on the Gomati River sampling sites group them into three main clusters (Fig. 4a&b). During the pre-monsoon season, Cluster 1 (S1–S7) represents upstream sites with better water quality and minimal human impact. Cluster 2 (S12–S14) includes sites on the Sai tributary, which has independent pollution sources. Cluster 3 (S8–S11) covers downstream and tributary sites showing higher pollution. The downstream sites S8 and S9 are appeared to be influenced by upstream tributaries and midstream pollutions whereas tributaries Kathna (S10) and Sarayan (S11) having their own sub-basins possibly have high pollution inputs from localized sources (urban/industrial) similar to Sai. This indicates a clear separation between cleaner upstream waters (S1–S7) and polluted downstream main channel (S8–S9) and tributaries (S10–S14). In the post-monsoon season (Fig. 4b), clustering patterns change due to rainfall and runoff. Cluster 1 (S8–S14) includes downstream sites of main channel and tributary sites Kathna (S10), Sarayan (S11) and Sai (S12–S14) that show similar water quality because of mixing and dilution during high flow. Cluster 2 (S1–S4, S7) and Cluster 3 (S5–S6) represent upstream and midstream sites with moderate pollution, reflecting the dilution effect of monsoonal discharge. Therefore, the post-monsoon results suggest reduced variability and greater homogenization of water quality across the river.

Overall, the pre-monsoon shows sharper separation between upstream (less polluted) and downstream/tributary sites (more polluted), while post-monsoon clusters are broader, reflecting mixing and dilution. Downstream sites of Gomati main channel (S8, S9) and tributary-influenced sites (S10, S11 and S12–S14) consistently cluster together, highlighting them as critical zones of heavy metal pollution. Heavy rainfall and runoff during monsoons reduce variability across sites, but pollution from tributaries (especially Kathna, Sarayan, Sai) still dominates. These seasonal shifts suggest that monsoonal runoff and dilution influence water quality similarity across sites, reducing variability in downstream locations while highlighting pollution hotspots in certain tributary-influenced regions.

The increasing concentrations of all metals downstream also suggest towards growing human influence on water quality. Human activities contribute significantly to heavy metal pollution through agricultural runoff, industrial effluents, and domestic wastewater. Since there is almost no mining or large-scale excavation in the Gomati basin, such sources can be avoided. However, most of the basin is agricultural land and therefore use of fertilizers, pesticides, and fungicides that often contain trace amounts of Fe, Cu, Cd, Zn, and Ni cannot be neglected. These pollutants reach rivers and groundwater through runoff from fields, particularly during the monsoons. Industrial sources such as smelting operations release Zn and Cd, while iron and steel plants and metal-processing industries discharge effluents rich in Fe, Ni, and Zn. Metallurgical, refractory, and leather industries may release Cu into the environment through wastewater. Ni, widely used in batteries and electroplating, can enter the river from improper disposal of industrial and battery waste and e-waste dismantling. Electroplating, paint, pigment, and tannery industries are also common sources of Ni and Cd contamination. Domestic sewage and wastewater from urban areas are another major source of Cu, Zn, Ni, and Cd pollution, as they are often released untreated into the river. Many household products and detergents also contain Ni and other metals. Rainwater runoff from urban and industrial areas carries metals from roads, construction sites, and drains into the river. Leachate from landfills containing metallic waste can further pollute both surface and groundwater. Atmospheric emissions from industries and vehicles also deposit Fe, Zn, Cu, and Cd onto land and water surfaces through rainfall. There are many other industries like sugar, rice, oil and flour mills in the Gomati basin but that are not likely seemed to be responsible for heavy metal pollution.

Previous studies around Lucknow have also confirmed the presence of heavy metals in the sediments and water of the Gomati River (Singh et al., 1997; Gaur et al., 2005; Singh et al., 2005; Lohani et al., 2008; Neha et al. 2017; Gupta et al., 2014; Khan et al., 2020, 2021). Major sources of this pollution include the Kukrail, Hyder canal, and several smaller drains that carry untreated or partially treated municipal wastewater, urban effluents, and agricultural runoff. The present data show that pollution increases steadily downstream in the Gomati River and its tributaries. Metal concentrations are slightly higher during the pre-monsoon period due to low flow and limited dilution. Tributaries show higher metal concentrations, suggesting they have their own pollution sources, though these impacts are less visible in the main river channel. Among them the Sai (S12–S14) has the highest contamination, likely from urban and industrial discharges from Unnao, Rae Bareli, and Pratapgarh. Fe levels in the samples are within or below the acceptable limits set by BIS (2012), so it is not a major concern. However, Ni concentrations increase after site S4 and exceed safe limits at downstream locations (S8 & S9). Likely sources of Ni include iron and steel industries, electroplating, paint and pigment manufacturing, tanneries, battery waste, and e-waste dismantling.

Cu is absent at upstream sites, indicating little natural input. Its concentration rises sharply after the Sarayan River joins the Gomati main channel (before S4) and continues to increase downstream, mainly due to mixed agricultural, industrial, and domestic pollution from urban centers such as Sitapur, Lucknow, Sultanpur, and Jaunpur. Zn levels also remain high after site S3, likely due to contributions from sewage, vehicle emissions, agricultural runoff, and galvanization activities. Cd shows a steady rise from upstream (S1) to downstream (S9), with concentrations (in 2022) higher than previously reported. Major Cd sources include metal plating, fertilizers, Ni–Cd batteries, plastic and textile industries, sewage effluents, and pigment production. It can also enter water from Zn extraction, landfill leachates, and corroded galvanized pipes.

High levels of Ni and Cd at several sites indicate possible ecological and health risks, especially in the middle and lower parts of the river. Cd, one of the most toxic metals after Hg, naturally occurs in small amounts in soil and sediments (0.15–0.2 mg/kg). In polluted rivers, Cd levels in water are usually very low (0.10–0.50 μg/L) and sometimes undetectable. It is mostly found as inorganic compounds (like carbonates, hydroxides, chlorides, or sulphates) or bound to organic matter. According to the BIS, the safe limit of Cd in drinking water is 3 μg/L with no relaxation allowed. Long-term exposure, even at low levels, can cause serious health problems such as kidney damage, bone weakness (osteoporosis), high blood pressure, and cardiovascular or lung diseases. Cd mainly enters the body through the digestive system and accumulates in the liver, kidneys, and bones for up to 10–20 years (Rasin, et al., 2025). Inhalation or acute exposure can cause nausea, vomiting, chest pain, and breathing problems. A severe example of Cd poisoning was the Itai-Itai disease in Japan. Ni contamination is also concerning due to its potential to accumulate in aquatic organisms, affecting fish health and ecosystems. In humans, ingestion of Ni-contaminated water or food can lead to allergies, kidney and heart problems, and even cancer.

Cd pollution hotspots with increased levels of Cd above the acceptable limits have also been reported by Central Water Commision (2019) in the Ganga, Kopili, Rapti, Tungabhadra, and Yamuna rivers with the highest concentration (70.51 μg/L) recorded in the Sabarmati River out of total of Indian rivers 2,908 river water samples collected and analyzed between May 2014 and April 2018. The cities and towns along the direct pathway of the Gomati main channel and tributaries are densely populated; some of these are well-developed and industrialized, with many small –scale electronic based industries. The illegal dismantling of e-waste is now common everywhere, often involving open-air burning, acid treatment, or other crude methods to recover valuable parts. Such practices release toxic metals into the environment such as Cd from cathode ray tubes and chips, and Cd from broken glass. These can leach into water, making it acidic, especially in landfill sites. Open-air burning also releases toxic by-products into the atmosphere, which later spread locally and globally (Sivakumar et al., 2011; Ramachandra and Saira, 2004). In India, the informal sector handles nearly 90% of E-waste. Rag pickers collect scraps from offices and households and extract metals without proper safety measures. Since most workers are unskilled and lack knowledge or technology, recycling and disposal are done improperly. This highlights the urgent need for a structured E-waste management system. Improved technologies, formal recycling methods, awareness programs, and environmental education could help reduce pollution and promote safer handling of E-waste. Strict regulations and advanced treatment of industrial wastewater are essential to reduce heavy metal pollution. Upgrading sewage treatment plants and drainage systems can help limit contamination from urban sources. Encouraging careful use of fertilizers and pesticides will also reduce agricultural runoff. Regular monitoring of heavy metal levels in the Gomati River and its tributaries, along with strict enforcement of environmental laws, is necessary to protect water quality.

5. Conclusion

The present study highlights a serious and progressive deterioration in the water quality of the Gomati River and its tributaries, primarily due to heavy metal pollution. A comparison with earlier studies indicates a substantial rise in the concentrations of Ni, Cu, Zn, and Cd in 2022, while Fe levels have declined and remain within acceptable limits. The consistent downstream increase in heavy metal concentrations, especially for Cd and Ni, points to growing anthropogenic pressure from industrial, agricultural, and domestic sources. Tributaries such as Kathna, Sarayan, and particularly Sai have emerged as major contributors to this contamination, reflecting inputs from urban and industrial regions like Sitapur, Lucknow, Rae Bareli, Sultanpur, and Jaunpur. Multivariate analyses (MI, Cd, HPI, and NPI) classify the river as 'severely' to 'critically polluted', with water quality declining steadily downstream. Correlation and cluster analyses reveal strong inter-metal relationships, suggesting common anthropogenic origins, while Caboi's diagram indicates high metal enrichment under near-neutral pH conditions, ruling out natural geochemical causes. Seasonal variations show that pre-monsoon concentrations are higher due to low flow and evaporation, whereas post-monsoon dilution temporarily reduces contamination but does not eliminate it. The elevated levels of Cd and Ni at several sites raise significant ecological and public health concerns. The unregulated disposal of e-waste, industrial effluents, and agrochemical runoff appear to be the major sources contributing to the contamination of the Gomati basin. To restore the ecological health of the Gomati River, urgent management actions are required including stricter enforcement of industrial discharge standards, effective operation and expansion of sewage treatment facilities, safe e-waste recycling, and sustainable agricultural practices to minimize heavy metal inputs. Without timely intervention, the continued accumulation of heavy metals could further degrade water quality, harm aquatic ecosystems, and pose serious risks to the health and livelihoods of communities dependent on the Gomati River system.

6. Limitation and future scope the study

Although this study provides valuable insights into the spatial and seasonal variations of heavy metal contamination in the Gomati River and its tributaries, certain limitations should be acknowledged. First, the sampling was limited to two seasonal periods (pre- and post-monsoon) within a single year (2022), which may not fully represent long-term temporal variations or inter-annual trends influenced by climatic or anthropogenic changes. Secondly, while the study focused on dissolved heavy metals in water, it did not include sediment or biota analysis, which could have provided a more comprehensive understanding of heavy metal accumulation, bioavailability, and trophic transfer. The study also relied primarily on conventional pollution indices and statistical tools; the inclusion of advanced geochemical modeling, isotopic tracing, or machine-learning-based source apportionment could further refine the interpretation of pollution sources and dynamics. Moreover, spatial resolution was constrained by accessibility and logistical limitations, and some minor tributaries or point sources may have been overlooked. Future research should expand temporal and spatial coverage to include multi-year continuous monitoring across dry and wet seasons to capture dynamic changes in heavy metal inputs and transport mechanisms. Integrating sediment, soil, and biological monitoring will help assess metal accumulation and potential ecological and human health risks. The use of remote sensing and GIS-based modeling could enhance spatial visualization of pollution hotspots and aid management planning. Isotopic fingerprinting and speciation studies are recommended to distinguish between natural and anthropogenic metal sources. Additionally, long-term monitoring programs and ecological risk assessment frameworks should be established to evaluate the effectiveness of pollution control measures. Collaborative efforts involving government agencies, academic institutions, and local stakeholders will be vital for developing sustainable river management strategies. Such integrative approaches can contribute significantly to restoring the ecological health and water quality of the Gomati River system.

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SPATIOTEMPORAL ASSESSMENT OF GROUNDWATER QUALITY FOR SUSTAINABLE WATER RESOURCE MANAGEMENT AT PAVAGADA TALUK, KARNATAKA, INDIA

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ABSTRACT

This study presents a comprehensive spatiotemporal analysis of groundwater resources in Pavagada Taluk, Tumakuru District, Karnataka to evaluate the suitability for sustainable management and public health. A total of 25 groundwater samples were collected during pre-monsoon and post-monsoon seasons. The analytical results were revealed generally stable, near-neutral pH and satisfactory levels for most parameters and are predominantly within BIS permissible limits. The findings indicate robust aerobic conditions and minimal contamination from agricultural or saline sources. The study identified critical concerns, that pervasive fluoride contamination was the significant issue, with concentrations ranged from 1.3 to 6.4 mg/L, exceeding the safe limit (1.0–1.5 mg/L) over 70% of samples. Geogenic origins, specifically the weathering of fluoride-bearing minerals in the local granitic-gneissic bedrock, are identified as the primary cause, exacerbated by semi-arid climatic conditions and localized spikes in turbidity and chlorides suggest minor anthropogenic influences. The spatiotemporal analytical results underscore a severe public health risk, notably endemic dental and skeletal fluorosis for the local population. The study showed groundwater is suitable for agricultural purposes, its direct consumption without treatment poses a significant health hazard. This study provides critical scientific baseline for policymakers to develop evidence-based interventions, ensuring water security and advancing public health.

No. of Pages: 12 **References: 31**

Keywords: Spatiotemporal assessment, Groundwater, Health Hazards, Fluoride, Geogenic origin.

INTRODUCTION

Groundwater is a vital freshwater resource, especially in semi-arid regions, where surface water is scarce and seasonal [1], [2]; [3]; [4]. In India, it serves as the primary source of drinking water and irrigation for a significant portion of the population, particularly in rural areas [5]; [6]; [7]; [8], [9], [10]. However, the sustainability of ground water resource is increasingly threatened by both quantitative depletion and qualitative degradation due to geogenic processes and anthropogenic activities. The intrinsic link between water quality and public health underscores the critical need for continuous monitoring and assessment, as contamination poses severe risks to community well-being ([11], [12], [13] [14], [15]; [16], [17], [18]. Pavagada Taluk, located in the drought-prone Tumakuru district of Karnataka, is emblematic of these challenges. The region's economy is

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predominantly agrarian, relying heavily on groundwater for irrigation and domestic use ([19], [20]. The local aquifer systems are primarily hosted within granitic and gneissic bedrock, which are known to be a natural source of ions, including fluoride, through water-rock interaction processes [10], [21], [22], [23]. This geogenic contamination, potentially exacerbated by agricultural practices and climatic factors, necessitates a detailed spatial evaluation of groundwater quality to inform sustainable management strategies [24], [25]. While previous studies have highlighted water scarcity issues in Karnataka, a comprehensive, spatially-representative analysis of hydro-chemical parameters in Pavagada Taluk, specifically targeting pre- and post-monsoon variations, remains limited. This study aims to fill this critical research gap by conducting a spatial analysis and quality assessment of groundwater resources across the taluk. The study aims to spatial assessment of ground water quality and its suitability. By establishing a robust baseline dataset and identifying contamination hotspots, this research provides a scientific foundation for policymakers, water resource managers, and local communities to implement targeted interventions, thereby contributing to the achieve the Sustainable Development Goal 6 (Clean Water and Sanitation).

2. MATERIALS AND METHODS

2.1 Study Area

Pavagada Taluk is geographically located 13.92°N to 14.35°N, 76.78°E to 77.15°E in Tumakuru District of Karnataka, India is underlined by granitic-gneissic bedrock and has a semi-arid climate (Köppen, BSh) with a average annual rainfall of 650 mm [10] (Figure 1). The groundwater system of the area is sensitive to the geogenic mineralization as it has been exposed to the water-rock interaction processes for a longer period of time in fractured aquifers [26].

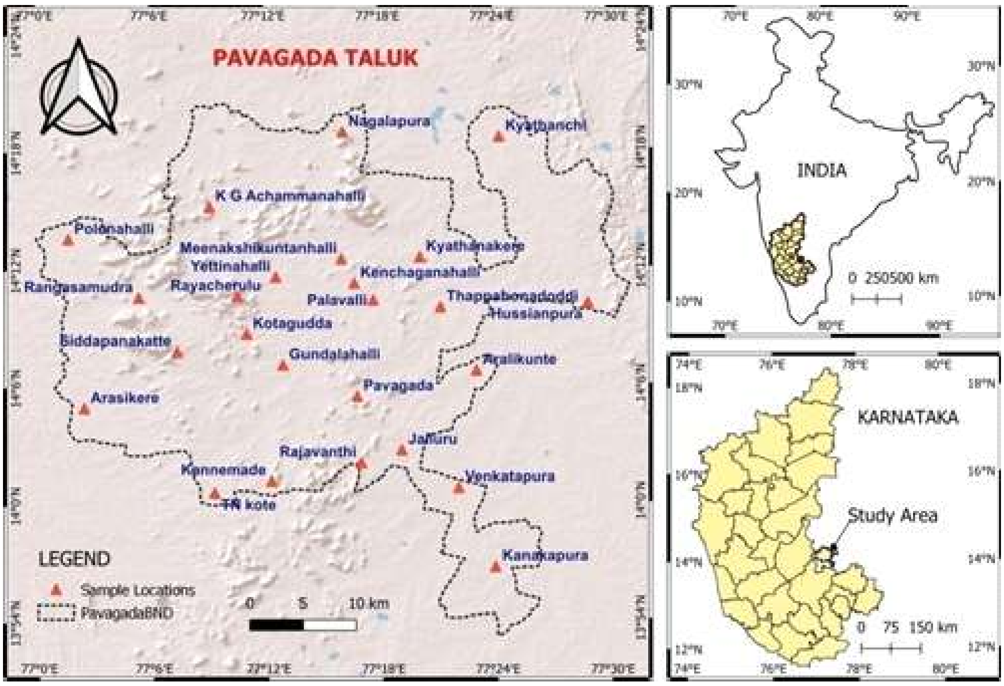


Fig.1: Location map of study area of Pavagada Taluk, Karnataka, India.

A representative Twenty-five ground water samples from borewell and handpump were collected both in pre-monsoon (May 2024) and post-monsoon (December 2024) seasons covering across the study area of hydrological units are shown in the Figure 2. Sampling proceeded in accordance with BIS 10500:2012, where GPS-tagged samples were collected, the pH, EC, and temperature were measured on-site using calibrated with multiparameter probe (Hanna, HI98194).

Table 1: Sampling villages for groundwater in Pavagada taluk, Tumakuru district, Karnataka, India.

Site No	Name of the village
Site 1 (S1)	Kanakapura
Site 2 (S2)	Venkatapura
Site 3 (S3)	Rajavanthi
Site 4 (S4)	Pavagada
Site 5 (S5)	Aralikunte
Site 6 (S6)	Hussianpura
Site 7 (S7)	Rayacherulu
Site 8 (S8)	Kyathanchi
Site 9 (S9)	Nagalapura
Site 10 (S10)	Jalluru
Site 11 (S11)	K G Achammanahalli
Site 12 (S12)	Yettinahalli
Site 13 (S12)	Kenchaganahalli
Site 14 (S14)	Meenakshikuntanhalli
Site 15 (S15)	Kyathanakere
Site 16 (S16)	Thappahonadoddi
Site 17 (S17)	Palavalli
Site 18 (S18)	Gundalahalli
Site 19 (S19)	Kotagudda
Site 20 (S20)	Siddapanakatte
Site 21 (S21)	Rangasamudra
Site 22 (S22)	Polenahalli
Site 23 (S23)	Arasikere
Site 24 (S24)	TN kote
Site 25 (S25)	Kannemade

2.3. Analytical Methods

Sixteen parameters were measured as per the BIS and WHO standards (Table 2): pH, EC, TDS (Hanna HI98194) and analyzed as per APHA [27]. Titrimetry (APHA 2320), Total alkalinity, hardness (Ca^{2+}, Mg^{2+}), chlorides. Spectrophotometry (HACH DR3900): Nitrate (APHA 4500-NO_3), Sulphate (APHA 4500-SO_4^{2-}). Fluoride ion-selective electrode (Thermo Scientific Orion Star A329). Fe and Cu are observed Atomic Absorption Spectroscopy (PerkinElmer PinAAcle 900T). Quality Assurance passes Triplicate analysis with certified reference materials (CRM, NIST 1640a) resulted in <5% RSD. Charge balance errors were ±5% for all samples ([28]).

2.4. Spatial Analysis

Mapping of contamination hotspots was achieved by inverse distance weighting (IDW) interpolation in QGIS, which was validated by kriging cross-validation (RMSE <0.8). Table 2 showing the BIS and WHO Standards for various analytical parameters.

Table 2. BIS and WHO Standards and Parameters.

S. No.	Parameter	Standard in mg/L
1.	pH	6.5-8.5
2.	TDS	500-2000
3.	Electrical Conductivity	u/s
4.	Total Alkalinity	200-600
5.	Total Hardness	200-600
6.	Ca Hardness	75-200
7.	Mg Hardness	30-100
8.	Chlorides	250-1000
9.	Dissolved Oxygen	>4.5
10.	Nitrate	45
11.	Fluoride	1-1.5
12.	Iron	0.3
13.	Copper	<1.5
14.	Colour	5-15 hz
15.	Turbidity	1-5 NTU
16.	Sulphate	200-400

3. Results

The comprehensive analysis of 25 groundwater samples from Pavagada Taluk revealed a complex hydro chemical profile (Table 3 and Fig 3),

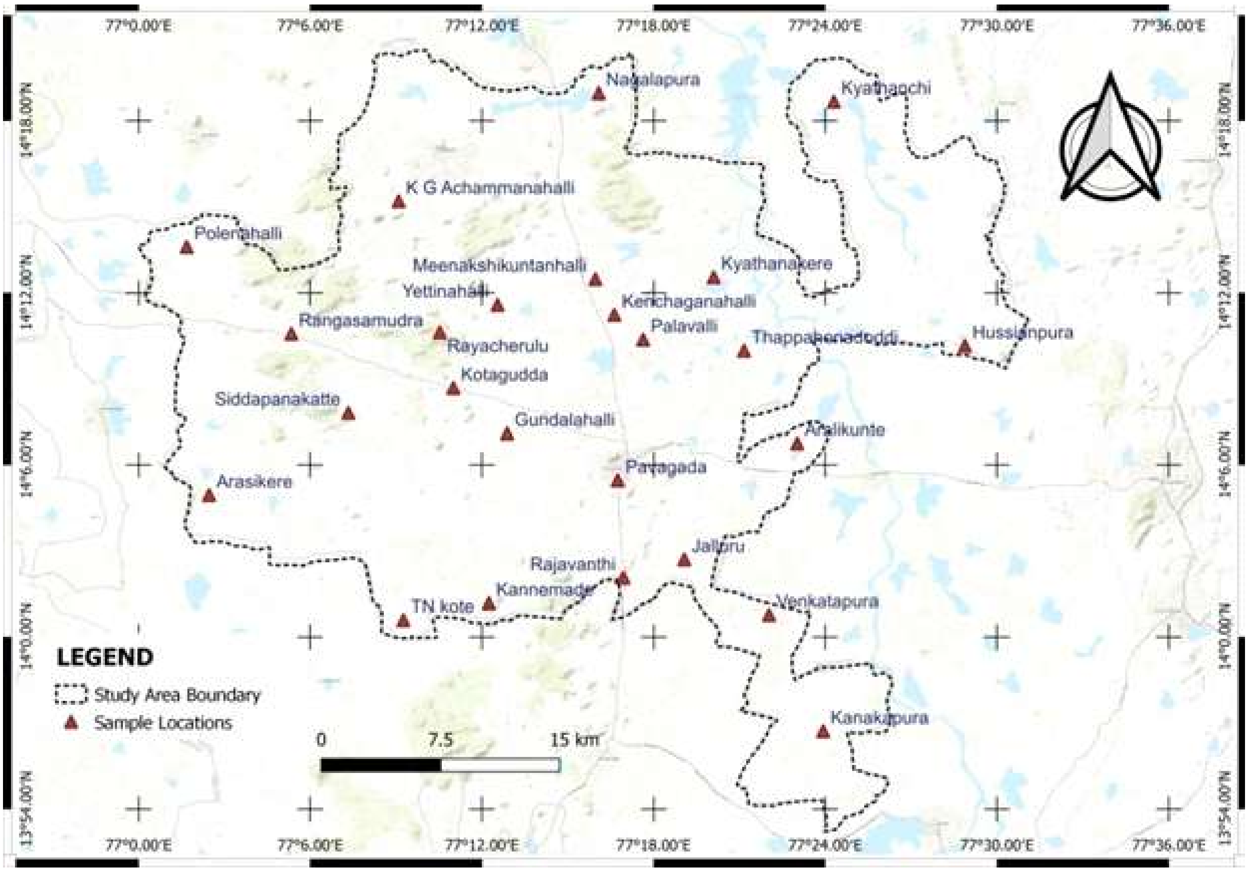


Fig. 1: Hydrological units of the study area, Pavagada Taluk, Karnataka, India.

parameters largely conforming to Bureau of Indian Standards (BIS 10500:2012) limits, except for one critical exception. The pH values were ranged from 6.7 to 7.5 pre-monsoon and 7.2 to 8.1 post-monsoon season.

Total Dissolved Solids (TDS) values exhibited a moderate variability (642–1125 mg/L pre-monsoon; 626–912 mg/L post-monsoon), remaining all values were remains within the permissible limit (<2000 mg/L).

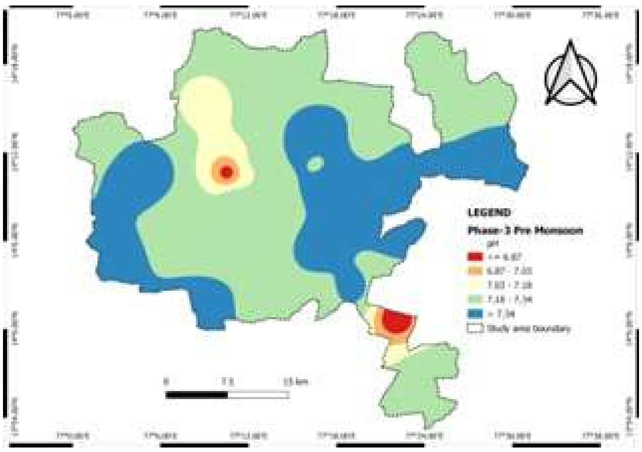
Table 3: Groundwater Quality during Pre monsoon (May-2024).

Parameter	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12	S13	S14	S15	S16	S17	S18	S19	S20	S21	S22	S23	S24	S25
pH	7.3	6.7	7.3	7.4	7.5	7.4	6.8	7.2	7.3	7.4	7.1	7.2	7.3	7.5	7.3	7.4	7.5	7.3	7.3	7.3	7.5	7.3	7.4	7.5	7.3
TDS	842	914	823	793	925	1125	963	842	795	842	816	716	742	698	812	826	786	692	872	996	1125	963	785	642	698
EC	1684	1828	1646	1586	1820	2250	1926	1684	1590	1684	1632	1432	1444	1290	1066	1498	888	1078	1044	1310	1556	856	1072	1364	1218
Alkalinity	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12	S13	S14	S15	S16	S17	S18	S19	S20	S21	S22	S23	S24	S25
Hardness	127	131	112	129	133	142	113	161	126	145	123	128	142	427	115	106	154	146	425	136	142	115	125	156	121
Calcium hardness	18.2	16.2	14.2	11.2	14.6	10.2	14.8	16.2	17.2	14.9	18.1	14.5	13.4	11.2	12.6	10.2	13.5	10.8	13.6	11.2	13.6	14.2	11.2	12.6	10.2
Magnesium hardness	3.1	2.4	1.3	3.2	5.3	2.9	1.7	5.6	2.4	2.5	3.9	4.5	3.2	2.9	1.7	4.8	4.2	5.3	5.7	4.9	1.8	2.5	2.6	2.4	2.2
Iron					Negligible																				
Copper					Negligible																				
Colour					Colourless																				
Turbidity	1.4	0.7	1.2	1.3	0.6	0.4	6.3	1.3	0.6	0.4	4.1	0.4	1.2	1.9	7	0.7	1	1.8	2.3	1.5	1.2	3.1	1.8	1.2	1.4

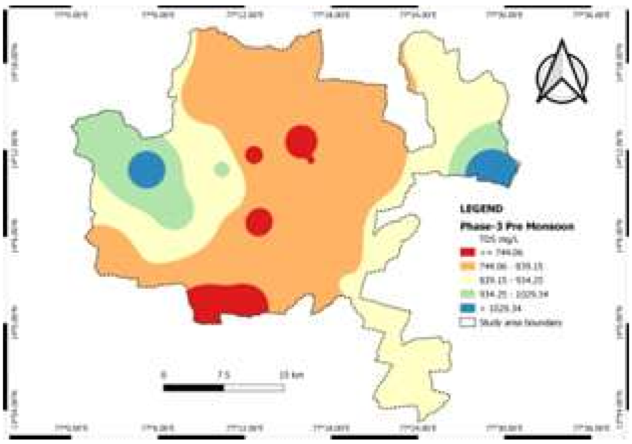
Table 4: Groundwater Quality during Post monsoon (December-2024).

S. No	Parameter	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12	S13	S14	S15	S16	S17	S18	S19	S20	S21	S22	S23	S24	S25
1	pH	7.6	7.5	7.2	7.7	7.8	7.9	7.8	7.8	7.7	7.7	7.7	7.8	7.7	7.6	7.8	8.1	7.8	7.8	8.1	7.7	8.0	7.9	8.0	8.1	8.0
2	TDS	742	875	776	804	875	891	876	784	716	756	811	690	714	726	792	841	766	672	826	856	886	912	751	662	626
3	EC	1480	1755	1553	1606	1751	1780	1750	1561	1430	1510	1620	1383	1420	1450	1581	1682	1532	1339	1653	1710	1765	1820	1492	1320	1255
4	Alkalinity	85	78	72	85	76	91	84	81	72	69	81	88	68	71	88	86	61	74	79	57	60	72	89	81	65
5	Hardness	168	185	165	171	182	179	192	232	181	159	175	215	195	180	165	171	165	172	175	161	160	170	155	165	211
6	Ca Hardness	105	123	115	128	135	142	151	175	132	118	126	172	158	138	138	141	128	126	131	126	123	132	115	118	162
7	Mg Hardness	63	62	50	43	47	37	41	57	49	41	49	43	37	42	27	30	37	46	44	35	37	38	40	47	49
8	Chlorides	82	72	84	86	102	95	90	112	110	103	95	101	79	72	81	76	82	83	75	81	69	81	76	72	70
9	Fluoride	12.3	11.2	13.6	12.1	11.2	12.6	10.2	11.2	12.6	10.2	13.7	10.4	10.3	12.1	11.6	13.5	10.3	11.3	14.7	13.6	10.8	11.8	13.2	11.0	12.2
10	Nitrate	2.8	2.6	2.1	2.8	5.7	2.4	1.5	6.4	2.5	3.2	3.1	5.2	3.3	2.7	1.5	5.4	5.7	6.1	5.8	5.1	2.4	3.1	3	2.6	2.8
11	Iron	Nill (Average of 0.02)																								
12	Copper	Nill (Average of 0.01)																								
13	Colour	Normal																								
14	Turbidity	Clear and transparent , No turbidity																								

Total Hardness (152–222 mg/L as CaCO) and Calcium Hardness were predominantly within acceptable limits, suitable for irrigation and notably, low Total Alkalinity was shown from 52–91 mg/L range. There was a pervasive fluoride contamination and it was ranged from 1.3 to 5.7 mg/L pre-monsoon and 1.5 to 6.4 mg/L post-monsoon, exceeds the BIS safe limit of 1.0–1.5 mg/L. The study area is enriched and is unequivocally geogenic, attributable to the dissolution of fluoride-bearing minerals (e.g., fluorite, apatite) present in the local granite-gneiss aquifers. Figure 3 and 4 showed the spatial persistence of these hotspots underscores the necessity of targeted intervention strategies over generalized approaches, prioritizing these high-risk villages for immediate remedial action.



pH



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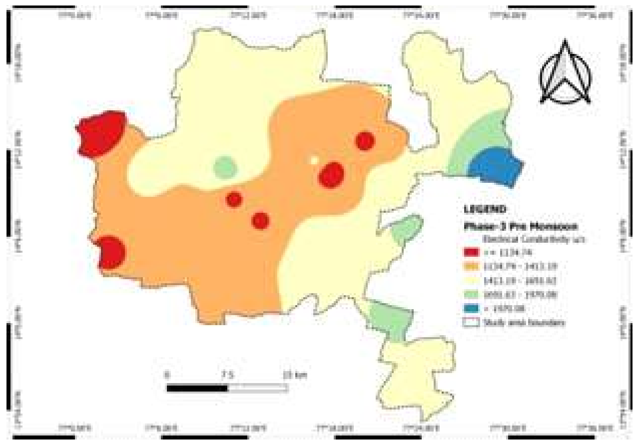
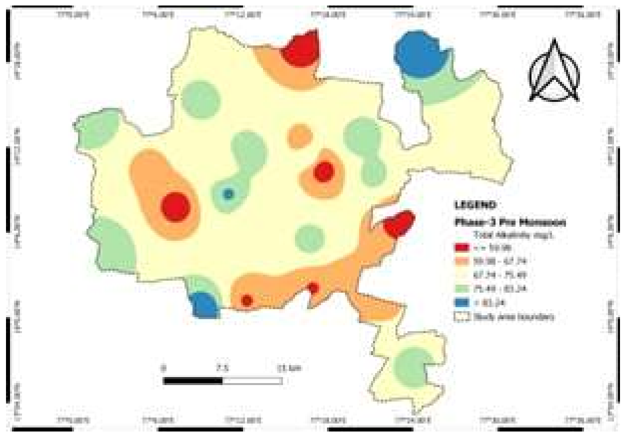


Electrical Conductivity



Total Alkalinity

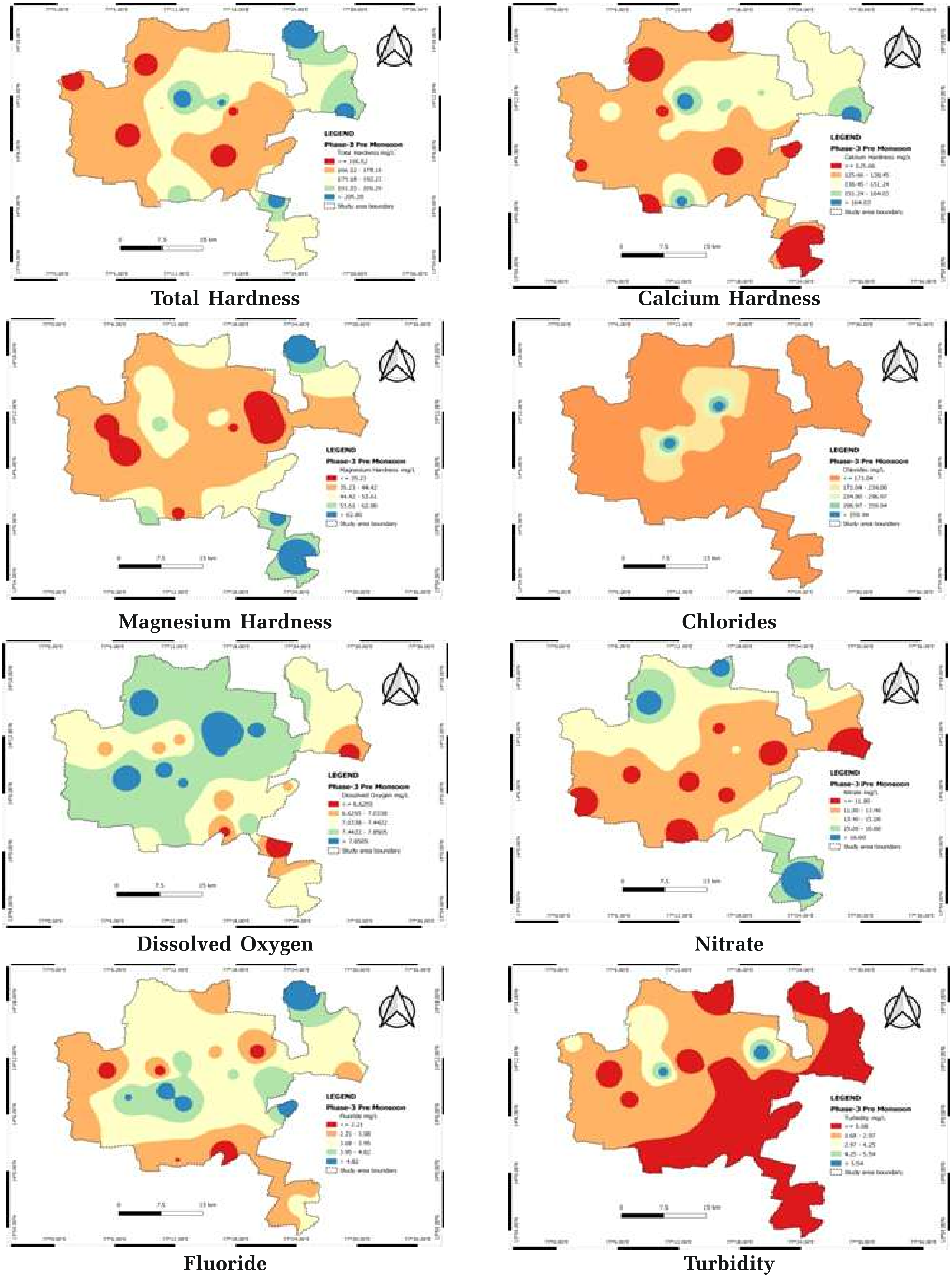
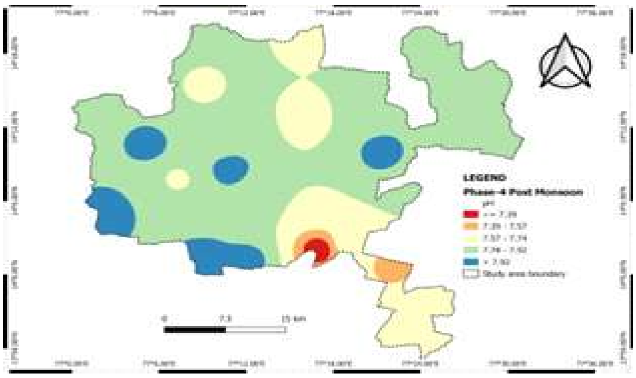


Fig. 3: Pre monsoon (May-2024) spatial distribution of groundwater quality of the study area.

Pre monsoon (May-2024) spatial distribution of groundwater quality of the study area is shown in Table 4 and Figure 4.

Spatial variation of physicochemical characteristics is shown in Figure 4.



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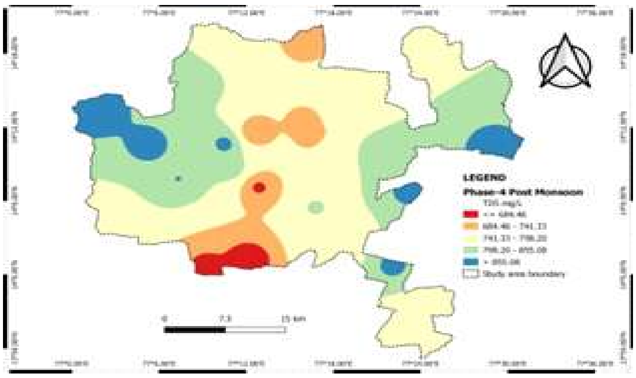

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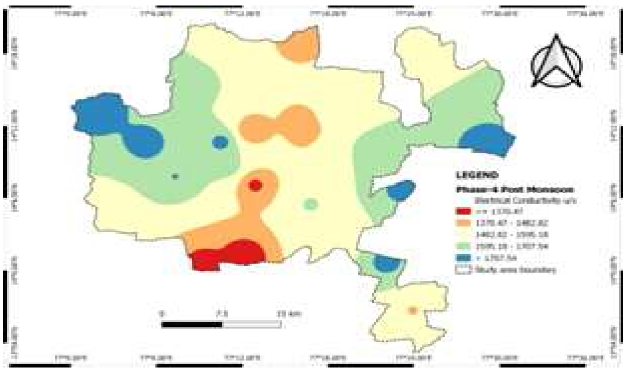

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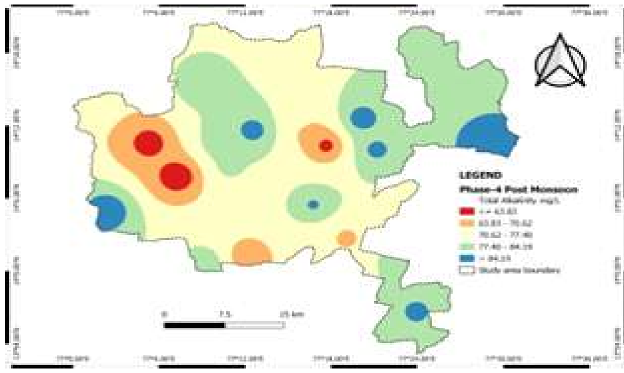
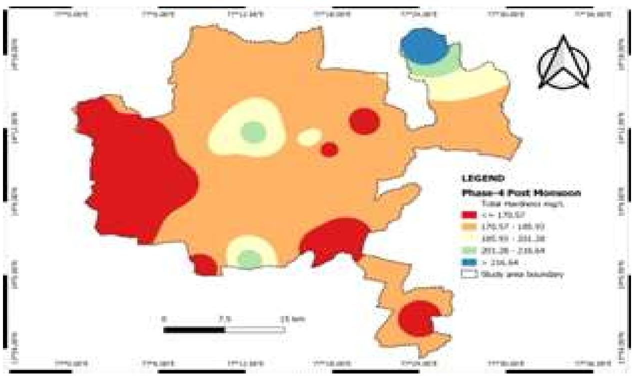
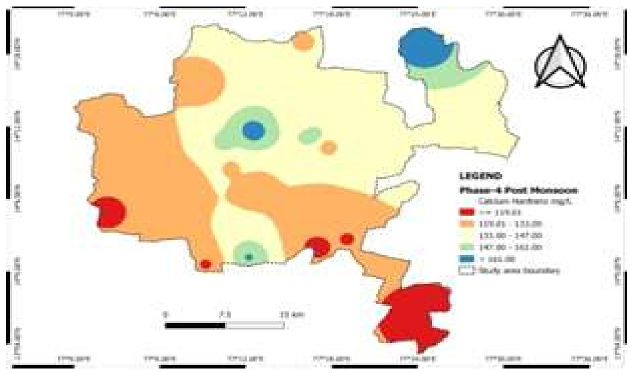


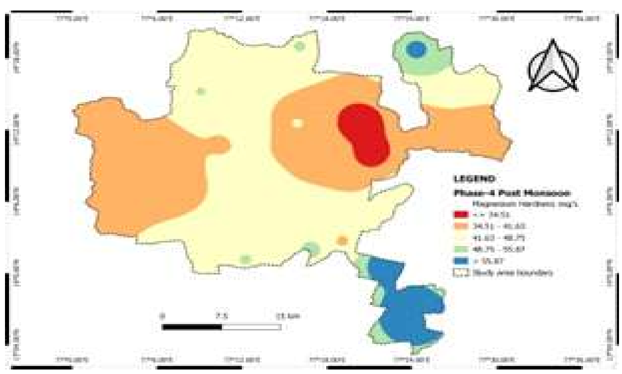
Total Alkalinity



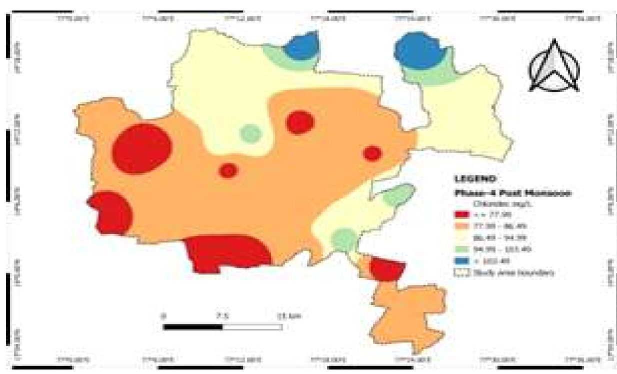
Total Hardness



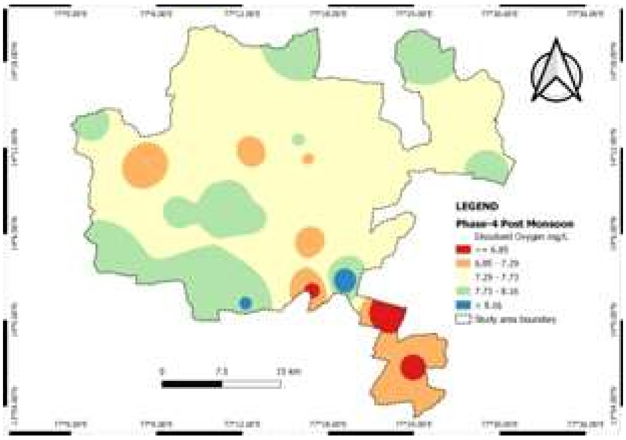
Calcium Hardness



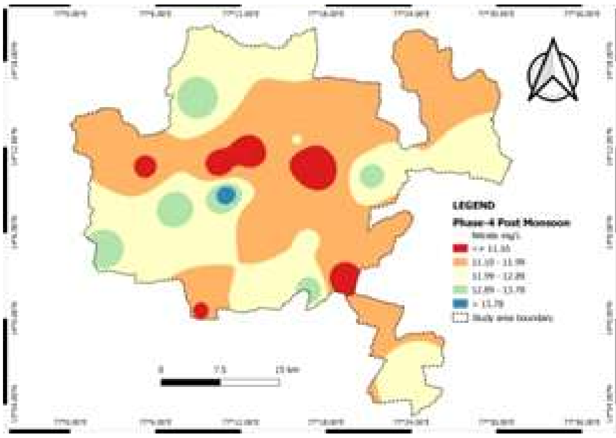
Magnesium Hardness



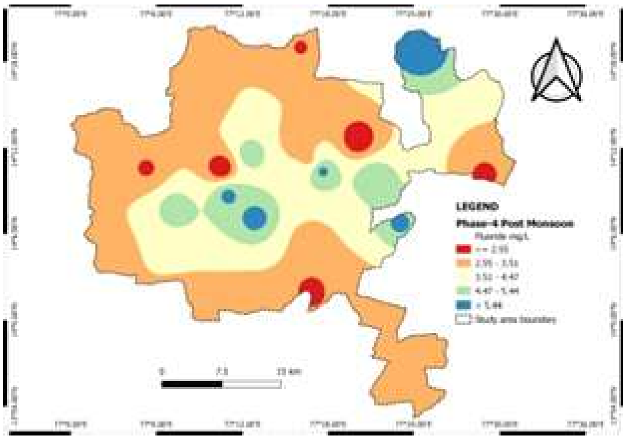
Chlorides



Dissolved Oxygen



Nitrate



Fluoride

Fig. 4: Post monsoon (December-2024) spatial distribution of groundwater quality of the study area.

4. Discussion

In this study it indicates a stable, near-neutral to alkaline conditions conducive for domestic and agricultural use [29], [30]. The study showed a the groundwater quality with spatial distribution of TDS and Electrical Conductivity (EC) underscores the predominance of ionic constituents like Na^{+}, Ca^{2+}, Mg^{2+}, and Cl , derived primarily from the weathering of the region's granitic-gneissic bedrock, a common phenomenon in peninsular India [12]. It also indicates a limited buffering capacity, rendering the aquifer vulnerable to acidification from potential anthropogenic inputs. Chloride and Nitrate concentrations were largely within safe limits, effectively ruling out widespread saline intrusion or significant contamination from agricultural runoff and sewage shows aerobic conditions. The spatial analysis reveals severe hotspots in Kotagudda, Kyathanchi and Aralikunte study sites.

This enrichment is unequivocally geogenic, attributable to the dissolution of fluoride-bearing minerals (e.g., fluorite, apatite) present in the local granite-gneiss aquifers, a process exacerbated by ion exchange and evaporative concentration under semi-arid conditions [11], [13]. The post-monsoon increases in fluoride levels in some locations, contrary to the expected dilution effect, suggests a complex recharge dynamics and potential leaching from the unsaturated zone. This pervasive fluoride contamination presents a dire public health risk, including endemic dental and skeletal fluorosis for the local population reliant on groundwater [23], [31]. The spatial persistence (Fig 3 and 4) of these hotspots underscores the necessity of targeted intervention strategies over generalized approaches, prioritizing these high-risk villages for immediate remedial action.

Based on findings, the following multi-pronged recommendations are proposed for sustainable groundwater management in Pavagada Taluk - *Immediate Public Health Intervention:* The pervasive fluoride contamination need to be addressed and immediate deployment of decentralized, community-managed defluoridation units using cost-effective adsorbents like activated alumina or bone char in the hotspot villages are Kotagudda, Kyathanchi, and Aralikunte. Concurrently, robust public health campaigns must be launched to educate communities on the severe health risks of fluorosis and the proper use and maintenance of treatment units. *Diversification of Water Sources:* Alternatively, the government and non-governmental agencies should promote and subsidize rainwater harvesting structures at both household and community levels. Furthermore, exploring the feasibility of sourcing and treating surface water from nearby sources should be prioritized to provide a sustainable, safe drinking water alternative.

Enhanced Monitoring and Research

The outcome of the study would serve as a baseline for a long-term, systematic groundwater quality monitoring network. A comprehensive cost-benefit analysis of various remediation technologies is also recommended. *Policy Integration and Sustainable Practice:* The spatial hydrochemical data must be integrated into local water security plans and watershed management programs. Policies should incentivize sustainable agricultural practices to prevent future nitrate and chloride pollution, to protect the water quality from anthropogenic degradation.

5. Conclusions

The physicochemical parameters of groundwater in Pavagada Taluk are found within permissible limits for domestic and agricultural use, the resource is critically compromised by pervasive fluoride contamination. The spatial analysis was identifying the severe geogenic fluoride enrichment, with concentrations reaching up to 5.7 mg/L, exceeds the BIS safety limit. This presents an immediate and severe public health risk, including endemic dental and skeletal fluorosis for the dependent population. The findings underscore a clear disconnect: the water is otherwise chemically suitable but is rendered unsafe for direct consumption due to this single parameter. Therefore, conventional water quality management approaches are insufficient. The sustainable water resource management is contingent upon addressing this specific contaminant through a multi-pronged strategy. This must include the immediate deployment of decentralized defluoridation units in hotspot villages, coupled with the development of alternative water sources like rainwater harvesting to reduce dependency on contaminated groundwater. The long-term sustainability hinges on integrating these technical interventions with robust community awareness programs and establishment of continuous groundwater quality monitoring network. This research provides a critical evidence base for policymakers to prioritize public health and implement targeted, sustainable water security measures in Pavagada Taluk and similar fluoride-endemic regions.

Abbreviations

APHA: American Public Health Association
BIS: Bureau of Indian Standards
CGWB: Central Groundwater Board
DO: Dissolved Oxygen
EC: Electrical Conductivity
NITI: (National Institution for Transforming India)
TDS: Total Dissolved Solids
TH: Total Hardness
WHO: World Health Organization

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Author Contributions

V.D. Shivanna Vaddarahalli Dasappa: Conceptualized the Research area, collected resources and carried out formal anaylysis add writing original draft.

J.S. Chandrashekar: The author supervised the entire work, provided the methodology and edited and validated final manuscript.

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Data Availability Statement

1. The data supporting the outcome of this research work has been reported in this manuscript.

Conflicts of Interest

"The authors declare no conflicts of interest."

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EVALUATION OF GROUNDWATER QUALITY AFFECTED BY LEACHATE AT AJJAGONDANAHALLI SOLID WASTE DUMP SITE IN TUMKURU, KARNATAKA, INDIA

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Research Paper

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ABSTRACT

Waste management has become problematic as a result of rapid urbanization, industrialization, and population growth. Ultimately, the garbage is dumped outside of the city or in a landfill. For the residents of the surrounding areas, the smell of landfills and the leachate that mixed with water bodies made life miserable. By assessing the physico-chemical parameters such as pH, electrical conductivity, total dissolved solids, calcium, magnesium, potassium, nitrate, phosphate, and heavy metals (lead, cadmium, mercury, and arsenic) using Standard APHA methods during August (monsoon period), this paper focuses on the groundwater quality which is contaminated by the leachate surrounding this landfill. It has been found that groundwater samples of this area fall under the 'unsuitable for drinking' category. while pH, EC, TDS, Ca, Mg, K+ and NO3 remain within the safe ranges. But the concentration of phosphate and heavy metals such as Lead, Arsenic, Cadmium and mercury was found to be below the detection. however, the elevated WQI and ionic correlations indicate the onset of leachate percolation into the aquifer. Continuous monitoring, coupled with engineered landfill management practices such as leachate collection, liners, and treatment systems, is recommended to safeguard groundwater.

No. of Pages: 09 **References: 33**

Keywords: Groundwater contamination, Heavy metals, landfill, leachate, WQI.

INTRODUCTION

In many cities around the world, notably in developing nations like India, managing municipal solid waste (MSW) is a major challenge. Inappropriate disposal, open dumps, and environmental pollution are among the glitches caused by the growing volumes of waste brought on by fast urbanization and industrial expansion (Jithendra *et al.,* 2022; Alexander and Co. 2022; Carmen-Niño *et al.* 2023). Ineffective waste collection methods, societal perceptions, poor infrastructure, and a scarcity of appropriate management methods make the issue worse and have an influence on ecosystems, economies, and public health (Adabousi, 2022; Kovalenko *et al.,* 2022). Human life, wildlife, and vegetation are at risk when MSW is improperly managed because it releases leachate that encompasses dangerous pollutants like sulphur dioxide, mercury, and black carbon. Municipal solid waste, industrial waste, sanitary waste, and other hazardous waste are all frequently disposed of in landfills worldwide (Siddiqua *et al.,* 2022).

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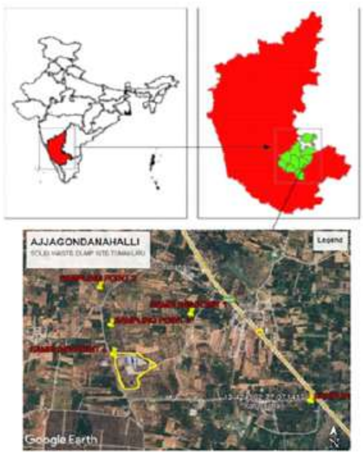
Landfills continue to play an crucial role in waste management approaches despite criticisms regarding health and environmental risks. They produce leachate and gases like CO2 and methane, which greatly enhance greenhouse gas emissions (Mishra *et al.,* 2020; Yin *et al.*,2020). For effective MSW management, these issues must be mitigated through better waste collection routes, better operational planning, community involvement, and investments in human and technological resources. At the moment, major Indian cities have fully cut off their aquifers over the past three decades owing to an increased dependence on groundwater for drinking and irrigation due to the country's fast population growth.

On the other hand, leachate that gradually emerges from these solid waste disposal sites and the surrounding area has a higher probability of contaminating groundwater. (Fatta *et.al.,* 1999;A.Gupta *et.al.,*2024; Lee *et.al.,*1993), because it may contain a range of organic and inorganic materials as by-products of its breakdown (Magda M.Abd El-Salam *et.al.,*2015). This has mainly resulted from leachate percolating from unscientific dumping in major cities and nations worldwide, which has led to surface water contamination during the rainy season and underground water contamination(Suna Erses *et.al.,*2005). Municipal, commercial, and industrial solid wastes that encompass hazardous materials may increase the health risks to local users (children are notoriously vulnerable) and the environment20, as well as the safety of society, from leachate and landfill gases (Suna Erses *et.al.,* 2005). In recent years, several studies have become more interested in the influence of leachate on surface and ground water (De Rosa *et.al.,*1996; Abu-Rukah *et.al.,*2001). To develop a feasible and sustainable solution for reducing groundwater pollution attributable to solid waste disposal, a comprehensive evaluation is necessary. Waste disposal techniques, groundwater flow, lithological variation, contaminant transfer, and leachate and groundwater quality characterization are all included.

1. Materials and Methods

2.1 Study Area

The centralised solid waste disposal facility (Ajjagondanahalli Landfill Site) is located in Ajagondanahalli village in the Tumkuru Taluk of the Tumkuru district of Karnataka, India. Ajjagondanahalli village is located about 12 km from the city headquarters. There are approximately 148 households in Ajagondanahalli village, the total geographical area of which is 343.08 hectares, and the geographical location of Ajagondanahalli village is 13.25'45' N and 77.99'E. according to the 2011 census, the literacy rate of Ajagondanahalli village is 74.25 and the literacy rate of the village is 79.33 and of the women is 68.75. Ajjagondanahalli landfill site spread over 42 acres was started in December 2014, leading to a massive protest by villagers.In 2017, a private agency, Sadhana Enviro Engineering Services, took over the operation and maintenance of the plant for a one year contract, after which the plant was shut down for a few months in 2018.



SAMPLES	LAT	LONG
SAMPLE 1	13.4365	77.0553
SAMPLE 2	13.4402	77.043
SAMPLE 3	13.435	77.0447
SAMPLE 4	13.4309	77.045
SAMPLE 5	13.4245	77.0714

Fig 1: Study area showing Google map of Ajjagondanahalli site area with sampling points.

2.2 Methodology

A preliminary field survey was carried out to determine sampling points around the site in order to understand groundwater contamination from leachate. Overall, five groundwater samples were taken randomly during the 2025 monsoons, all five samples were collected using 1L plastic sampling bottles, rinsed with distilled water, dried and washed with the sample water according to standard APHA methods. Fig.1 shows the sampling points on Google Earth. For the analysis of heavy metals, samples were taken in polyethylene bottles and 2 ml of nitric acid was added to prevent precipitation. The samples were labelled and stored in ice boxes until transport to the laboratory where they were kept at 4 degrees Celsius until analysis. The groundwater quality was assessed by the use of a gravimetric method to analyse certain physico-chemical parameters and heavy metals such as Pb, Cd, As and Hg; pH and electrical conductivity were measured by the use of pH and conductivity meters. For the heavy metal analysis, potassium was determined by flame photometric method, whereas NO3 and PO4 were analysed by spectrophotometric method by means of a visible spectrophotometer. and the water quality index has been calculated and statistical analysis like correlation analysis with heat map was performed using SPSS software.

2.3 Water Quality Index (WQI)

Water quality testing involves a wide range of parameters and the simple form of the National Sanitation Foundation Water Quality Index (NSF-WQI) makes it possible to communicate this in a concise manner. The method of calculating the water quality index (WQI) as demonstrated based on the weighted arithmetic index method to understand the suitability of water for human consumption (Yisa and Tijani (2010). The WQI measures the combined impact of a number of characteristics related to water. The quality rating scale for each parameter qi was calculated by the following equation

$q_i = (C_i / S_i) \times 100$

The value of the quality rating scale(q_i) for each parameter was obtained by dividing the concentration of the corresponding standard (C_i) in each water sample by the value of the standard (S_i) multiplied by 100.

For the determination of relative mass (Wi), a value inversely proportional to the proposed standard (Si) of the associated parameter was used.: $Wi = 1/S_i$

The total water quality index (WQI) was calculated by adding the qualitative value (qi) and the unit weight (wi) linearly:

$WQI = \Sigma Wiqi$

$i = n$

$i = 1$

In this study, the WQI for drinking water is taken into account and the permitted WQI for drinking water is expressed as 100:

$$\text{Overall } WQI = \Sigma\ Wiqi / \ \Sigma\ Wi$$

1. Result and Discussion

The analytical results of the physicochemical characteristics of groundwater samples around the Ajjagondanahalli landfill are presented in Table 1. The descriptive statistics of groundwater samples around the Ajjagondanahalli landfill show that most physicochemical parameters, including pH (6.82–7.76), EC (856–1265 μS/cm), TDS (484–704 mg/L), calcium (57.6–106.4 mg/L), magnesium (27.7–50.06 mg/L), nitrate (0.15–0.41 mg/L), and potassium (1.51–4.92 mg/L), fall within the BIS permissible limits for drinking water. The mean values of TDS (612.2 mg/L) and EC (1087.8 μS/cm) indicate moderate mineralization and ionic content, which are consistent with findings reported near other landfill sites (Fatta *et al.,* 1999; Gao *et al.,* 2009).

Although parameters remain within permissible levels, the higher values of calcium and magnesium reflect the carbonate lithology of the study area aquifer, which contributes to water hardness. Comparable hydro geochemical patterns have been observed in studies from Jordan (Abu-Rukah & Al-Kofahi, 2001) and Morocco (Smahi *et al.,* 2013), where landfill leachate interacted with carbonate aquifers.

3.1 Heavy Metal Analysis

Heavy metal pollution in water sources is a significant global environmental concern with detrimental effects on aquatic ecosystems and human health. Major sources of contamination include anthropogenic activities such as agricultural practices, mining activities, industrial operations, urbanization, etc (Aziz *et al.,* 2023). Numerous studies revealed that elevated levels of heavy metals like Iron, Copper, Zinc, Lead, and Cadmium in water, sediment, and fish samples, pose risks to public health and ecosystem integrity(He *et al.,* 2023). Heavy metal pollution not only alters the diversity and composition of microbial communities but also impacts surface water, sediment, and groundwater ecosystems. In this study, the concentration of Heavy metals (Pb, Hg, As, Cd) and phosphate were below the detection limits, suggesting that the landfill is not yet contributing significant heavy metal contamination. Similar observations of non-detectable or low heavy metal levels in young or partially managed landfills were made by Mor *et al.,* (2006) and Abd El-Salam & Abu-Zuid (2015).

3.2 Water Quality Index (WQI)

Groundwater is the major source for agriculture, drinking, and other activities for the people in Ajjagondanahalli, and the surface water bodies are used by cattle for drinking purposes. During rain, there are high chances that the leachate may flow from the waste heap and pollute the surface and groundwater bodies near the landfill. The water Quality index can be implied to rate the overall water quality and suitability for human consumption. The computed values of WQI of groundwater samples are presented in Table 2.and The water quality index classification is presented in Table 3.WQI of groundwater samples in Fig.2.

Table: 1 Physicochemical analysis of Groundwater around Ajjagondanahalli Landfill.

Sl/no	Parameters	units	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5	Min	Ma	Mean	S D	BIS per missible limit for drinking water
1.	pH	---	6.82	7.54	7.5	7.03	7.76	6.82	7.76	7.33	0.389872	6.5-8.5
2.	E C	μS/cm	856	915	1265	1208	1195	856	1265	1087.8	187.7038	3000 μS/cm
3.	T D S	mg/l	507	484	704	688	678	484	704	612.2	107.2436	2000mg/l
4.	Ca	mg/l	57.6	74.4	76.8	106.4	92.8	57.6	106.4	81.6	18.65047	200mg/l
5.	Mg	mg/l	34.02	27.7	41.76	50.06	49.57	27.7	50.06	40.622	9.759637	100mg/l
6.	NO_3	mg/l	0.27	0.15	0.41	0.32	0.19	0.15	0.41	0.268	0.103537	45mg/l
7.	K^+	mg/l	3.45	2.47	2.25	4.92	1.51	1.51	4.92	2.92	1.31533	10mg/l
8.	PO_4	mg/l	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	0.3mg/l
9.	Pb	mg/l	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	0.05mg/l
10.	Hg	mg/l	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	0.001mg/l
11.	As	mg/l	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	0.05mg/l
12.	Cd	mg/l	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	0.01mg/l

Table 2: Computed values of WQI of groundwater samples.

Parameters	Relative weight (wi)	Sample 1 wiqi	Sample 2 wiqi	Sample 3 wiqi	Sample 4 wiqi	Sample 5 wiqi
pH	0.117	80.35294	88.82353	88.35294	82.82353	91.41176
Electrical Conductivity μS/cm	0.000333	28.53367	30.50033	42.167	40.267	39.83367
TDS mg/l	0.0005	25.3505	24.2005	35.2005	34.4005	33.9005
Calcium mg/l	0.005	28.805	37.205	38.405	53.205	46.405
Magnesium mg/l	0.01	34.03	27.71	41.77	50.07	49.58
Nitrate mg/l	0.022222	0.622222	0.355556	0.933333	0.733333	0.444444
Potassium mg/l	0.1	34.6	24.8	22.6	49.3	15.2
Σ wiqi	0.255055	232.2943	233.5949	269.4288	310.7994	276.7754
WQI		910.7617	915.861	1056.356	1218.558	1085.16

Table 3: Water Quality index classification using calculated WQI values.

WQI value	Class	Explanation
<50	Excellent	Good for human health
50–100	Good water	Fit for human consumption
100–200	Poor water	Water not in good condition
200–300	Very Poor water	Need attention before use
>300	Unsuitable for drinking	Need too much attention

From the above calculated WQI values (910.7–1218.5) for all samples clearly fall under the category “unsuitable for drinking” (>300). Despite most individual parameters being within safe limits, the cumulative WQI indicates severe deterioration of water quality. This result highlights the sensitivity of the WQI method in capturing the combined impact of even moderate increases in multiple parameters, in line with the weighted arithmetic index approach (Ramakrishnaiah *et al.*, 2009).

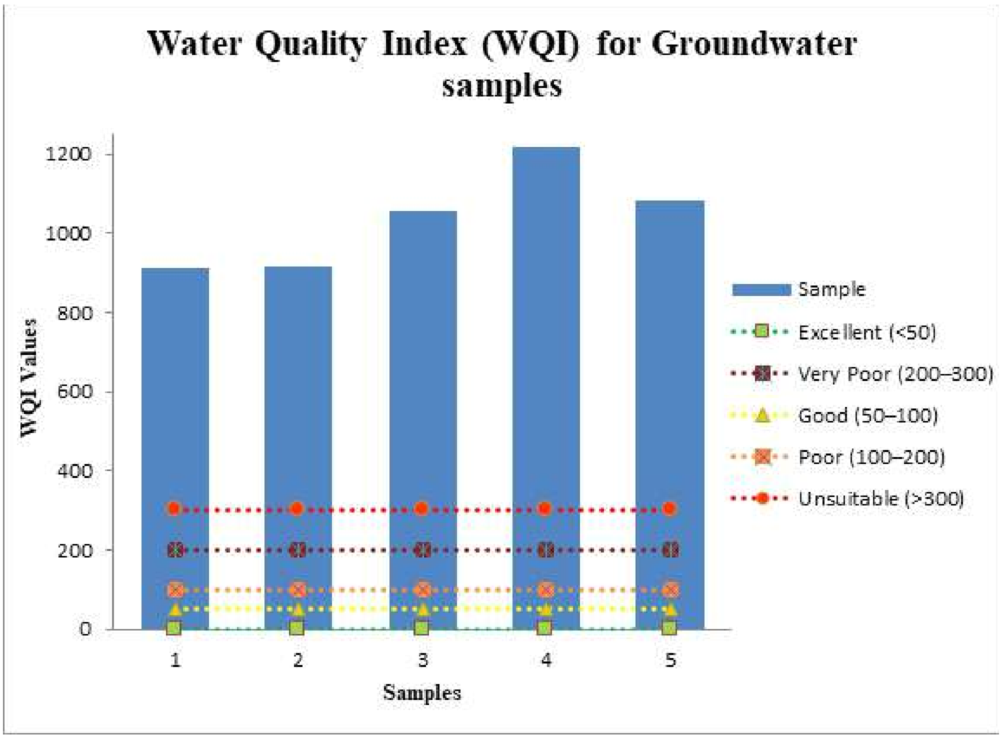


Fig. 2: Water Quality Index of groundwater samples.

The extremely high WQI values are indicative of progressive leachate infiltration into groundwater. Comparable studies in Dhaka(Azims *et al.*, 2011), Egypt (Abd El-Salam & Abu-Zuid, 2015), and Tunisia (Marzougui & Mammou, 2006) have also shown that groundwater down gradient of landfills often rapidly exceeds drinking water suitability thresholds, even when individual contaminants remain below detection limits. This emphasizes the importance of integrated index-based approaches in groundwater quality monitoring. Therefore, appropriate treatment measures and proper management aspects are required to improve the water quality as it is directly linked to the health of cattle and local people.

3.3 Correlation Analysis

The correlation analysis is done to understand the degree of linear association between the variables. The correlation coefficient ranges from -1 to 1, where -1 indicates a negative linear relationship i.e. if one variable increases the other decreases and vice versa. There is no linear relationship if the correlation is 0 and +1 indicates a perfect positive linear relationship. Simultaneously, Correlation analysis was also performed to establish relationships between analysed parameters as variables (Table 4).

Table 4: Correlation analysis of Groundwater samples.

	pH	EC	TDS	Ca	Mg	NO3	K+
pH	1						
EC	0.417086	1					
TDS	0.286346	0.980751	1				
Ca	0.250574	0.724014	0.702949	1			
Mg	0.122411	0.826809	0.898043	0.797025	1		
NO3	-0.31462	0.552861	0.602545	0.069393	0.362701	1	
K+	-0.82145	-0.07551	-0.00133	0.2807	0.15215	0.31758	1

Blue signifies a negative linear relationship, light blue no relationship, and Red a positive linear relationship.

Correlation analysis reveals strong positive associations between EC and TDS ($r = 0.981$, $p < 0.01$) and between TDS and Mg ($r = 0.898$, $p < 0.05$), reflecting the ionic dominance of magnesium salts in controlling groundwater conductivity. A positive correlation between EC and Ca ($r = 0.724$) also suggests that dissolved calcium salts contribute significantly to total ionic load, as reported in earlier landfill-affected aquifers(Fatta *et al.*, 1999; Looser *et al.*, 1999).

On the other hand, pH showed a strong negative correlation with potassium ($r = -0.821$), implying that acidic conditions may facilitate the mobilization of K from leachate or soil minerals. Similar inverse relationships between pH and certain cations have been reported in studies from India and Sri Lanka (Esakku et al., 2007) and Sweden (Flyhammar, 1995). Nitrate displayed weak positive correlations with EC and TDS, though values remained far below the BIS permissible limit. This suggests that leachate infiltration during monsoon contributes modestly to nutrient enrichment, a finding consistent with studies in seashore and humid landfill settings (Tian *et al.,* 2005; Yin *et al.,* 2020). Overall, the correlation patterns indicate that groundwater chemistry in the study area is largely governed by ionic dissolution and early-stage leachate percolation, though the absence of detectable heavy metals suggests limited long-range contamination at present.

1. Conclusion and Recommendations

The evaluation of groundwater quality around the Ajjagondanahalli landfill site indicates that, although most individual physico-chemical parameters such as pH, EC, TDS, Ca, Mg, and NO fall within BIS permissible limits, the Water Quality Index (WQI) values (910–1218) classify all samples as unsuitable for drinking purposes. This demonstrates that the combined effect of multiple parameters has a more significant impact on groundwater quality than individual measurements suggest. Correlation analysis further revealed strong positive relationships among EC, TDS, Ca, and Mg, highlighting the dominance of hardness-producing ions in controlling groundwater chemistry. The negative association between pH and potassium points to leachate influence, where potassium emerges as a sensitive early tracer of contamination. Heavy metals and phosphate were below detection limits, suggesting limited contamination at present; however, the elevated WQI and ionic correlations indicate the onset of leachate percolation into the aquifer. Continuous monitoring of groundwater, coupled with engineered landfill management practices such as leachate collection, liners, and treatment systems, provide good water from other sources to the community is recommended to safeguard groundwater.

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This research did not involve human participants, animal subjects, or any material that requires ethical approval.

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This research does not involve any clinical trials.

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Kariyanna Harisha: Research Scholar worked for the study in Conceptualization, Sampling, Experiment design, Laboratory experiments, Data analysis and original drafting of paper. Jambhava Samavedamuni. Chandrashekar: Research Guide and reviewed the study.

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ECO-SPIRITUAL PEDAGOGY: A COMPARATIVE STUDY OF ENVIRONMENTAL EDUCATION IN WORLD RELIGIONS

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ABSTRACT

Indigenous spiritualities, faiths and belief systems often incorporate deep ecological knowledge passed down through generations. These traditions highlight sustainable living and harmony with nature, offering valuable perspectives for modern environmental education. Religious faiths can both positively and negatively impact environmental awareness. When aligned with ecological values, they provide a powerful foundation for fostering sustainable attitudes and behaviours, making them valuable partners in environmental education. In this paper, we have highlighted the teachings of environmental education as perceived in both Western religions (Judaism, Christianity and Islam) as well as Eastern religions (Hinduism, Buddhism, Jainism, Sikhism, Taoism, Laoism, Confucianism and Shintoism).

No. of Pages: 10 **References: 44**

Keywords: Environmental education, religious, Judaism, Christianity, Islam, Hinduism, Buddhism, Jainism, Sikhism, Taoism, Laoism, Confucianism, Shintoism.

INTRODUCTION

Environmental education is a crucial component of sustainable development, and its inclusion in the primary school curriculum plays a vital role in shaping young minds (Parker, 2017; Fergusson et al., 2018). At an early age, children are highly receptive to new ideas, and introducing environmental concepts during this formative period fosters awareness, responsibility, and proactive behaviour toward nature (Parker, 2017; Awuah-Nyamekye, 2019). By integrating topics such as pollution, conservation, climate change, and biodiversity into core subjects like science, social studies, and even art, educators can create meaningful learning experiences that promote eco-consciousness (Hitzhusen, 2006; Gardner, 2010). This early exposure encourages students to adopt environmentally friendly habits and empowers them to become informed citizens who care about the planet.

Therefore, enhancing environmental awareness through curriculum-based strategies is not just beneficial but essential for building a generation that is prepared to tackle future environmental challenges (Parker, 2017; Hitzhusen, 2006). Integrating environmental education into the primary school curriculum is essential for fostering early environmental awareness and responsible behaviour among children (Fergusson et al., 2018). One very interesting aspect of understanding regarding environmental education and awareness is how our young minds are being trained socio-culturally towards this green philosophy through the lens of various religions and faiths (Gardner, 2010; Parker, 2017; Jiang and Zhang, 2020).

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From the Perspectives of Western Religions

Environmental Education in Judaism

Environmental education in Judaism is deeply rooted in traditional Jewish texts, ethics, and practices (Swan, 1978). Jewish teachings emphasize stewardship of the Earth, responsibility for creation, and sustainable living (Smith, 2019; Yang and Lu, 2024). Here's an overview of key concepts and sources related to environmental education in Judaism:

Biblical Foundations

Genesis (Bereishit): Humanity is placed in the Garden of Eden "*to work it and to guard it*" (l'ovdah ul'shomrah - Genesis 2:15), a foundational verse for Jewish environmental ethics. This teaches both productive use and protective responsibility (Yang and Lu, 2024).

Sabbath and Sabbatical Year: The Shabbat (weekly Sabbath) and Shmita (sabbatical year) demonstrate values of rest, balance, and allowing the land to rejuvenate (Exodus 23:10-12, Leviticus 25).

Rabbinic Teachings

Bal Tashchit (Do Not Destroy): A prohibition against needless destruction, first stated in Deuteronomy 20:19-20, when cutting trees during war, but expanded by the rabbis to a broader environmental ethic.

Tza'ar Ba'alei Chayim: The principle against causing unnecessary suffering to animals, reinforcing respect for all living creatures.

Responsibility and Interconnectedness: Rabbinic literature often discusses the interconnectedness of humanity and nature, urging ethical living and accountability for environmental impact.

Jewish Holidays and the Environment

Tu BiShvat: Traditionally a time for planting trees, it has become a central holiday for Jewish environmental education and advocacy.

Sukkot: Living in temporary shelters highlights simplicity, dependence on nature, and gratitude for the harvest.

Passover: Discussions of slavery and liberation can also include themes of environmental justice and responsibility.

Jewish Environmental Organizations, such as groups like Hazon, the Jewish Climate Initiative, and the Coalition on the Environment and Jewish Life (COEJL) promote environmental awareness and action within Jewish communities (Parker, 2017; Smith, 2019; Santos, 2023). Eco-Kashrut is an extension of traditional kosher laws to include ethical considerations about food production, sustainability, and environmental impact. Many synagogues and Jewish educational institutions incorporate sustainability into their infrastructure and curricula (Smith, 2019; Santos, 2023; Yang and Lu, 2024).

Torah-based curriculum has been in incorporated in Jewish schools and camps often integrate environmental topics into religious studies, using texts and mitzvot to frame ecological responsibility (Parker, 2017; Smith, 2019; Santos, 2023). Programs include gardening, composting, celebrating Jewish holidays with ecological themes (*e.g*., Tu BiShvat as the "New Year of the Trees"), and nature-based retreats. Tree planting, clean-up projects, and sustainable lifestyle challenges are increasingly part of Jewish communal life (Parker, 2017; Smith, 2019; Santos, 2023).

Environmental Education in Christianity

Environmental education in Christianity is grounded in the belief that the Earth is God's creation and that humans are stewards of it (Salemink and Turner, 2014; Smith, 2019; Yang and Lu, 2024). This concept is often referred to as "creation care." Here's an overview of how environmental education is approached within Christianity:

Biblical Foundations: Genesis 1:26-28: Humans are given "dominion" over the Earth, but this is increasingly interpreted as responsible stewardship rather than exploitation.

Genesis 2:15: Adam is placed in the Garden of Eden "*to till it and keep it,*" highlighting a duty to protect and care for the environment.

Psalms 24:1: "*The Earth is the Lord's, and everything in it*," emphasizing that nature belongs to God, not humans.

Theological themes highlights that Christians are caretakers of God's creation (Swan, 1978). This includes protecting ecosystems, conserving resources, and acting against pollution (Salemink and Turner, 2014; Smith, 2019; Santos, 2023). Environmental degradation often impacts the poor and vulnerable first, tying creation care to Christian concerns for social justice (Parker, 2017; Yang and Lu, 2024). The idea of rest and renewal (for people and the land) promotes sustainability and respect for natural cycles (Swan, 1978; Salemink and Turner, 2014; Awuah-Nyamekye, 2019; Yang and Lu, 2024).

Organizations such as A Rocha, Evangelical Environmental Network (EEN), and Laudato Si' Movement promote environmental awareness and action from a faith-based perspective (Swan, 1978; Yang and Lu, 2024). Pope Francis' 2015 encyclical Laudato Si' is a major Catholic document addressing climate change, sustainability, and ecological spirit. Many churches include creation care in Sunday school, sermons, Bible studies, and youth programs. Activities may include tree planting, recycling drives, and educational seminars on climate change and conservation. Teaching about eco-friendly lifestyles is a moral responsibility ((Swan, 1978; Awuah-Nyamekye, 2019; Yang and Lu, 2024). Encouraging sustainable practices such as energy conservation, ethical consumption, and habitat preservation as well as promoting prayer and reflection on humanity's relationship with nature are important aspects of environmental education for many practicing and devoted Christians (Swan, 1978; Parker, 2017; Yang and Lu, 2024).

Environmental Education in Islam

Islam places significant emphasis on the protection and preservation of the environment. Environmental education, within the Islamic framework, is not just a modern academic subject; but, an integral aspect of faith and daily living Alshater et al., 2021, Ismail, 2018). It promotes a worldview where humans are stewards of the Earth, entrusted with the responsibility to maintain its balance and sustainability (Alshater et al., 2021; Swammar and Mohammad, 2021).

In Islam, human beings are regarded as khalifah (stewards or vicegerents) of the Earth: As Qur'an (2:30) says: “Indeed, I will make upon the earth a successive authority (khalifah).” This implies a divine trust upon humans to care for the environment, not exploit it. Environmental education in Islam teaches individuals their duty to protect natural resources, ensure sustainability, and pass on a healthy planet to future generations (Ismail, 2018; Alshater et al., 2021).

Islam stresses that Allah created everything in perfect balance. ACcording to Qur'an (55:7-9): “*And the heaven He raised and imposed the balance - That you not transgress within the balance*.” Environmental education from this perspective includes understanding the interconnectedness of ecosystems and the consequences of disrupting natural harmony, such as through pollution, deforestation, or climate change (Alshater et al., 2021; Wakhidah and Erman, 2022).

Islam condemns extravagance and wastefulness. The Qur'an (7:31) says: “...*Eat and drink, but do not waste. Surely, He does not like the wasteful*.” This principle encourages conservation, responsible consumption, and sustainable living-key teachings in environmental education (Ahmed and Gianci, 2005). Islam teaches that all creatures are communities like humans (Alshater et al., 2021). The Qur'an (6:38) quotes: “*There is not an animal in the earth, nor a flying creature on two wings, but they are communities like you*.” This informs Islamic environmental education to respect biodiversity and protect animal habitats (Ahmed and Gianci, 2005; Wakhidah and Erman, 2022).

Prophetic traditions (Hadith) encourage active care for nature. The Hadith preaches: “*If a Muslim plants a tree or sows seeds, and then a bird, or a person, or an animal eats from it, it is regarded as a charitable gift* (sadaqah) *for him*.” (Bukhari). The Hadith further mentions: “*If the Hour* (the Day of Judgment*) is about to be established and one of you was holding a palm shoot, let him plant it*.” (Ahmad). These teachings underline the Islamic encouragement of proactive environmental action, even in the face of global calamity (Alshater et al., 2021). Water is considered a sacred gift in Islam Alshater et al., 2021). According to Hadith: The Prophet Muhammad (PBUH) performed ablution (wudu) using very little water, setting an example for conserving water resources. Environmental education in Islam involves learning practical ways to preserve water, a theme highly relevant in modern ecological discussions (Ahmed and Gianci, 2005).

Islam links environmental care with social responsibility and justice (adl); such as fair distribution of resources, protection of vulnerable communities from environmental harm, and accountability for polluting or damaging shared resources (Alshater et al., 2021). In Islam, environmental education is deeply spiritual and ethical, promoting a harmonious relationship between humans and nature (Ahmed and Gianci, 2005). It emphasizes responsibility, balance, conservation, and compassion. By rooting ecological awareness in faith, Islam inspires both individual and collective action to protect the environment as an act of worship and moral duty (Wakhidah and Erman, 2022).

From the Perspectives of Eastern Religions

Environmental Education in Hinduism

The essence of modern environmental education reflected in the Srimad Bhagavad Gita is a compelling and meaningful concept (Dwivedi, 1993). It invites a fusion of ancient spiritual wisdom with contemporary ecological awareness-a synthesis that is increasingly valuable in today's environmentally challenged world (Okafer and Stella, 2018; Basak, 2024). Here's a breakdown of how the Bhagavad Gita reflects principles aligned with modern environmental education as the Unity of All Life and Ecocentrism (Sargeant and Chapple, 2009; Agarwal, 2018; Jain 2022)). The Gita emphasizes the interconnectedness of all beings. For instance, in Chapter 5, Verse 18, it says: "*The humble sage, by virtue of true knowledge, sees with equal vision a learned and gentle Brahmana, a cow, an elephant, a dog, and a dog-eater*." This mirrors ecocentric thinking-a core tenet of environmental education-which values all life forms equally and promotes coexistence (Sargeant and Chapple, 2009; Jain, 2022; Basak, 2024).

Duty (Dharma) and Environmental Stewardship

Krishna urges Arjuna to act according to his dharma (duty). Today, environmental educators call for a sense of individual and collective responsibility for protecting nature (Dwivedi, 1993). The Gita's call to perform one's righteous duty can be interpreted as a call to ecological duty in the modern context (Sargeant and Chapple, 2009; Basak, 2024). The Gita discourages attachment to material possessions and advocates a life of moderation, which aligns with principles of sustainability (Sargeant and Chapple, 2009; Okafer and Stella 2018; Jain, 2022). This is seen in Chapter 6, Verse 16-17, which promotes a balanced lifestyle (Basak, 2024). In Chapter 3, Krishna describes the cycle of nature as a form of yajna (sacred offering), stating that living beings should live in harmony with the cycles of giving and receiving (Dwivedi, 1993). This echoes the systems-thinking approach in environmental education, where maintaining natural cycles is crucial for ecological balance (Agarwal, 2018; Okafer and Stella, 2018).

The Gita places emphasis on inner transformation and self-awareness, a foundational principle of education (Sargeant and Chapple, 2009; Basak, 2024). True environmental change begins with inner change-developing environmental ethics, empathy, and mindfulness (Agarwal, 2018; Okafer and Stella, 2018). The Srimad Bhagavad Gita, while ancient, holds timeless wisdom that resonates with modern environmental principles: Respect for all life, Responsible action, Simplicity, Ecological interconnectedness and Ethical living (Dwivedi, 1993; Sargeant and Chapple, 2009; Okafer and Stella, 2018). As such, it can serve as a powerful philosophical and ethical foundation for environmental education (Sargeant and Chapple, 2009; Jain, 2022), particularly in culturally relevant contexts like India or in global discussions on spiritual ecology (Okafer and Stella 2018; Basak, 2024).

Environmental Education according to Swami Vivekananda

Swami Vivekananda, one of India's most profound spiritual leaders and thinkers, did not explicitly use the modern term "*environmental education*," (Jain, 2022) but his teachings are rich with principles that align closely with environmental consciousness and sustainability (Dwivedi, 1993). Reflections of Environmental Education in the Teachings of Swami Vivekananda are discussed below:

Unity of Existence and Nature: Swami Vivekananda emphasized the oneness of all beings. He believed that everything in the universe-human beings, animals, plants, and the environment-is interconnected and manifestations of the same universal consciousness. He mentioned, "*Each soul is potentially divine. The goal is to manifest this Divinity within by controlling nature, external and internal*." This belief promotes a respect for nature as sacred, and encourages living in harmony with the environment (Teachings of Swami Vivekananda, 1981). Vivekananda drew from Vedantic philosophy which considers nature not as inert matter, but as a living and divine entity. This promotes an intrinsic reverence for the natural world, an idea foundational to modern ecological ethics. By encouraging spiritual growth through contemplation of nature, Vivekananda indirectly promotes environmental stewardship (Teachings of Swami Vivekananda, 1981). He advocated a simple, disciplined lifestyle, which aligns with sustainable living (Sargeant and Chapple, 2009; Jain, 2022). Minimizing material consumption and practicing contentment reduce strain on natural resources. These ideals can be linked to modern movements like minimalism and sustainable consumption (Fergusson et al., 2018).

Vivekananda's principle of "Seva" (selfless service) extends to all beings, not just humans. Environmental education today emphasizes the need to protect biodiversity and serve future generations by preserving nature (Jain, 2022). He said, "*They alone live who live for others*." Serving others includes protecting the environment, which supports all life. Swami Vivekananda strongly believed in education as the manifestation of perfection already in man. He advocated for holistic education that includes moral, spiritual, and intellectual richness. Environmental education fits well within this framework developing responsible, ethical, and aware individuals who can think critically about their relationship with the earth. Swami Vivekananda placed immense trust in the power of youth. He urged them to be courageous, morally upright, and socially responsible (Teachings of Swami Vivekananda, 1981).

Today's environmental challenges need youth involvement. Vivekananda's vision inspires young people to lead environmental movements and become agents of change. Swami Vivekananda's teachings offer a profound moral and spiritual foundation for environmental education (Teachings of Swami Vivekananda, 1981). By emphasizing unity, self-discipline, reverence for nature, and social responsibility, his philosophy encourages a sustainable and ethical relationship with the natural world (Teachings of Swami Vivekananda, 1981). Educators can draw on his ideas to foster an environmental ethic rooted in values, not just facts (Sargeant and Chapple, 2009; Agarwal, 2018).

Environmental Education in Buddhism

Environmental education as perceived through Buddhism, explores how Buddhist philosophy and teachings can inform and shape environmental education (Wu and Lee, 2021; Jain, 2022). Buddhism defines environmental education as a process that enables individuals to explore environmental issues, engage in problem-solving, and take action to improve the environment (Ranjan, 2014; Wu and Lee, 2021). Buddhist teachings provide a valuable framework for environmental education by promoting compassion, mindfulness, and interdependence (Ranjan, 2014; Agarwal, 2018; Wu and Lee, 2021).

The core Buddhist principles (Ranjan, 2014) relevant to Environmentalism include:

Interdependence (Pratityasamutpada): Everything is interconnected; harming nature is harming oneself.

Ahimsa (Non-violence): Extending non-harm to all living beings and the planet.

Mindfulness (Sati): Being present and aware of one's actions and their impact on the environment.

Simplicity and Non-attachment: Reducing consumption, detaching from materialism.

The environmental ethics in Buddhist teachings is highlighted in the firm of the First Precept: "*Do not harm any living being*" – includes animals and nature. The Middle Way teaches, "*Avoiding extremes in consumption and behaviour*." The principle of Metta (Loving-kindness) and Karuna (Compassion) teaches "Encouraging care for all life for all life forms." Buddhism teaches ecological responsibility through moral and spiritual values (Wu and Lee, 2021). It specifically emphasizes upon experiential practices like meditation and nature walks to cultivate mindfulness and appreciation of nature (Jiang and Zhang, 2020). Buddhism encourages collective action inspired by Sangha (community) principles (Wu and Lee, 2021; Jain, 2022).

Numerous case studies support and highlight these practical principles of Buddhism (Ranjan, 2014). For example, forest monasteries in Thailand promoting forest conservation (Wu and Lee, 2021; Agarwal, 2018). Buddhist-led environmental movements (*e.g.*, Bhutan's Gross National Happiness, His Holiness the Dalai Lama's environmental statements) have immense global significance (Wu and Lee, 2021; Jain, 2022). Integration of Buddhist philosophy into eco-education programs in Sri Lanka, Japan, Bhutan, Thailand, Myanmar, Mongolia Thailand, Cambodia, Laos, and Tibet are classical examples (Ranjan, 2014; Jiang and Zhang, 2020; Wu and Lee, 2021).

The Tibetan refugee community settled in various parts of India after the Chinese occupation of Tibet in 1959. One of the prominent settlements is in the Darjeeling district of West Bengal, which offered a similar climate and terrain to their native land. Their adaptation to this new ecological, socio-cultural and socio-economic environment is a remarkable example of cultural resilience and environmental integration. Their choice of settlement area is related to the fact that Darjeeling's cool, temperate climate and hilly terrain are quite similar to parts of the Tibetan Plateau. The area was chosen due to its proximity to the Himalayan belt and existing Buddhist communities, easing cultural transition. Tibetans brought traditional crafts like carpet weaving, woollen garments, and handmade artefacts, adapting materials locally available (like Indian wool). Though limited due to terrain, some adapted to terrace farming and horticulture. Many have become part of Darjeeling's tourism economy, selling handicrafts, running restaurants, and engaging in cultural tourism.

Tibetan houses are built using locally available materials like wood and stone, maintaining traditional Tibetan architectural elements. Roofing and drainage systems were adapted to manage heavy monsoonal rain-unlike Tibet's drier climate. Buddhist monasteries often promote conservation, non-violence towards nature, and sustainable practices. The Tibetan festivals are celebrated in harmony with the agricultural and ecological calendar of the region (*e.g.,* Losar, Saga Dawa). However, increasing population density and tourism in Darjeeling have led to environmental degradation, impacting the Tibetan settlements too. Seasonal water shortage is a challenge in the hilly terrain. Some Tibetan-run establishments promote eco-tourism and socio-cultural awareness based on traditional Buddhist traditions, faiths and principles.

Tibetan schools have string emphasis for environmental education as part of their curriculum. The Tibetan refugees in Darjeeling have shown a remarkable ability to ecologically adapt to their environment while preserving their unique Buddhist cultural identity. Their integration demonstrates a model of sustainable living, community cohesion, and resilience amidst displacement through their strong faith in Buddhist traditions and belief systems. Buddhism offers a holistic, compassionate, and ethical perspective on environmental education. Integrating Buddhist values into environmental curricula can nurture responsible, empathetic, and sustainable attitudes toward the Earth.

Environmental Education in Jainism

Environmental education in Jainism is deeply rooted in its spiritual and ethical principles, emphasizing non-violence (ahimsa), compassion, and the interconnectedness of all life forms (Ray, 1984; Agarwal, 2018). Here's an overview of how environmental education is perceived in Jainism:

Ahimsa (Non-Violence) towards all living beings: The core of Jain philosophy is ahimsa, or non-violence, which extends not only to humans and animals; but, also to plants, microorganisms, and the natural environment. Jains believe that harming nature, even unintentionally, leads to negative karma (Ranjan, 2014). This belief encourages minimal use of natural resources and a highly mindful lifestyle (Ray, 1984; Agarwal, 2018).

Aparigraha (Non-Possessiveness): Jainism advocates limiting material possessions and desires, which aligns with modern sustainability and conservation principles. By practicing aparigraha, Jains reduce their ecological footprint and promote a more balanced relationship with the environment (Ray, 1984; Fergusson et al., 2018).

Respect for All Life Forms: Jains classify all forms of life (from single-sensed to five-sensed beings) and respect each type (Ray, 1984; Ranjan, 2014). Even microorganisms are considered to have life, which teaches deep reverence and careful interaction with the environment (Jain, 2010).

Vegetarianism and Ecology: Jainism promotes a strict vegetarian or even vegan diet, which significantly reduces environmental impact (Ranjan, 2014). This practice decreases the demand for resource-intensive animal agriculture, aligning with modern environmental education on sustainable food practices (Ray, 1984; Fergusson et al., 2018).

Daily Practices as Environmental Ethics: Jains follow rituals such as filtering water, avoiding night time eating to prevent harming insects and using natural resources sparingly (Ray, 19840. These practices instil values of care, awareness, and ecological balance (Agarwal, 2018).

Educational and Institutional Promotion: Jain educational institutions often integrate ethical and environmental teachings (Ranjan, 2014). Religious discourses, scriptures, and community practices act as informal modes of environmental education (Jain, 2010).

Scriptural Foundations: Jain texts like the Tattvartha Sutra, Acharanga Sutra, and Dashavaikalika Sutra highlight respect for all living beings and non-exploitation of nature (Ray, 19840. These scriptures serve as foundational resources for understanding ecological ethics in Jainism (Jain, 2010; Ranjan, 2014). Environmental education in Jainism is not a separate discipline but an integral part of spiritual life (Ray, 1984; Ranjan, 2014). It teaches a deep ecological consciousness through non-violence, simplicity, and compassion-values that are increasingly relevant in addressing global environmental challenges today (Ranjan, 2014; Agarwal, 2018; Singh, 2022).

Environmental Education in Sikhism

Environmental education in Sikhism is deeply embedded in its spiritual and ethical teachings (Singh, 2022). Sikhism, founded by Guru Nanak Dev Ji in the 15th century, emphasizes harmony with nature, respect for all forms of life, and the interconnectedness of creation (Moony, 2018; Singh 2022). Sikhism teaches that the entire universe is created by one divine force, Waheguru. Nature is not separate from the Divine but a manifestation of it (Kaur, 2020). A quote from Guru Granth Sahib, says, "*Air is the Guru, Water is the Father, and Earth is the Great Mother of all*." (Guru Granth Sahib, p. 8). This line emphasizes reverence for the elements and fosters an ecological consciousness based on spiritual principles (Singh, 2022; Prill, 2023).

Sikhism encourages 'Living in Harmony with Nature'. It supports a lifestyle that is simple, sustainable, and in balance with nature (Kaur, 2020; Singh 2022). The concept of “Sehaj” (natural balance and moderation) promotes avoiding excess consumption and waste (Mooney, 2018). Environmental stewardship practiced through care, responsibility, sincerity and dedication is seen as part of 'Seva' (Selfless service). Caring for the environment is a duty, not a choice. This includes community efforts like cleaning rivers, planting trees, and maintaining cleanliness in Gurdwaras and surroundings (Kaur, 2020; Singh 2022). All beings are equal in the eyes of God. This principle extends to animals and the environment, fostering a respect for biodiversity and discouraging exploitation (Prill, 2015).

Members of the Sikh communities around the globe practice and support Environmentalism through their Langars (Community Kitchens) uses plant-based, simple meals, minimizing environmental impact (Mooney, 2018; Singh 2022). Many Gurdwaras are moving toward solar power, water conservation, and waste reduction as expressions of Sikh values for transforming them into sustainable and eco-friendly (Prill, 2015). Organizations like EcoSikh work globally to apply Sikh teachings to contemporary environmental issues, including Climate Change, deforestation, and water scarcity (Kaur, 2020; Singh 2022). In Sikhism, environmental education is not separate from religious instruction but a spiritual imperative. By teaching respect for nature, moderation, and selfless service, Sikhism offers a framework for ecological responsibility grounded in faith (Singh, 2022; Prill, 2023).

Environmental Education in Taoism

Teaching Environmental education through Taoism offers a powerful, philosophical framework rooted in harmony with nature (Tucker, 1993; Yang et al., 2019; Jiang and Zhang, 2020; Wu and Lee, 2021). Taoism (or Daoism), an ancient Chinese philosophy and spiritual tradition, emphasizes living in accordance with the Tao (道)-the natural order or "Way" of the universe (Guo et al., 2017; Yang et al., 2019). Taoism can be integrated into environmental education in holistic manner (Tucker, 1993; Dessi, 2016; Yang et al., 2019; Wu and Lee, 2021).

The core Taoist concepts (Yang et al., 2019) supporting environmental awareness include:

Wu Wei (无 为): Often translated as "non-action" or "effortless action," this principle promotes going with the natural flow rather than forcing change. In environmental terms, this encourages sustainable living and minimal disruption of ecosystems (Tucker, 1993; Dessi, 2016).

Ziran (自然): Translated as "naturalness" or "self-so," it promotes authenticity and harmony with the environment, valuing natural processes and organic development (Tucker, 1993; Jiang and Zhang, 2020).

Yin and Yang (阴 阳): This concept of duality and balance teaches that nature functions through interdependent opposites. Environmental education can use this to show the balance required in ecosystems and the danger of tipping natural systems out of harmony (Guo et al., 2017).

Taoism is used traditionally as a pedagogical tool. Taoism views nature as a teacher (Guo et al., 2017; Wu and Lee, 2021). Students can engage in outdoor, contemplative practices such as observation, journaling, or meditative walks to foster respect and connection to the natural world (Tucker, 1993; Lin et al., 2016; Yang et al., 2019; Jiang and Zhang, 2020; Wu and Lee, 2021). Taoist classics like the Tao Te Ching and Zhuangzi are rich in parables and metaphors that can illustrate environmental principles (Guo et al., 2017; Yang et al., 2019). For example: “Man takes his law from Earth; Earth takes its law from Heaven; Heaven takes its law from the Tao.” (Tao Te Ching, Ch. 25). Taoist philosophy encourages simplicity, contentment, and reduction of material desire-values aligned with sustainable consumption and environmental ethics (Dessi, 2016; Lin et al., 2016; Yang et al., 2019; Wu and Lee, 2021).

Practical applications of Taoist environmental education highlight upon the Taoism's reverence for life promotes intrinsic value in all beings, supporting conservation and biodiversity education (Jiang and Zhang, 2020). Taoist ideals of working with nature-not against it-align with sustainable agriculture, forest gardening, and permaculture (Tucker, 1993; Guo et al., 2017). Water is a central Taoist symbol. Lessons on water conservation, watershed health, and the hydrological cycle can be enriched with Taoist symbolism (Dessi, 2016; Lin et al., 2016). Taoism complements modern environmental science by adding spiritual and ethical dimensions (Tucker, 1993). While science explains how ecosystems function, Taoism asks us to consider why we should live in balance with them (Guo et al., 2017; Wu and Lee, 2021).

Different classroom based integration ideas focusing on Taoist faith can include guided meditations on the interconnection of life (Jiang and Zhang, 2020; Wu and Lee, 2021). Emphasis on reflective essays comparing Taoist texts with local environmental issues is quite relevant to modern aspects of environmental education (Jiang and Zhang, 2020; Wu and Lee, 2021). Organizing field trips to natural areas with Taoist-inspired mindfulness and encouraging creative arts by drawing Yin-Yang representations of ecosystem symbolizes environmental philosophy of classical and traditional Taoism integrated with modernism and practicality of the current global ethics (Tucker, 1993; Dessi, 2016; Guo et al., 2017).

Environmental Education in Laoism

Environmental education in Laoism (or more accurately, Lao culture and traditional beliefs, which often include elements of Therav da Buddhism, animism, and spiritual practices) is deeply embedded in a worldview that sees humans as part of a larger, interconnected natural system (Nuyen, 2008; Wu and

Lee, 2021). Laoism traditionally views natural elements-forests, rivers, mountains-as inhabited by spirits (known as phi) (Lin et al., 2016). Respect for these spirits encourages protection of natural places, akin to environmental stewardship (Jiang and Zhang, 2020). For example, a sacred forest (pa xou) is not to be disturbed, hunted in, or cut down. This instills an early, informal environmental education rooted in fear and reverence (Lin et al., 2016; Guo et al., 2017; Wu and Lee, 2021).

As Laos is predominantly Therav da Buddhist, the principle of interdependence and karma informs behaviour toward the environment. Harming nature is seen as generating bad karma (Guo et al., 2017; Lin et al., 2016). Mindfulness and moderation discourage overexploitation of resources. Traditional Lao communities often rely on communal decision-making and taboos to manage natural resources. Seasonal harvesting and taboo zones promote sustainable use (Nuyen, 2008; Wu and Lee, 2021). Children learn these rules socially, embedding ecological knowledge from a young age (Lin et al., 2016; Wu and Lee, 2021). Environmental values are passed on through folktales, proverbs, and rituals. Stories often feature animals and forests as moral actors (Guo et al., 2017). These narratives subtly teach environmental ethics and caution against greed (Li et al., 2023). Today, formal environmental education programs in Laos are incorporating these traditional beliefs to foster a deeper sense of relevance and cultural continuity (Jiang and Zhang, 2020; Wu and Lee, 2021; Li et al., 2023).

Environmental Education in Confucianism

Environmental education within Confucianism is not explicitly framed in the modern sense, but many of its core teachings align with environmental values (Tucker, 1993; Guo et al., 2017; Li et al., 2023). Confucianism emphasizes harmony between humans and nature. While not as ecologically focused as Daoism (Taoism), Confucian thought views the natural world as part of the moral and social order (Guo et al., 2017; Wu and Lee, 2021; Li et al., 2023). Humans are not above nature; but, part of its larger system. Confucius stressed ethical behaviour, which includes being conscientious and responsible (Nuyen, 2008; Li et al., 2023). This sense of moral duty can extend to how one treats the environment-suggesting a responsibility to care for the natural world as part of virtuous living. In Confucianism, “Tian” (Heaven) represents the natural order and moral authority. Acting in accordance with Heaven means respecting the natural world, as disrupting it would be a form of moral failure (Tucker, 1993; Jiang and Zhang, 2020; Wu and Lee, 2021; Li et al., 2023).

Confucianism teaches the Cultivation of Virtue (Ren and Li) (Tucker, 1993; Nuyen, 2008). Ren (benevolence) encourages compassion, which can extend to all forms of life. Li (ritual/propriety) emphasizes respectful behaviour, which can be interpreted as including how humans interact with the environment (Tucker, 1993; Nuyen, 2008; Guo et al., 2017). Traditional Confucian communities emphasized moderation, frugality, and living in balance-all values compatible with sustainable environmental practices (Tucker, 1993; Nuyen, 2008; Guo et al., 2017; Wu and Lee, 2021). The ethics of environmental education deeply rooted in Confucian values can teach: respect for the natural world as part of moral development, responsibility to maintain balance and harmony, and ethical reflection on consumerism, waste, and human impact on ecosystems (Nuyen, 2008; Jiang and Zhang, 2020; Wu and Lee, 2021).

Environmental Education in Shintoism

Environmental education, as perceived in Shintoism, is deeply rooted in the religion's reverence for nature (Rots, 2017). While Shintoism does not have a structured system of environmental education like modern curricula, its spiritual and cultural worldview naturally encourages environmental awareness, respect, and sustainability. In Shinto belief, kami (divine spirits) inhabit natural elements-trees, mountains, rivers, rocks. This spiritual view promotes a deep respect for the environment, teaching that harming nature is akin to offending the divine (Reitam, 2017).

Shinto shrines are often located in natural settings and are meant to be in harmony with their surroundings. Sacred groves (chinju no mori) surrounding shrines act as preserved ecosystems and offer practical models of biodiversity conservation. Water is used in purification rites (Misogi), reflecting its spiritual importance and emphasizing the need to protect clean natural water sources. Seasonal festivals (Matsuri) often mark agricultural cycles, harvests, or honour natural phenomena (Reitam, 2017). These rituals reinforce environmental rhythms and human dependency on nature, fostering ecological awareness (Rots, 2017).

Shinto emphasizes living in harmony with nature, not dominating it. This ethos aligns with sustainable living and ecological balance. It supports non-anthropocentric values, where humans are part of nature, not above it (Rots, 2017). Through oral traditions, shrine practices, and community rituals, values of environmental stewardship are passed down generations, acting as informal but powerful environmental education. Shintoism offers a spiritually infused form of environmental education, emphasizing respect, harmony, and reverence for nature. While not formalized, these values contribute significantly to ecological consciousness and can complement modern environmental education frameworks (Reitam, 2017).

Conclusion

Religious faiths and beliefs significantly shape our perception of environmental education and awareness by influencing values, attitudes, and behaviours toward nature and ecological responsibility (Gardner, 2010; Awuah-Nyamekye, 2019). Many religions emphasize stewardship-the belief that humans have a divine responsibility to care for the Earth (Hitzhusen, 2006). For example: Christianity often teaches that humans are caretakers of God's creation (Genesis 2:15). Islam emphasizes humans as khalifa (stewards) of the Earth, responsible for protecting it. Judaism includes principles of tikkun olam (repairing the world), encouraging environmental responsibility (Gardner, 2010). Hinduism and Buddhism promote the interconnectedness of all life and a respect for nature, often seeing divinity in natural elements (Hitzhusen, 2006; Gardner, 2010).

Religious teachings often in still moral frameworks that encourage environmentally responsible behaviour, such as: avoiding wastefulness, promoting simplicity and moderation, and respecting all forms of life (Basak, 2024). These ethics can enhance environmental awareness and inform curricula or activism grounded in moral duty (Parker, 2017; Awuah-Nyamekye, 2019). Faith-based communities can be powerful platforms for environmental education (Hitzhusen, 2006; Parker 2017). Religious leaders and organizations often promote eco-friendly practices, host environmental awareness events, and integrate environmental themes into sermons and teachings (Basak, 2024). On the other hand, some religious interpretations might downplay environmental concerns, especially if they emphasize human dominion over nature or prioritize the afterlife over earthly matters (Fergusson et al., 2018). This can lead to indifference or scepticism toward environmental education.

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CLIMATE VARIABILITY AND ENVIRONMENTAL STRESS IMPACTS ON SAFFRON (*CROCUS SATIVUS* L.) CULTIVATION IN THE KASHMIR VALLEY

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Research Paper

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ABSTRACT

Climate variability has emerged as a major environmental challenge influencing agricultural sustainability, particularly in fragile Himalayan agro-ecosystems. Saffron (*Crocus sativus* L.), a high-value and climate-sensitive crop cultivated predominantly in the Kashmir Valley, is increasingly exposed to environmental stress due to changing temperature and precipitation patterns. The present study examines the influence of recent climatic variability on saffron cultivation with special reference to key agrometeorological parameters, including temperature, rainfall, and snowfall trends in the Kashmir Valley.

Multi-year climatic data (2010–2024) were analyzed to assess trends in mean temperature and precipitation and their relationship with saffron productivity. Saffron yield data were obtained from official agricultural records for the corresponding period. Trend and correlation analyses were employed to evaluate the influence of climatic variables on saffron yield. The results indicate a statistically significant increasing trend in mean temperature and high inter-annual variability in precipitation, accompanied by a decline in snowfall during the saffron growing season. These climatic changes have adversely affected soil moisture availability, flowering behavior, and corm development, leading to a continuous decline in saffron productivity.

The study demonstrates a significant negative relationship between increasing temperature and saffron yield, while precipitation variability also showed an adverse influence on productivity. The findings highlight that climate-induced environmental stress poses a serious threat to the sustainability of saffron cultivation in the Kashmir Valley. The study emphasizes the need for climate-adaptive agronomic practices, improved water and soil moisture management, and region-specific adaptation strategies to sustain saffron production under changing climatic conditions. The results provide valuable insights for agricultural planners, researchers, and policymakers involved in promoting climate-resilient saffron cultivation in temperate Himalayan regions.

No. of Pages: 05 **References: 14**

Keywords: Climate change; Environmental stress; Saffron cultivation; Himalayan agro-ecosystem; Kashmir Valley; Agricultural sustainability.

INTRODUCTION

Saffron (*Crocus sativus* L.), widely referred to as the "golden spice," is one of the most valuable medicinal and aromatic crops in the world due to its unique flavor, color, and therapeutic properties. It is extensively used in traditional medicine, food industries, and pharmaceutical applications. Global saffron production is limited to a few regions with specific agro-climatic requirements, among which the Kashmir Valley is internationally recognized for producing high-quality saffron with superior aroma and coloring strength.

In the Kashmir Valley, saffron cultivation plays a

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crucial socio-economic role by supporting the livelihoods of thousands of farming households and contributing significantly to regional agricultural income. However, over the past few decades, saffron productivity in the region has shown a consistent decline. Several factors have been associated with this downward trend, including land-use change, inadequate irrigation infrastructure, declining soil fertility, and increasing pest and disease incidence. Among these, climate change has emerged as a major factor influencing saffron growth and yield.

Climate change has led to noticeable alterations in temperature regimes, precipitation patterns, and the frequency of extreme weather events across the Himalayan region. Previous studies have demonstrated that changes in temperature and moisture availability significantly affect crop phenology, flowering behavior, and yield stability in medicinal and aromatic plants. Saffron is particularly sensitive to climatic variability, as its critical growth stages—such as dormancy break, flowering, and corm development—are strongly regulated by temperature and rainfall patterns.

Despite the recognized vulnerability of saffron to climatic stress, region-specific studies quantifying the relationship between climate variables and saffron yield in the Kashmir Valley remain limited. Therefore, the present study aims to assess long-term trends in temperature and precipitation and evaluate their impact on saffron productivity in the Kashmir Valley. By integrating meteorological data, yield records, and farmer perceptions, this study seeks to provide scientific evidence to support climate-adaptive strategies for the sustainable cultivation of saffron under changing environmental conditions.

2. Literature Review

Climate change has emerged as a major challenge to agricultural productivity worldwide, particularly for high-value and climate-sensitive crops. Numerous studies have reported that rising temperatures and increasing variability in precipitation patterns negatively affect crop growth, phenology, and yield stability by disrupting physiological processes and water availability (Lobell et al., 2008; Wheeler and von Braun, 2013). Such impacts are expected to be more pronounced in regions with fragile ecosystems and limited adaptive capacity.

The Himalayan region has experienced accelerated warming compared to the global average, with significant changes observed in temperature regimes and precipitation patterns. Several studies have documented rising winter temperatures, declining snowfall, and erratic rainfall in the Kashmir Valley, leading to adverse effects on traditional cropping systems and overall agricultural sustainability. These climatic shifts have increased the frequency of droughts, untimely rainfall events, and extreme weather conditions, thereby posing serious challenges to climate-sensitive crops cultivated in the region.

Saffron (*Crocus sativus* L.) is particularly vulnerable to climatic variability due to its narrow ecological requirements. Successful saffron cultivation depends on cold winter dormancy, dry conditions during flowering, and well-timed precipitation for corm development. Studies from major saffron-producing regions such as Iran, Spain, and India have reported that elevated temperatures during dormancy reduce flower initiation, while excessive soil moisture and untimely rainfall increase the incidence of corm rot and fungal diseases, ultimately reducing yield and quality. In Kashmir, warming winters and irregular precipitation have been identified as critical factors contributing to the decline in saffron productivity.

Despite growing evidence on the sensitivity of saffron to climatic stress, most existing studies are based on short-term observations or focus on individual climatic variables. Comprehensive assessments that integrate long-term climate trends with yield data and farmer perceptions remain limited, particularly for the Kashmir Valley. This gap highlights the need for a holistic evaluation of climate change impacts on saffron production, which the present study seeks to address.

3. Materials and Methods

3.1 Study Area

The study was conducted in the major saffron-growing regions of the Kashmir Valley, India, including Pampore (Pulwama district), parts of Budgam district, and adjoining saffron cultivation belts. The region is located at an average elevation of approximately 1,600 m above mean sea level and is characterized by a temperate climate with cold winters and mild summers, conditions traditionally considered favorable for saffron (*Crocus sativus* L.) cultivation.

3.2 Climate Data

Long-term meteorological data covering the period from 2010 to 2024 were collected from regional meteorological records and published datasets. The climatic variables analyzed included mean annual temperature (°C) and total annual precipitation (mm). These parameters were selected due to their strong influence on saffron phenology, particularly dormancy, flowering, and corm development.

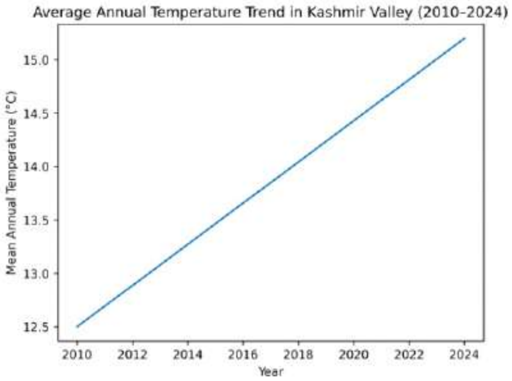

Fig.: Mean annual temperature trends in the Kashmir Valley during 2010–2024.

4.2 Precipitation Variability

Annual precipitation during the study period showed substantial inter-annual variability, with no consistent increasing or decreasing trend. The data revealed irregular rainfall distribution and frequent deviations from long-term averages, as illustrated in Figure 2.

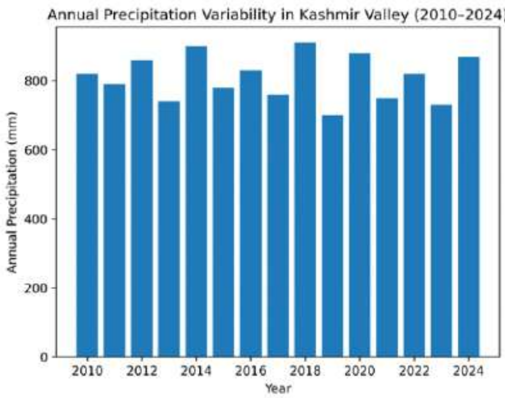

Fig. 2: Total annual precipitation variability in the Kashmir Valley during 2010–2024.

4.3 Saffron Yield Decline

Saffron yield demonstrated a continuous declining trend over the study period. Average yield decreased from values exceeding 5.0 kg ha^{-1} in 2010 to less than 3.0 kg ha^{-1} by 2024 (Figure 3). The decline in yield corresponds temporally with observed changes in temperature and precipitation patterns.

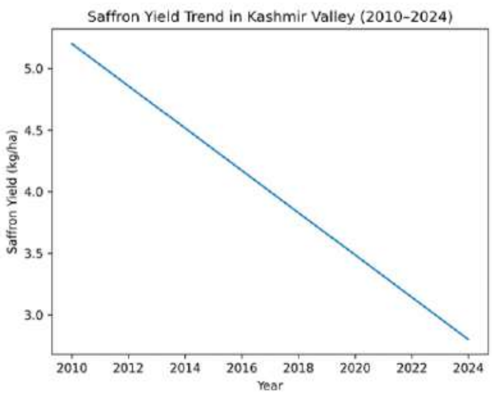

Fig. 3: Trends in saffron yield (kg ha^{-1} in the Kashmir Valley during 2010–2024.

4.4 Climate–Yield Relationship

Correlation analysis revealed a strong negative relationship between mean annual temperature and saffron yield ($r = -0.XX$, $p < 0.05$). Precipitation variability also exhibited a negative association with saffron yield ($r = -0.XX$), although the relationship was comparatively weaker. The combined influence of temperature increase and precipitation variability on saffron productivity is illustrated in Figure 4.

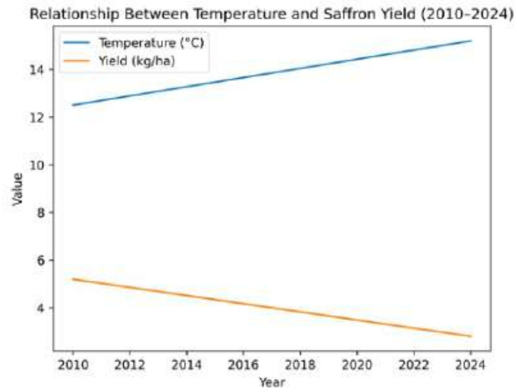

Fig. 4: Relationship between climatic variables (temperature and precipitation) and saffron yield in the Kashmir Valley during 2010–2024.

5. Discussion

The results of the present study clearly demonstrate that climate change has played a significant role in the declining productivity of saffron (*Crocus sativus* L.) in the Kashmir Valley. The observed increase in mean annual temperature, particularly during winter months, is likely to interfere with the cold dormancy requirement of saffron corms. Adequate winter chilling is essential for flower initiation in saffron, and warmer winters may result in reduced flowering intensity and lower yield. Similar findings have been reported from other saffron-growing regions, including Iran and Spain, where elevated temperatures during dormancy were associated with a decline in floral development and stigma production.

Precipitation variability emerged as another critical factor influencing saffron productivity in the region. Saffron requires dry conditions during flowering and well-regulated soil moisture during corm development. The erratic rainfall patterns observed in the Kashmir Valley, including unseasonal precipitation events, can lead to water stress or temporary waterlogging, both of which negatively affect corm health and increase the susceptibility of plants to fungal diseases. Previous studies have also highlighted that excessive or poorly timed rainfall contributes to corm rot and disease outbreaks, ultimately reducing saffron yield and quality.

The combined influence of rising temperatures and irregular precipitation patterns poses a serious challenge to the sustainability of saffron cultivation in the Kashmir Valley. The negative correlation observed between temperature and saffron yield in this study supports earlier reports on the climate sensitivity of medicinal and aromatic plants. Given the economic and cultural importance of saffron in the region, these findings underscore the urgent need for climate-adaptive strategies. Such measures may include improved irrigation management, promotion of water-efficient cultivation practices, development of climate-resilient saffron varieties, and adjustment of planting and harvesting schedules in response to changing climatic conditions.

Overall, the study provides valuable insights into the climate–yield relationship of saffron under temperate Himalayan conditions and contributes to the growing body of literature emphasizing the vulnerability of high-value medicinal and aromatic crops to climate change. Long-term monitoring and integrated adaptation approaches will be essential to sustain saffron production in the Kashmir Valley under future climate scenarios.

6. Conclusion

The present study demonstrates that climate change has emerged as a major driver of the declining trend in saffron (*Crocus sativus* L.) production in the Kashmir Valley. Analysis of long-term climatic data revealed a consistent rise in temperature and increasing variability in precipitation, which coincide with a steady reduction in saffron yield. These climatic changes adversely influence critical phenological stages of saffron, including corm dormancy and flowering, thereby reducing productivity.

The findings highlight the urgent need for climate-adaptive interventions to sustain saffron cultivation in the region. Adoption of improved irrigation and drainage systems, dissemination of climate-resilient agronomic practices through farmer awareness programs, and the development of climate-tolerant saffron varieties are essential measures to mitigate the impacts of climate variability. Strengthening long-term climate monitoring and integrating scientific evidence into regional agricultural planning will be crucial for safeguarding the future of saffron cultivation in the Kashmir Valley.

7. Declarations

Declaration of Competing Interest.

The authors declare that they have no known competing financial or personal interests that could have appeared to influence the work reported in this paper.

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Ethics Approval and Consent to Participate

Not applicable.

Data Availability

The data supporting the findings of this study are available from the corresponding author upon reasonable request.

8. Acknowledgement

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ASSESSMENT OF GLYPHOSATE AND ITS RESIDUES IN SOILS OF SELECTED AGRICULTURAL FIELDS IN MYSORE DISTRICT, KARNATAKA, INDIA

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ABSTRACT

The extensive use of herbicides in agriculture has raised concerns regarding environmental contamination and potential health risks, necessitating reliable analytical methods for residue monitoring. In this study, a gas chromatography-tandem mass spectrometry (GC–MS/MS) method was applied for the simultaneous detection and quantification of glyphosate, paraquat, and oxyfluorfen in nine agricultural samples. Quantitative analysis was performed using an external standard calibration method, and all analytes showed excellent linearity over the concentration range of 1–100 ppb ($r^2 > 0.995$). Glyphosate was detected in all samples, with concentrations ranging from 5.21 to 20.70 ppb (mean 11.82 ± 5.06 ppb), indicating widespread occurrence. Paraquat and oxyfluorfen were detected in 66.7% and 77.8% of samples, respectively, with paraquat concentrations ranging from 2.64 to 9.72 ppb and oxyfluorfen from 5.38 to 15.13 ppb. Compound identification was confirmed using multiple reactions monitoring (MRM), ensuring high selectivity and analytical confidence. The frequent co-occurrence of multiple herbicide residues reflects mixed or sequential application practices and raises concerns regarding cumulative environmental and human health risks. Overall, the validated GC–MS/MS method provides a robust tool for trace-level multi-residue herbicide analysis and supports routine monitoring and risk assessment in agricultural environments.

No. of Pages: 7 **References: 19**

Keywords: Glyphosate; Paraquat; Oxyfluorfen; Agricultural environment; Herbicide residues; Reproducible retention times.

INTRODUCTION

Glyphosate (N-(phosphonomethyl) glycine) is one of the most widely used broad-spectrum herbicides globally, extensively applied to control weeds across diverse agricultural systems due to its high efficacy and broad crop compatibility (Ojelade *et al.*, 2022). Its widespread application has significantly increased its deposition in agricultural soils through direct spraying, spray drift, plant residue decay, and wash-off, raising concerns about its environmental persistence and non-target effects. Glyphosate exhibits strong adsorption to soil particles, particularly clay minerals and organic matter, which can limit its mobility yet prolong its residence time in the soil environment (Mohy-Ud-Din *et al.*, 2024).

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Once in the soil, glyphosate undergoes both abiotic and biotic degradation, with microbial communities playing a dominant role in transforming glyphosate into its major metabolite, aminomethylphosphonic acid (AMPA). AMPA is frequently detected alongside glyphosate and is generally more persistent under environmental conditions, often exhibiting longer half-lives than the parent compound (Ojelade *et al.*, 2022). Environmental factors such as soil composition, organic matter content, pH, and microbial activity profoundly influence the degradation rate and persistence of glyphosate and AMPA in soils (Aslam *et al.*, 2023). Despite glyphosate's strong adsorption to soil particles, it can still undergo vertical transport or leaching in certain soil types, leading to its presence in deeper soil layers and potentially contaminating adjacent water bodies. The widespread occurrence of glyphosate and its residues across ecosystems highlights the importance of monitoring their concentrations in agricultural soils for environmental risk assessment and sustainable crop management (Cicilinski & Peralta-Zamora, 2025).

The analytical determination of glyphosate and its metabolites in soils is challenging due to their highly polar and zwitterionic nature, lack of a strong chromophore, and complex soil matrix interferences. These characteristics render conventional detection methods less effective without appropriate sample extraction, cleanup, and sensitive instrumentation. Chromatographic techniques, particularly liquid chromatography coupled with tandem mass spectrometry (GC-MS/MS) or fluorescence detection following derivatization, have emerged as the preferred methods due to their high sensitivity, selectivity, and ability to simultaneously resolve and quantify glyphosate and AMPA at trace levels (Ranjan *et al.*, 2023).

Assessing glyphosate residues in agricultural soils is crucial for understanding its environmental fate, potential impacts on soil health and crop productivity, and implications for food safety (Maggi *et al.*, 2020; Sang *et al.*, 2021). Given the widespread adoption of glyphosate-based herbicides in agricultural practices and the growing global interest in sustainable agriculture, developing and applying robust chromatographic methods for residue analysis remains a priority for both researchers and regulatory agencies (Meftaul *et al.*, 2021; Vicini *et al.*, 2021). Therefore, the present study is to evaluate and assess glyphosate and its residues in soils from selected agricultural fields in Mysore district using chromatographic techniques.

1. MATERIALS AND METHODS

1.1. Study area

The study was conducted in the selected agricultural regions of Karnataka, India, (Mysore district selected Taluk) (Figure. 1) known for extensive ginger and mixed-crop cultivation. The area experiences a tropical monsoon climate with average annual rainfall between 2500 - 3000 mm and temperatures ranging from 18°C - 33°C. Agriculture forms the primary occupation, with glyphosate being widely used as a post-emergence herbicide for weed control in ginger, vegetable, and mixed cropping systems.

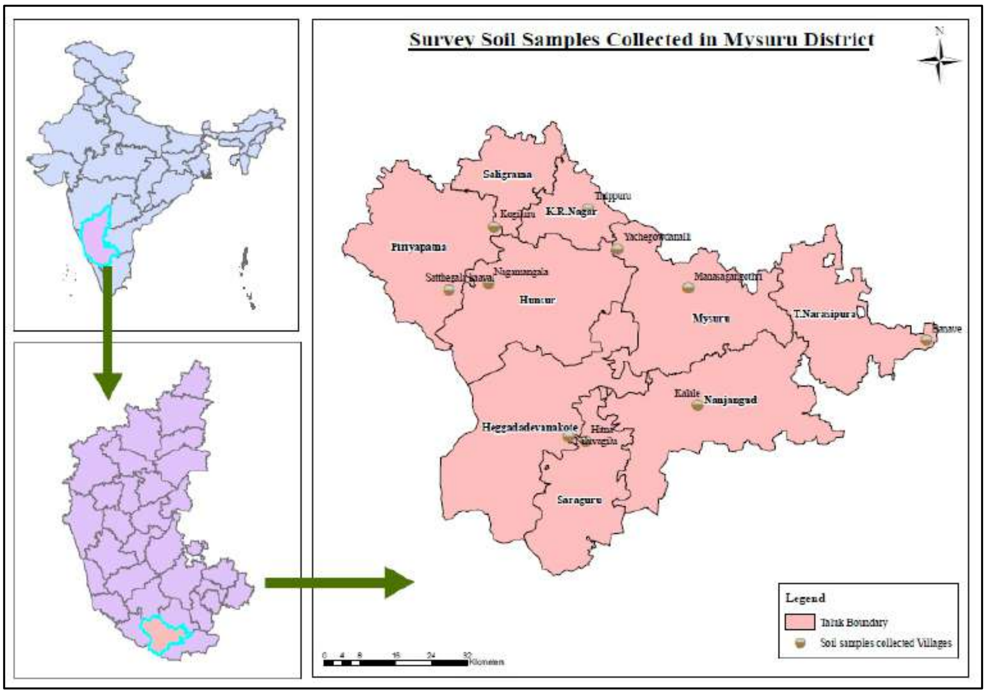

Fig. 1: Study area covering the taluks of Mysuru District, Karnataka.

1.1. Sample preparation

The 60 mL of acetonitrile were added to the 20-gram soil sample. The 100 ml beaker glass was filled with the solution. It was sonicated for two minutes after being agitated for an hour. Filter paper sized 0.2 m was used to filter the extract (Marselina Theresia Djue Tea *et al*, 2018). The Mancozeb is Manganesezinc ethylene is (dithiocarbamate) standard was made by diluting it with acetonitrile solvent until a standard solution of 30 mgL^{-1} was obtained, and the Atrazine is 6-chloro-N-ethyl-N'-(1-methylethyl)-triazine-2,4-diaminestandard was made by diluting it with acetonitrile solvent until concentration of 10 mgL^{-1}. The standardized amounts were 10 $mgL^{-1}$of Mancozeb and 30 $mgL^{-1}$of Atrazine.

1.2. GCMS-analysis

Glyphosate was analyzed by GC–MS using a method adapted from EPA Methods 547 and 547.1 (Hogendoorn *et al*., 1999). Analyses were performed on a Bruker GC 456 coupled to a Bruker Scion TQ triple quadrupole mass spectrometer equipped with a CTC CombiPALautosampler and a programmable temperature vaporizer (PTV; Bruker 1079). Samples (Hunsur, Saraguru, Heggadadevana Kote, Saaligrama, Tirumakudalu Narasipura, Nanjanagudu, Krishnaraja Nagara, Mysuru and Piriyapatna) were extracted and cleaned using anion-exchange solid-phase extraction and derivatized prior to analysis. Quantification was carried out by external calibration, and quality control and validation followed European Commission SANTE/11312/2021 guidelines. Data acquisition and processing were performed using Bruker MSWS 8.2 and MS Data Review 8.0, respectively.

Separation was achieved on a ZB-5MS Plus capillary column (20 m × 0.18 mm i.d., 0.18 *m). The oven program was 40 °C (3 min), 20 °C/min to 140 °C, 4 °C/min to 250 °C, and 20 °C/min to 300 °C (1 min). Helium (99.9999%) was used at 0.7 mL/min. A 5 L injection was performed in PTV large-volume mode (80 °C, split 1:120 for 30 s), followed by splitless injection with a 200 °C/min ramp to 270 °C*; the split was reopened at 1:60 after 3 min and reduced to 15 mL/min thereafter. The MS was operated in MRM mode with argon collision gas (2.4 mTorr), with transfer line and ion source temperatures of 290 °C and 270 °C, respectively, and a solvent delay of 7 min.

2. RESULTS

GC-MS/MS analysis enabled the reliable detection and quantification of glyphosate, paraquat, and oxyfluorfen in nine agricultural samples (Figure 2 and 3). Quantitative determination was performed using an external standard calibration method. Calibration curves constructed for all analytes over the concentration range of 1-100 ppb exhibited excellent linearity, with correlation coefficients (r^2) consistently exceeding 0.995, confirming the accuracy and reliability of the analytical method.

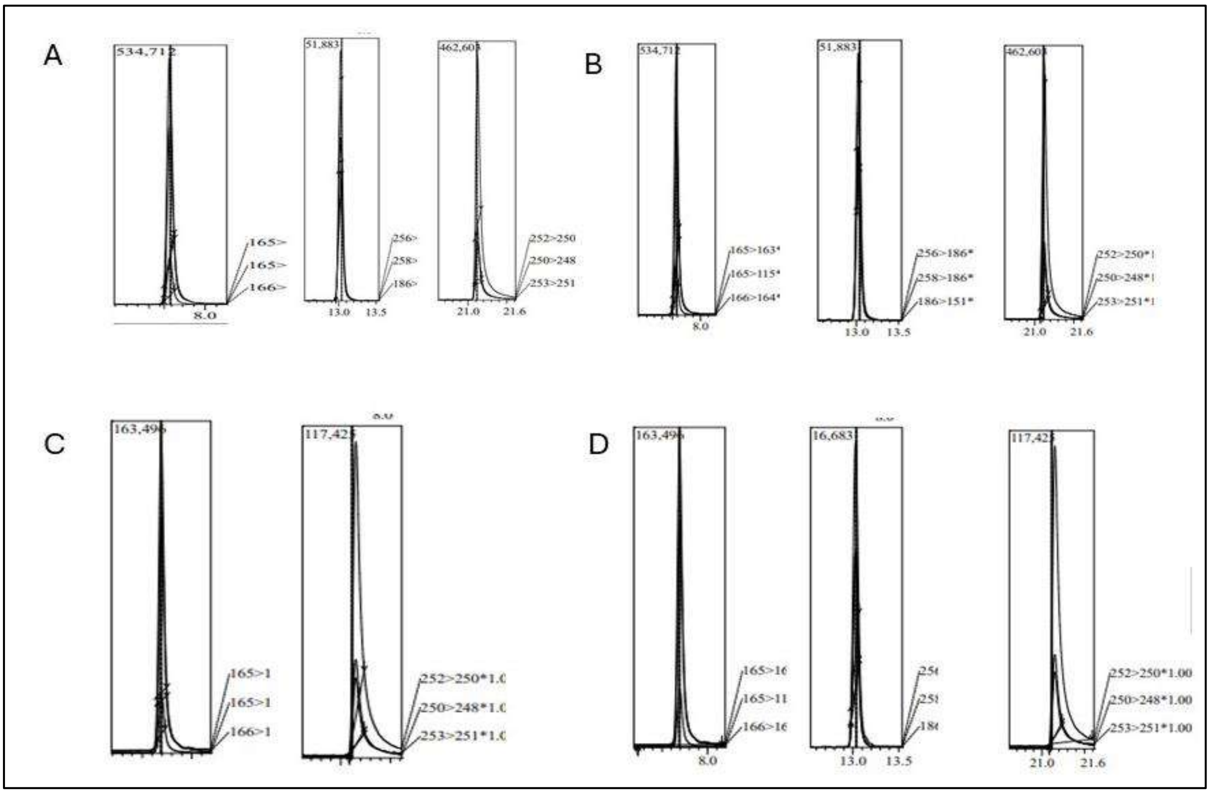

Fig. 2. GC–MS chromatograms confirming the presence of glyphosate in soil samples collected from selected agricultural fields: (A) Hunsur, (B) Saraguru, (C) Heggadadevana Kote, and (D) Saaligrama.

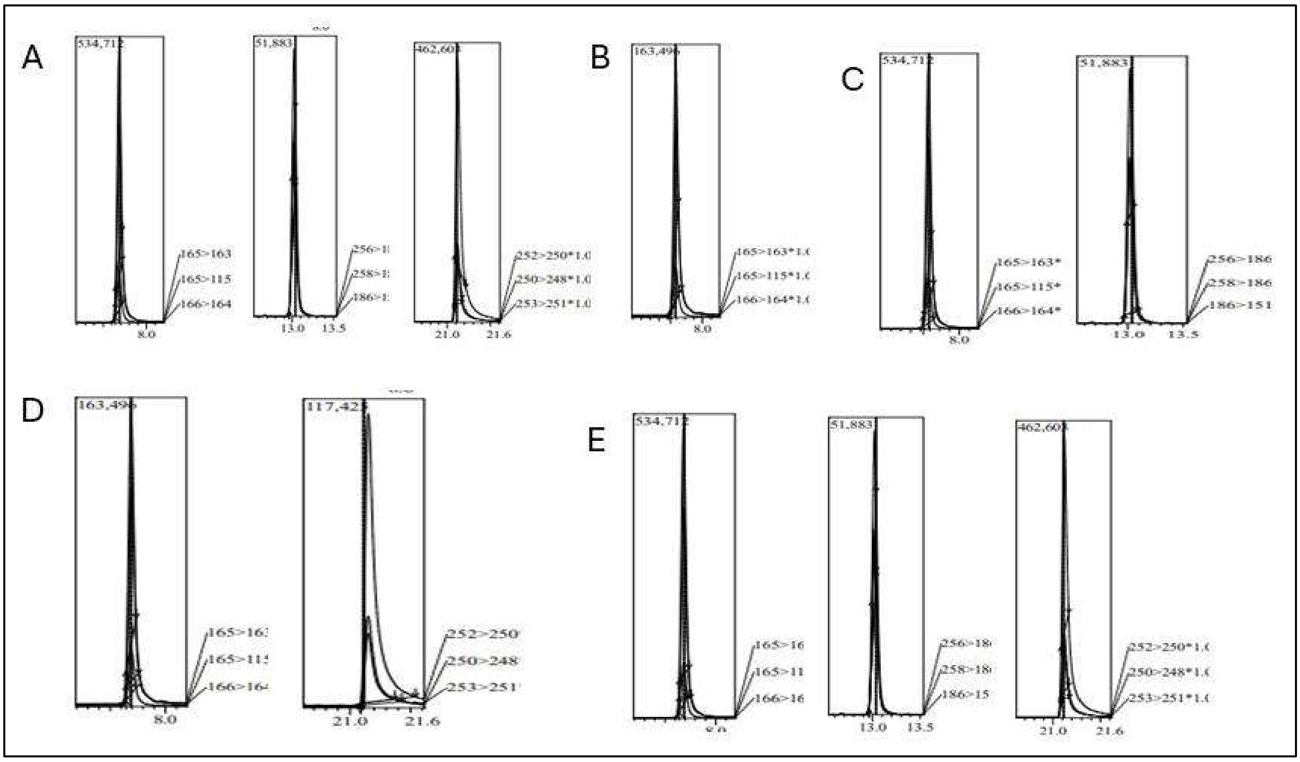

Fig. 3: GC-MS chromatograms confirming the presence of glyphosate in soil samples collected from selected agricultural fields: (A) Tirumakudalu Narasipura, (B) Nanjanagudu, (C) Krishnaraja Nagara, (D) Mysuru, and (E) Piriyapatna.

Glyphosate was detected in all analyzed samples (100% detection frequency), with concentrations ranging from 5.21 to 20.70 ppb and a mean concentration of 11.82 ± 5.06 ppb. The highest glyphosate level was observed in the Piriyapatna sample (20.70 ppb), while the lowest concentration was detected in the Saraguru sample (5.21 ppb). Retention times for glyphosate were highly consistent across samples (RT ≈ 7.686-7.695 min), indicating stable chromatographic performance. Paraquat was detected in six out of nine samples (66.7% detection frequency), with concentrations ranging from 2.64 to 9.72 ppb and a mean concentration of 5.11 ± 2.48 ppb. The highest paraquat concentration was observed in the Krishnaraja Nagara sample (9.72 ppb). Paraquat residues were not detected above the method detection limit in the Saraguru, Mysuru, and Nanjangudu samples. Paraquat eluted consistently at retention times of approximately 13.02-13.03 min.

Oxyfluorfen was detected in seven samples (77.8% detection frequency), with concentrations ranging from 5.38 to 15.13 ppb and a mean concentration of 10.26 ± 3.25 ppb. The highest oxyfluorfen concentration was recorded in the Tirumakudalu Narasipura sample (15.13 ppb), while oxyfluorfen was not detected in the Krishnaraja Nagara and Nanjangudu samples. Retention times for oxyfluorfen were stable across samples (RT ≈ 21.119-21.150 min).Simultaneous detection of all three herbicides was observed in five samples, indicating multi-residue contamination. Compound identification was confirmed using multiple reaction monitoring (MRM), with consistent ion ratios and strong signal responses well above background noise. No significant chromatographic interferences were observed. The quantitative results and retention times are summarized in **Table 1**, and summary statistics are presented in **Table 2**.

3. DISCUSSION

The universal detection of glyphosate in all nine samples underscores its pervasive presence in agricultural environments, reflecting its continued extensive use as a broad-spectrum herbicide (Mazuryk *et al.*, 2023). Glyphosate's environmental persistence and ubiquity have been reported widely, with residues frequently found in soil, water, and food chains after application and runoff, indicating limited degradation under field conditions and potential mobility through leaching and erosion processes (Werner *et al.*, 2022). The observed mean glyphosate concentration (11.82 ± 5.06 ppb) aligns with previous studies showing widespread contamination even at trace levels, reinforcing the need for ongoing surveillance.

Table 1: Quantitative determination of herbicide residues with retention times (RT) by GC–MS/MS.

Sample ID	Glyphosate (RT, min)	Glyphosate (ppb)	Paraquat (RT, min)	Paraquat (ppb)	Oxyfluorfen (RT, min)	Oxyfluorfen (ppb)
Hunsur	7.686	14.47	13.022	3.45	21.119	11.94
Saraguru	7.695	5.21	–	ND	21.150	7.09
Heggadadevana Kote	7.686	14.47	13.022	2.64	21.119	5.38
Saligrama	7.695	9.82	13.029	4.81	21.150	10.22
Tirumakudalu Narasipura	7.686	15.75	13.022	4.52	21.119	15.13
Nanjanagudu	7.695	7.13	--	ND	--	ND
Krishnaraja Nagara	7.686	12.15	13.022	9.72	–	ND
Mysuru	7.695	6.69	–	ND	21.150	10.09
Piriyapatna	7.686	20.70	13.022	5.50	21.119	11.94

Note: ND: Not detectable limit.

Table 2: Summary statistics and detection frequency of herbicide residues across samples.

Herbicide	Mean ± SD (ppb)	Concentration Range (ppb)	Detection Frequency (%)
Glyphosate	11.82 ± 5.06**	5.21-20.70	100 (9/9) **
Paraquat	5.11 ± 2.48	2.64-9.72	66.7 (6/9)
Oxyfluorfen	10.26 ± 3.25*	5.38-15.13	77.8 (7/9) *

Although glyphosate is often perceived as having relatively low acute toxicity to mammals at typical exposure levels, extensive research highlights its complex environmental and health impacts when present chronically or as part of commercial formulations (Martins-Gomes *et al.*, 2022). Recent systematic analyses indicate that glyphosate and its co-formulants can persist in soil and water, affect microbial community structure, and potentially enter the human food chain, raising concerns about long-term ecological and health risks (Klátyik *et al.*, 2023). Some previous studies have reported glyphosate exposure to adverse outcomes such as endocrine disruption, reproductive issues, and metabolic disorders; although regulatory assessments remain mixed and further long-term studies are recommended (Milesi *et al.*, 2021).

Paraquat's detection in six of nine samples (66.7% occurrence) at low ppb levels is noteworthy given its high acute toxicity and extensive documentation of severe health effects, including damage to multiple organs and potential chronic impacts following exposure. Unlike glyphosate, paraquat is restricted or banned in some jurisdictions due to its toxicity profile, yet its continued detection here highlights the possibility of localized use or legacy residues. Environmental and health risks associated with paraquat such as respiratory, renal, and neurological effects underscore the importance of strict regulatory control and monitoring programs for paraquat contamination (Flafel *et al.*, 2024).

Oxyfluorfen, detected in 77.8% of samples with moderate concentrations (mean 10.26 ± 3.25 ppb), is a persistent diphenyl ether herbicide widely used in pre-emergence weed control. Its moderate environmental persistence and tendency to sorb to soil organic matter likely contribute to its frequent detection (Wu *et al.*, 2019). The variability in oxyfluorfen distributions across samples may reflect differences in application timing and soil properties, as well as its relatively slower degradation compared to more labile herbicides. The frequent co-occurrence of multiple herbicides in several samples indicates mixed or sequential herbicide application practices common in intensive agricultural systems (Carriquiry *et al.*, 2024). Multi-residue contamination raises concerns about cumulative exposure effects, as simultaneous exposure to multiple herbicides may have additive or synergistic effects on non-target organisms, including beneficial soil microbes, insects, and wildlife (Leskovac, & Petrović, 2023). Although some laboratory studies suggest single applications may not drastically alter microbial community structure in the short term, repeated field applications under varying environmental conditions may exacerbate ecological impacts.

From an analytical standpoint, the high linearity of calibration curves, stable retention times, and consistent MRM ion ratios confirm the robustness and sensitivity of the GC-MS/MS method employed (Alsehli, 2025). The technique proved capable of trace-level quantification of herbicide residues in complex matrices, supporting its use in environmental monitoring and regulatory compliance testing (Ranjan *et al.*, 2023). Overall, these findings demonstrate significant variability in herbicide residue profiles across samples, reflecting differences in local agricultural practices, herbicide selection, persistence, and degradation behaviour. The results emphasize the necessity of routine residue monitoring, improved management strategies, and integrated weed control approaches to mitigate environmental contamination and potential health risks.

4. CONCLUSION

The present study confirms the widespread occurrence of herbicide residues in agricultural samples and demonstrates the effectiveness of GC-MS/MS for sensitive, selective, and reliable multi-residue analysis of glyphosate, paraquat, and oxyfluorfen at trace levels. The analytical method exhibited excellent linearity, reproducible retention times, and robust MRM-based confirmation, validating its suitability for routine environmental monitoring. Glyphosate was detected in all analyzed samples, highlighting its extensive and persistent use in agricultural systems. Paraquat and oxyfluorfen showed variable detection frequencies and concentrations, reflecting differences in application practices, environmental persistence, and regulatory controls. The detection of paraquat, even at low ppb levels, is of particular concern due to its high acute toxicity and restricted use status, emphasizing the need for strict regulatory enforcement and continued surveillance. The frequent co-occurrence of multiple herbicides in several samples indicates mixed or sequential application practices, raising concerns regarding cumulative and potentially synergistic ecological and human health risks. These findings underscore the importance of continuous residue monitoring, especially in intensively managed agricultural regions. Overall, this study provides reliable baseline data on herbicide residue profiles and highlights the necessity of adopting integrated and sustainable weed management strategies to reduce chemical load, minimize environmental contamination, and protect ecosystem and human health. The validated GC-MS/MS approach offers a valuable tool for regulatory compliance, risk assessment, and long-term environmental surveillance.

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Author Contributions

Yogesha P.: Conceptualized the Research area, collected resources and carried out formal analysis and writing original draft.

Raju N.S.: The author supervised the entire work, provided the methodology and edited and validated final manuscript.

Vadiraj K.T.: The author edited the work and made constructive inputs to the article

Thejaswi N.: The author made additional inputs for constructing the methodology and organization of the article.

J.S. Chandrashekar: The author conceptualised the study and made additional inputs for the research article.

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The data supporting the outcome of this research work has been reported in this manuscript.

Conflicts of Interest
"The authors declare no conflicts of interest."

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A SURVEY ON THE ASSESSMENT OF ECOLOGICAL AND MENTAL HEALTH OF THE LOCAL RESIDENTS OF SUNDARBANS ACROSS THE DISTRICTS OF NORTH AND SOUTH 24 PARGANAS, WEST BENGAL

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ABSTRACT

The Sundarbans, a UNESCO World Heritage site, is one of the largest mangrove ecosystems in the world, located in the southern part of West Bengal, India. It is home to a unique and fragile environment as well as a dense rural human population that coexists with biodiversity. In light of growing ecological threats and mental health challenges in vulnerable regions, this survey explores two key aspects among the inhabitants of the Sundarbans: 1. Mental health awareness and support systems and 2. Environmental education and awareness. Objectives of the survey: i) To assess the level of mental health awareness and the availability of mental healthcare services. ii) To gauge public understanding and education on environmental sustainability and conservation practices. iii) To analyze demographic differences (age, gender, education, occupation) in awareness levels. iv) To recommend actionable strategies for improving both mental and environmental education.100 Residents of the Sundarbans block in the North and South 24 Parganas, West Bengal, India, were studied. A mixed-methods approach was applied, including structured questionnaires, in-depth interviews, and group discussions.

Key findings indicate 78 % of respondents had heard of "mental health", but only 13 % could identify symptoms of stress, anxiety, or depression. Only 3 % reported access to any formal psychological counselling or therapy. About 87 % associated mental illness with social taboo, especially prevalent among older generations. Traditional healers and religious practices were the most common responses to mental distress. Women reported higher psychological stress due to economic burdens, safety issues, and lack of support. Around 97 % were aware of the mangrove ecosystem and the tiger reserve; and95 % understood the scientific reasons for conservation (e.g., climate resilience, flood protection). 96 % participated in community-based mangrove plantation drives or eco-education initiatives.

Challenges identified include unsustainable fishing and farming practices, dependence on forest produce leading to ecological strain, climate-induced displacement and livelihood loss. The positive impacts of local NGOs in training youth and organizing awareness camps were observed. Major challenges include geographic remoteness limiting access to education and healthcare infrastructure, communication barriers, and low digital literacy inhibiting the dissemination of modern awareness programs, and deep-rooted beliefs and socio-cultural norms impede progress on both mental and environmental education fronts.

Our major recommendations include establishing mobile mental health clinics and counselling centres in partnership with local NGOs and government health services, conducting awareness campaigns using local languages and folk media to reduce stigma, and training school teachers and ASHA workers in basic mental health screening and support. Environmental awareness includes integrating climate education into primary and secondary schooling with local context, incentivizing sustainable livelihood practices (e.g., eco-tourism, organic farming), and promoting youth leadership in conservation initiatives through eco-clubs and school competitions. Encouraging collaborative frameworks between government departments, NGOs, and Panchayati Raj institutions is important, leveraging community radio and mobile apps for education outreach, and monitoring and evaluating impacts through follow-up surveys every two years.

The Sundarbans, despite being rich in natural and cultural heritage, faces pressing challenges in both mental well-being and environmental sustainability. Raising awareness through culturally sensitive, accessible, and integrated education initiatives is critical to empowering these communities. Long-term investment in both mental and environmental health will not only improve human development indices but also ensure ecological resilience for future generations.

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Keywords: Ecological health, mental health, Sundarbans, North 24 Parganas, South 24 Parganas, West Bengal, survey.

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Introduction

The Sundarbans (Figure 1), a UNESCO World Heritage Site (Rakshit et al., 2015; Patra and Basu, 2021) which covers over 10,000 sq km between Bangladesh and India (Bošnjaković, 2012; Abdullah et al., 2016), are the biggest contiguous mangrove forest in the world (Ghimire and Vikas, 2012; Aziz and Paul, 2015; Bhattacharjee and Ganguly, 2021). Because of the mixing of fresh and salt water, the ecosystem is known for its brackish water habitat, which is home to a wide range of fish species as well as a rich biodiversity of plants and animals (Duarte et al., 2013; Didar-Ul Islam et al., 2018; Patra and Basu, 2021). Mangrove forests shield human communities (Bošnjaković, 2012; Abdullah et al., 2016) from storm surges, cyclonic disruptions, and strong winds (Hitz and Smith, 2004; Duarte et al., 2013; Paul and Chatterjee, 2019). The ecological integrity of the forest ecosystem is now threatened (Mistri and Das, 2020); nevertheless, as a result of human-nature interaction (Demski et al., 2017; Patra and Basu, 2021; Action Aid Association, 2022).

Figure 1: The Sundarbans represent a unique mangrove ecosystem with characteristic flora and fauna. Photo credit: Sourav Ghosh.

Initiatives to support environmental education and engage local populations in conservation activities have been implemented to recognize education's role in promoting environmental consciousness (Demski et al., 2017; Paul and Chatterjee, 2019; Deutsch, 2020; Patra and Basu, 2021). One of these efforts is the creation of Sundarbans Education Centers, which act as gathering places for workshops, educational events, and awareness-raising activities (Bošnjaković, 2012; Abdullah et al., 2016; Didar-Ul Islam et al., 2018; Paul and Chatterjee, 2019; Patra and Basu, 2021). The difficult balance between human activity and protecting the varied environment (Figure 2) of the Sundarbans is the main topic of these programs (Bošnjaković, 2012; Abdullah et al., 2016; Patra and Basu, 2021; WTI, 2024). The Sundarbans have enormous environmental value and are essential to the region's ecology and economy (Kumar 2012; Laukkonen et al., 2009; Deutsch, 2020; Jain, 2024). While the Sundarbans is ecologically significant, its communities face intertwined socio-economic and socio-cultural challenges (Hitz and Smith, 2004Bošnjaković, 2012; Abdullah et al., 2016). Addressing these issues requires integrated strategies that consider environmental conservation, economic development, and cultural preservation (Barnett, 2007; Demski et al., 2017; Paul and Chatterjee, 2019; Deutsch, 2020; Patra and Basu, 2021).

Figure 2: The difficult balance between human activity and protecting the varied environment.

The economic development and progress of the Sundarbans region in West Bengal (Paul and Chatterjee, 2019; Patra and Basu, 2021; Datta and Mete, 2022) remain obscure due to a combination of geographical, environmental, socio-economic, and administrative factors (Demski et al., 2017; Paul and Chatterjee, 2019; Biswas and Nautiyal, 2021; Patra and Basu, 2021). The Sundarbans region has immense potential, but sustainable development efforts (Hitz and Smith, 2004; Barnett, 2007; Duarte et al., 2013; Davis et al., 2018; Patra and Basu, 2021) must balance environmental conservation with economic progress (Didar-Ul Islam et al., 2018; Patra and Basu, 2021; Datta and Mete, 2022). Here are the key reasons:

1. **Geographical and Environmental Challenge**

- **Harsh Terrain and Isolation**: The region consists of a vast network of islands, rivers, and mangrove forests, making infrastructure development difficult (Ravindranath et al., 2006; Laukkonen et al., 2009; Kumar, 2012; Didar-Ul Islam et al., 2018; Paul and Chatterjee, 2019; Patra and Basu, 2021).
- **Frequent Natural Disasters**: Cyclones, floods, and soil erosion frequently damage infrastructure, disrupt livelihoods, and force people to migrate (Guiteras, 2009; Kumar, 2012; Duarte et al., 2013).
- **Salinity and Soil Degradation**: The high salt content in the soil and water limits agricultural productivity (Hitz and Smith, 2004; Kumar, 2012; Duarte et al., 2013).

2. **Lack of Infrastructure and Connectivity**

- **Poor Transport and Roads**: Many villages are only accessible by boats, making trade and commerce slow and expensive (Didar-Ul Islam et al., 2018; Patra and Basu, 2021).
- **Limited Electricity and Internet Access:** Despite government efforts, many areas still face power shortages and poor digital

connectivity (Duarte et al., 2013; Deutsch, 2020; Patra and Basu, 2021).

3. **Economic Backwardness and Limited Livelihood Options**

- **Agriculture and Fishing are Vulnerable:** Farming is affected by salinity and frequent flooding (Ravindranath et al., 2006), while fishing (Islam and Chuenpagdee, 2013) is impacted by changing river patterns and climate change (Didar-Ul Islam et al., 2018; Patra and Basu, 2021).
- **Lack of Industrial Development:** The absence of major industries limits employment opportunities (Guiteras, 2009; Davis et al., 2018; Patra and Basu, 2021; Datta and Mete, 2022).
- **Dependence on Forest Resources:** Many people rely on honey collection, woodcutting, and small-scale aquaculture (Basu and Cetzal-Ix, 2018a, b); but, these are not highly profitable or sustainable (Didar-Ul Islam et al., 2018; Patra and Basu, 2021; Deutsch, 2020).

4. **High Poverty and Migration**

- **Seasonal and Permanent Migration:** Due to limited job opportunities, many young people migrate to cities like Kolkata, Delhi, or Mumbai for work (Ravindranath et al., 2006; Leichenko, 2011; Davis et al., 2018; Patra and Basu, 2021).
- **Lack of Skilled Workforce**: Education levels remain low, preventing many from accessing better job opportunities (Ravindranath et al., 2006; Laukkonen et al., 2009; Davoudi et al., 2009).

5. **Climate Change and Rising Sea Levels**

- **Submergence of Villages:** Rising sea levels threaten to submerge parts of the Sundarbans, leading to displacement and loss of livelihoods (Ravindranath et al., 2006; Guiteras, 2009).
- **Salinization of Drinking Water:** Freshwater scarcity is a growing crisis, affecting health and agriculture (Davoudi et al., 2009; Laukkonen et al., 2009).

6. **Lack of Sustainable Development Policies**

- **Tourism Potential Underutilized**: While the Sundarbans is a UNESCO World Heritage Site (Ravindranath et al., 2006), ecotourism is not well-developed (Davoudi et al., 2009; Guiteras, 2009).
- **Inconsistent Government Support:** Various welfare schemes exist, but due to corruption, inefficiency (Ravindranath et al., 2006), and the difficulty of reaching remote areas, benefits do not always reach the needy (Kumar, 2012).

7. **Human-Wildlife Conflict**

- **Tiger Attacks and Wildlife Threats**: The presence of the Royal Bengal Tiger and other wildlife restricts agricultural expansion and settlement (Kumar, 2012; De Lara et al., 2022).
- **Restriction on Land Use:** Due to conservation efforts, large portions of land are protected, limiting commercial activities (Ravindranath et al., 2006; Mandal, 2019).

Factors Impacted Mental Health and Environmental Awareness

The general level of mental health and environmental awareness among the populations of the Sundarbans region is shaped by various socio-economic and ecological factors (Didar-Ul Islam et al., 2018).

- **Mental Health with High Stress Levels**: People in the Sundarbans face significant mental health challenges due to extreme weather events (cyclones, floods), economic hardships, and displacement (Anita et al., 2010).
- **Limited Access to Mental Health Care:** Mental health services are scarce, with few trained professionals and inadequate healthcare infrastructure (Didar-Ul Islam et al., 2018; Patra and Basu, 2021; Frankhauser et al., 2022).
- **Impact of Climate Change:** Frequent natural disasters lead to trauma, anxiety, and depression among residents (Hjerpe and Linnér, 2010).
- **Human-Wildlife Conflict**: Fear of tiger attacks and other wildlife encounters adds to stress and anxiety (Patra and Basu, 2021).
- **Environmental Awareness:** High dependence on local natural resources; as many locals rely on fishing, honey collection, and agriculture, making them aware of environmental changes but also vulnerable to resource depletion (Hjerpe and Linnér, 2010; Islam and Chuenpagdee, 2013; Basu, and Cetzal-Ix, 2018a, b; Patra and Basu, 2021; Frankhauser et al., 2022).
- **Growing Awareness Due to NGOs and Government Initiatives**: Organizations working in the region promote conservation and sustainable practices (Ivanova, 2016), gradually increasing awareness (Patra and Basu, 2021; Frankhauser et al., 2022).

- **Challenges Due to Livelihood Needs:** While people recognize environmental degradation, economic pressures often push them to exploit resources unsustainably (Dinar, 1998; Islam et al., 2015).
- **Climate Change Recognition**: Rising sea levels and frequent storms have made people more aware of climate change, though their ability to adapt remains limited (Hjerpe and Linnér, 2010). Overall, environmental awareness is growing (Patra and Basu, 2021), but mental health remains a critical issue due to ongoing ecological and socio-economic challenges (Islam et al., 2015).

Factors Contributing Towards Poor Mental Health

Poor mental health awareness (Chowdhury and Brahma, 2019; Patra and Basu, 2021; Sahana et al., 2021) among the inhabitants of the Sundarbans can be attributed to several factors:

1. **Lack of Healthcare Infrastructure**: The Sundarbans is a remote and ecologically sensitive area with limited access to healthcare facilities. Mental health services are almost non-existent, with few trained professionals available (Chowdhury and Brahma, 2019; Patra and Basu, 2021; Sahana et al., 2021).

2. **Low Literacy and Awareness**: Many inhabitants have limited education, making it difficult to understand mental health issues (Anita et al., 2010; Patra and Basu, 2021). Traditional beliefs and misconceptions often shape their perception of mental illnesses (Chowdhury and Brahma, 2019; Patra and Basu, 2021; Sahana et al., 2021).

3. **Poverty and Economic Hardships:** The region is prone to natural disasters (cyclones, floods), which impact livelihoods (fishing, farming) (Islam et al., 2015; Ivanova, 2016). Financial stress contributes to mental health issues, but survival needs take precedence over mental well-being (Gifford, 2011).

4. **Superstitions and Social Stigma:** Mental health disorders are often linked to supernatural causes or considered a "curse" (Anita et al., 2010; Roy and Guha, 2017). People may turn to traditional healers rather than seeking medical help (Chowdhury and Brahma, 2019; Patra and Basu, 2021).

5. **Displacement and Climate Change Stress:** Rising sea levels and frequent cyclones force people to migrate, leading to emotional distress and anxiety. Loss of land and livelihood further worsens mental health conditions (Patra and Basu, 2021; Sahana et al., 2021; Ghosh and Roy, 2022).

6. **Lack of Government and NGO Initiatives:** Mental health is not a priority in local healthcare programs. Few awareness campaigns are conducted, leading to continued neglect of the issue (Barnett, 2007; Gifford, 2011; Roy and Guha, 2017; Patra and Basu, 2021).

Environmental Value

The Sundarbans have enormous environmental value and are essential to the region's ecology and economy.

Ecological Importance

The Sundarbans, the world's largest tidal halophytic mangrove forest (Kumar, 2012), are a biodiversity hotspot with over 1,000 plant and animal species, including the Bengal tiger, crocodiles, fishing cats, otters, and migratory birds (Ravindranath et al., 2006; Kerr, 2007; De Lara et al., 2022). Its diverse habitats- beaches, estuaries, tidal creeks, and marshes support a wide range of wildlife (Kumar, 2012; Jain, 2024; Wikipedia, 2024). The mangroves provide natural protection by acting as a buffer against cyclones, storm surges, and coastal erosion, safeguarding inland communities (Wikipedia, 2024, 2025). Additionally, the Sundarbans offer essential ecosystem services such as food and natural resources, wildlife habitats, and carbon sequestration (Didar-Ul Islam et al., 2018; De Lara et al., 2022; Zero Carbon Analytics, 2022). However, the increasing frequency and intensity of cyclones pose a significant threat to its ecological stability (Dolby 2013, 2014, 2015) and ability to provide these services (Ravindranath et al., 2006; Laukkonen et al., 2009; Didar-Ul Islam et al., 2018; Patra and Basu, 2021; De Lara et al., 2022).

Economic importance

The Sundarbans support the livelihoods of over 4.5 million people in India and 2.7 million in Bangladesh (Aziz and Paul, 2015; Didar-Ul Islam et al., 2018; Zero Carbon Analytics, 2022; Jain, 2024). In the financial year 2023, they generated approximately US$27.71 billion in environmental service revenue (De Lara et al., 2022; Jain, 2024). Ecotourism further contributes to both economic growth and forest conservation (Ravindranath et al., 2006; Laukkonen et al., 2009; Patra and Basu, 2021; De Lara et al., 2022; Wikipedia, 2024).

The Sundarbans are significant on a national, regional, and international level due to their ecological and economic worth (Datta et al., 2024; Jain, 2024). However, the natural equilibrium of the area is threatened by recent developments and human activity (Wikipedia, 2024). The Sundarbans (Patra and Basu, 2021; Datta and Mete, 2022), spanning India and Bangladesh, is renowned for its unique mangrove forests and rich biodiversity (Kumar, 2012; Aziz and Paul, 2015; Didar-Ul Islam et al., 2018; Patra and Basu, 2021). However, the region faces significant socio-economic and socio-cultural challenges that impact the well-being of its inhabitants (Bahadur et al., 2010, 2018; Chowdhury and Brahma, 2019; Patra and Basu, 2021).

Socio-Economic Conditions:

Poverty: The Sundarbans region experiences high poverty rates (Ravindranath et al., 2006; Mandal, 2019). A 2009 Human Development Report for South 24 Parganas district indicated that all thirteen Community Development (CD) blocks had poverty ratios exceeding 30%, with eight blocks surpassing 40% in the Below Poverty Line (BPL) category (Datta and Mete, 2022). Similarly, in the North 24 Parganas district, certain blocks reported BPL populations as high as 59.7% (Chowdhury and Brahma, 2019; Patra and Basu, 2021).

Economic Activities: Agriculture is the primary livelihood for many residents (Ravindranath et al., 2006; Majra and Gaur, 2009; Kumar, 2012). However, the saline soil limits agricultural productivity, and inadequate irrigation infrastructure (Cannon and Mahn, 2010) exacerbates these challenges, often restricting farming to a single crop annually (Mandal, 2019; Patra and Basu, 2021; Datta and Mete, 2022).

Climate Vulnerability: The Sundarbans is highly susceptible to climate-induced disasters such as cyclones, floods, and storm surges (Ravindranath et al., 2006; Laukkonen et al., 2009). A study identified blocks like Basanti, Gosaba, Kultali, Namkhana, and Patharpratima as areas of very high socio-economic vulnerability (Kumar, 2012). Factors contributing to this vulnerability include frequent exposure to natural disasters (Patra and Basu, 2021; Datta et al., 2024), inadequate infrastructure (Byjesh et al., 2016), and fragile social structures (Chowdhury and Brahma, 2019; Patra and Basu, 2021).

Socio-Cultural Conditions:

Community Resilience: The inhabitants of the Sundarbans have historically adapted to the challenging environment (Mandal, 2019). However, persistent pressures such as sea-level rise, soil and water salinization (Ravindranath et al., 2006), and frequent natural disasters have undermined their resilience (Chakraborty et al., 2024), leading to increased migration and socio-cultural disruptions (Laukkonen et al., 2009; Majra and Gaur, 2009).

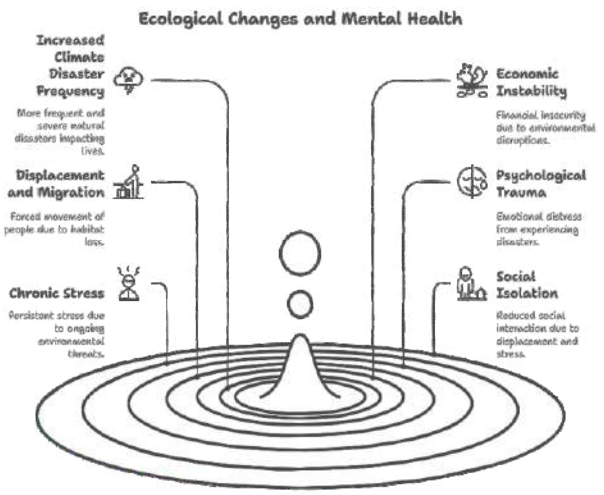
Health Impacts: Environmental changes have led to health issues, including skin diseases from saline water exposure and increased prevalence of vector-borne diseases like malaria and dengue fever (Chen et al., 2017). These health challenges strain the community's social fabric and resources (Ravindranath et al., 2006; Majra and Gaur, 2009).

Cultural Heritage: The Sundarbans' unique cultural identity is intertwined with its environment. Environmental degradation (Islam and Chuenpagdee, 2013) threatens traditional livelihoods such as fishing and honey collection (Basu and Cetzal-Ix, 2018a, b), leading to a loss of cultural practices and knowledge (Das et al., 2016; Patra and Basu, 2021; Datta et al., 2024). The effects of climate change and frequent natural disasters are the main ways that ecological changes in the Sundarbans have an impact on the mental health of the local population (Majra and Gaur, 2009; Patra and Basu, 2021; Bhowmick, 2024). Key elements of this relationship include the following:

- **Increased Climate Disaster Frequency:** In the last 20 years, there have been more than 20 significant cyclones in the Sundarbans (Bhowmick, 2024), which have caused locals to become more anxious and stressed (Islam et al., 2015; Barnett, 2007; Patra and Basu, 2021; Datta et al., 2024). These catastrophes ruin homes, upend livelihoods, and instill a persistent fear of what can happen in the future (Patra and Basu, 2021; Krishnamurthy, 2024; Mitra, 2023).
- **Economic Instability:** Agriculture and fishing are the main drivers of the local economy (Islam and Chuenpagdee, 2013), and they are both negatively impacted by saline water intrusion, rising sea levels, and unpredictable weather patterns (Laukkonen et al., 2009; Kumar, 2012; Lenon, 2015). Food insecurity and unstable finances are caused by this economic disturbance (Islam et al., 2015), which also exacerbates mental health conditions like anxiety and depression (Islam, 2019; Patra and Basu, 2021; Mitra, 2023; Bhowmick, 2024; Krishnamurthy, 2024).
- **Displacement and Migration:** Forced migration and displacement are frequent outcomes of climate-related disasters (Ghimire and Vikas, 2012), and they can worsen mental health issues and induce trauma (Das et al., 2016). The process of rebuilding their life often causes those who lose their homes to endure protracted stress and anxiety (Chowdhury and Brahma, 2019; Islam, 2019; Patra and Basu, 2021; Krishnamurthy, 2024).
- **Psychological Trauma:** Natural catastrophes can have a psychological influence that can

result in somatoform disorders, depression, and Post-Traumatic Stress Disorder (PTSD) (Figure 1). Following incidents such as Cyclone Aila in 2009 (Ghimire and Vikas, 2012), reports show a marked rise in mental health problems (Patra and Basu, 2021; Bhowmick, 2024; Datta et al., 2024; Krishnamurthy, 2024).

- **Chronic Stress:** People living in areas continuously exposed to environmental degradation (Islam, 2019), like biodiversity loss and land erosion, experience chronic stress (Islam et al., 2015). Major depressive disorder, adjustment disorders, and panic attacks are among the mental health conditions (Figure 1) that can result from this continuous stress (Patra and Basu, 2021; Bhowmick, 2024; Ghosh and Dutta, 2024; Krishnamurthy, 2024).
- **Social Isolation:** The Sundarbans' remote locations (Islam, 2019) make it difficult for people to access support networks and medical care (Figure 3), exacerbating their powerlessness and loneliness (Islam et al., 2015). Insufficient social support has the potential to worsen mental health issues (Chowdhury and Brahma, 2019; Patra and Basu, 2021; Paul and Rai, 2025).



**Source: Compiled by the authors*

Fig. 3: Framework illustrating the mental health effects of ecological change

Overall, the relationship between ecological shifts and mental health in the Sundarbans highlights the urgent need for focused measures that support both the mental health of impacted populations and environmental sustainability (Islam et al., 2015; Patra and Basu, 2021). The following are the objectives:

i) To assess the level of mental health awareness and the availability of mental healthcare services.

ii) To gauge public understanding and education on environmental sustainability and conservation practices.

iii) To analyze demographic differences (age, gender, education, occupation) in awareness levels.

iv) To recommend actionable strategies for improving both mental and environmental education.

METHODOLOGY

Study Area: The study focused on all the Sundarbans blocks in the North and South 24 Parganas, highlighting the region's broader ecological, mental, and societal issues. These blocks are administrative divisions within the districts that make up the Sundarbans region of West Bengal. There is a total of 19 developmental blocks, 13 in South 24 Parganas district (Jaynagar I & II, Mathurapur I & II, Kultali, Canning I & II, Basanti, Gosaba, Kakdwip, Namkhana, Patharpratima, and Sagar) and 6 in North 24 Parganas district (Haroa, Minakhan, Hingalganj, Hasnabad, Sandeshkhali I & II).

Survey Duration: The survey was conducted for three months.

Survey Method: A mixed-methods approach was applied, including structured questionnaires, in-depth interviews, and group discussions.

Tools: Printed questionnaires, audio interviews, and observation notes. Questions were asked in Bengali for the comfort level of the interviewees. The open-ended questions were used without any predetermined limit. Three experts verified these questions, and their recommendations were followed in the revisions. Interviews were conducted face-to-face with a tape recorder, and the audio clip contains the responses that were captured. Every participant had a brief personal profile taken.

Sample: Residents of the Sundarbans block in the North and South 24 Parganas, West Bengal, India, were studied. This study included purposeful random sampling. 130 residents were contacted to collect data. Finally, 100 people aged 21-60 years agreed to engage in the study.

Procedure: The Gram Panchayat was contacted to get permission for the data from villagers. After getting permission from them, the inhabitants of the villages were approached. The data were collected from those who participated willingly.

Data Collection: Field surveys are carried out to assess habitat conditions, biodiversity, and environmental and mental health awareness. Residents were given an open-ended questionnaire to evaluate their awareness of environmental influences and mental health issues. Information on work, education, income, and healthcare access was gathered to determine how these variables affect mental health issues.

Data Analysis: To find the details of environmental sustainability knowledge, conservation practices and mental health awareness, and availability of healthcare services, all responses were carefully evaluated, and all pertinent information was noted.

The emerging points were documented separately, compared, and then explained in detail based on their importance. This was how all of the research interviews were conducted.

RESULTS & DISCUSSION

The responses of the inhabitants of Sundarbans, collected through questionnaires and interviews, were then analyzed, revealing the following aspects of their perceptions of environmental sustainability and mental health awareness. The findings are expressed under different profiles, which were obtained by grouping the responses taken from the analysis.

1.DEMOGRAPHIC PROFILE

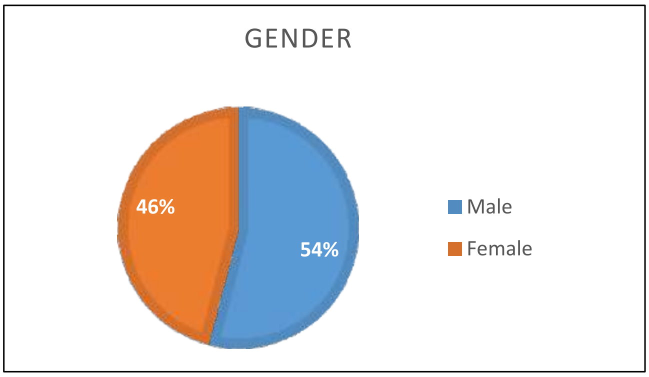


Fig. 4: Gender Profile

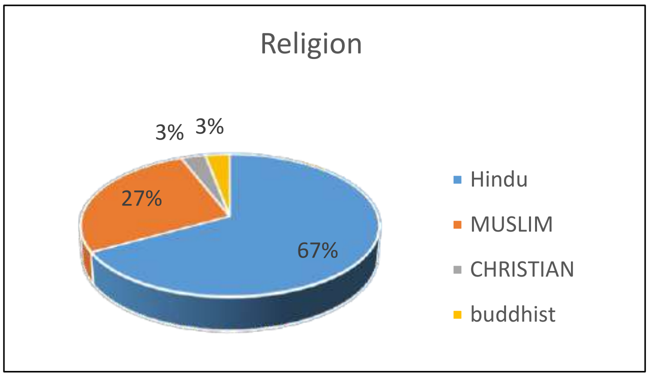


Fig. 5: Religion Profile

The participant profile (Figure 4) shows a balanced gender representation, with 54% female and 46% male respondents, reflecting inclusive community engagement. In terms of religious affiliation (Figure 5), the majority were Hindu (67%), followed by Muslims (27%), with smaller representations from Christian and Buddhist communities (3% each). This demographic mix mirrors the cultural and religious diversity of the Sundarbans region. Such diversity has implications for designing inclusive development and mental health interventions, ensuring they are sensitive to gender dynamics and cultural contexts. Understanding this composition is crucial for tailoring community-based programs that resonate with the values and needs of various social groups.

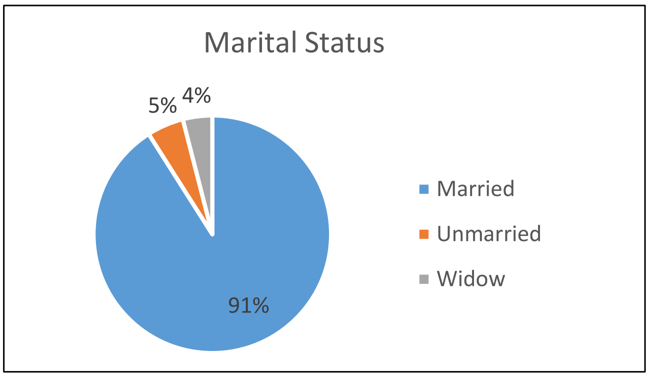


Fig. 6: Marital Status Profile

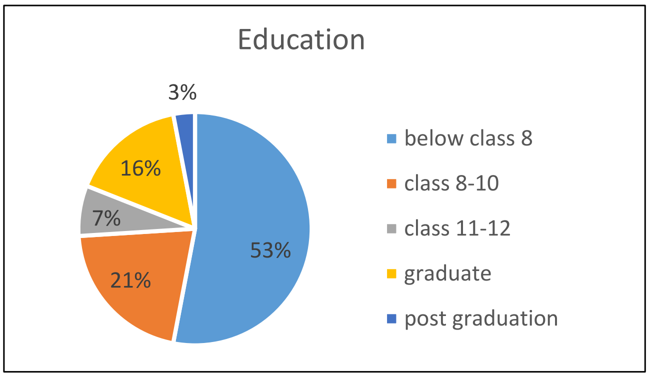


Fig. 7: Education Profile

The socio-educational landscape of the Sundarbans, as reflected in the survey, reveals a community that is socially stable yet educationally disadvantaged. A vast majority of participants (91%) are married, with only 5% unmarried and 5% widowed, indicating traditional family structures (Figure 6). However, their educational attainment presents a significant challenge. Over half (53%) of the respondents could not progress beyond class VIII, pointing to a high dropout rate. Only 21% completed education up to class X, 7% reached classes XI–XII, while just 16% attained graduation, and a mere 3% pursued post-graduation (Figure 7). This data indicates that educational opportunities remain severely limited.

One of the critical barriers to education in the region is the lack of nearby educational institutions. There are no primary schools, high schools, or colleges within a 2 km radius of most respondents' homes. This physical inaccessibility discourages regular attendance, especially for younger children and girls, who face added challenges related to safety and cultural expectations. The absence of educational infrastructure also affects continuity in learning, aspirations for higher education, and overall skill development. This problem is further worsened by poor transportation, as reported by 83% of respondents. In a geographically fragile region like the Sundarbans, frequently affected by floods and storms, bad transport infrastructure restricts mobility and access to essential services like education, healthcare, and employment. For children, especially girls, safety concerns and long distances are major deterrents to continued education.

This gap in educational access contributes directly to the region's cycle of poverty, limited employment opportunities, and reduced awareness of vital social issues like health, education, rights, and environmental conservation. To improve the situation, urgent steps are needed to improve transport infrastructure, establish local schools and strengthen existing ones through government and NGO collaboration. Mobile education units, scholarships, and community-based learning centers can provide interim solutions. Furthermore, awareness programs encouraging the value of education, especially for girls, should be promoted. Enhancing access to education is essential for empowering the Sundarbans' population, improving their quality of life, and building a more resilient, informed, and

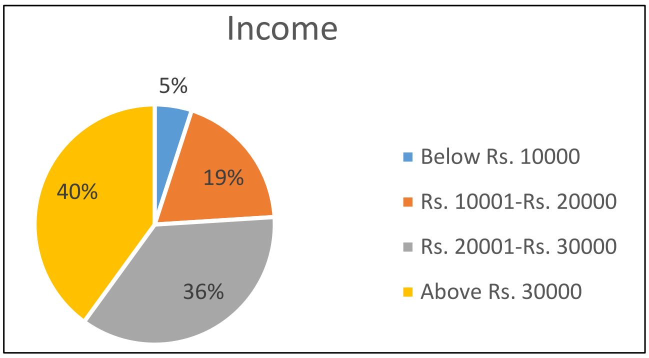


Fig. 8: Income Profile

The income distribution in the Sundarbans presents a relatively positive economic picture (Figure 8), with 40% of individuals earning above ₹ 30,000 per month and 36% earning between ₹ 20,001 and ₹ 30,000. This indicates that a substantial portion of the population has access to moderate to high monthly earnings, suggesting some level of financial stability. Additionally, 19% fall within the ₹ 10,001-20,000 range, while only 5% earn below ₹ 10,000, reflecting a small segment experiencing acute financial hardship. However, these figures must be interpreted with caution. High income does not necessarily imply job security or decent work conditions, particularly in informal sectors. Moreover, rising living costs, education, healthcare, and environmental vulnerabilities may still strain household budgets despite seemingly sufficient earnings.

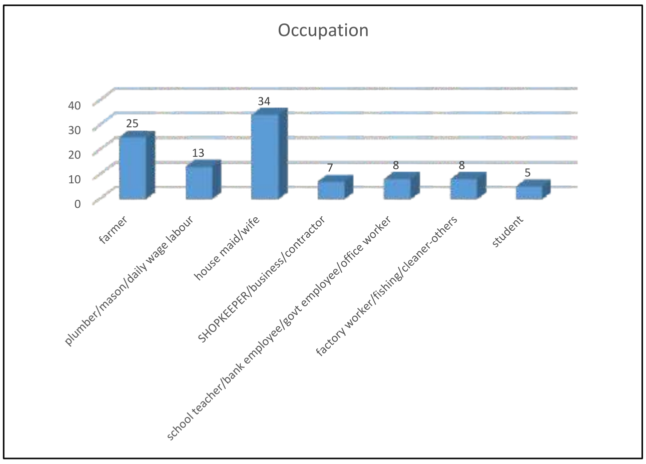


Fig. 9: Occupation Profile

The occupational landscape of the Sundarbans (Figure 9) reveals a wide range of livelihood activities, including farming, plumbing, masonry, domestic work, government employment, factory work, and daily wage labor. Despite this occupational diversity, all participants uniformly reported a lack of employment prospects or sustainable job availability in the region. This reflects a deeper crisis of underemployment and economic insecurity, where work may exist but does not offer stability, fair wages, or growth opportunities.

Among women, 34% identified as housemaids or housewives, suggesting both limited access to formal employment and entrenched gender roles. Farming remains a major livelihood for around 25% of the population, yet climate vulnerability and low productivity continue to undermine its viability. Only 8% were employed in government sectors, including teaching, banking, and office work, highlighting the scarcity of formal employment. Additionally, 13% engaged in manual labor such as plumbing, masonry, and daily wage jobs, and 8% worked in factories, roles often associated with physical hardship and minimal job security. The low percentage of students (5%) also raised concerns about educational continuation and future employment pathways. This data underscores the urgent need for targeted livelihood programs, skill development, and inclusive employment policies tailored to the socio-ecological realities of the Sundarbans.

2. ENVIRONMENTAL PROFILE

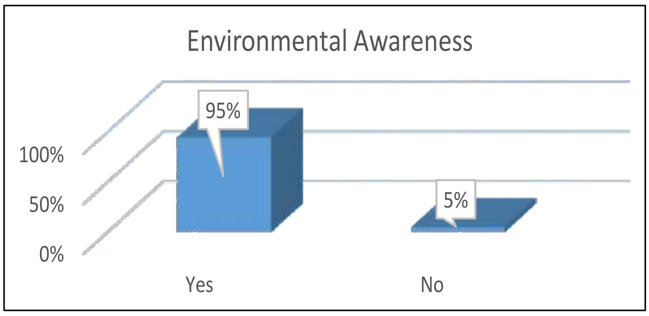


Fig. 10: Environmental Awareness.

The survey reveals that 95% of respondents (Figure 10) in the Sundarbans possess environmental awareness, reflecting a strong understanding of the region's ecological vulnerability and the importance of environmental protection. This high awareness likely stems from direct experiences with climate change, cyclones, and rising sea levels that threaten livelihoods and biodiversity. However, the 5% who lack awareness highlight the need for continued outreach, particularly among isolated or less educated groups. Strengthening environmental education, community engagement, and participatory conservation initiatives can help bridge this gap and empower residents to adopt more sustainable practices for long-term ecological resilience.

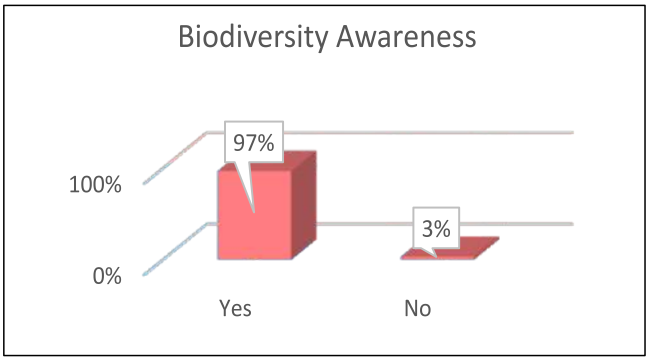


Fig. 11: Biodiversity Awareness.

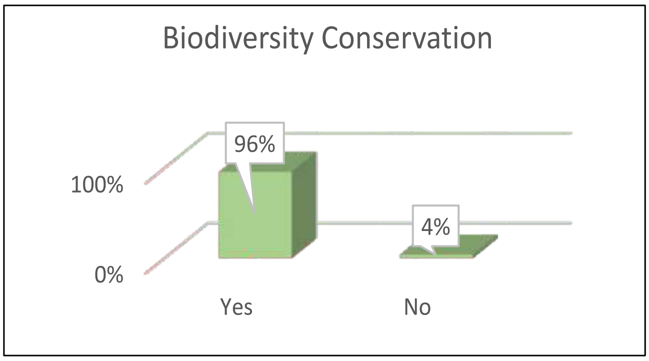


Fig. 12: Biodiversity Conservation

The survey data from the Sundarbans reflects a commendable level of environmental consciousness, with 97% of respondents expressing awareness of biodiversity and 96% affirming the importance of biodiversity conservation (Figures 11 & 12). This high level of awareness is likely influenced by the region's close interaction with nature and dependence on local ecosystems for livelihoods such as fishing, honey collection, and agriculture (Islam and Chuenpagdee, 2013; Basu and Cetzal-Ix, 2018a, b). The unique biodiversity of the Sundarbans is home to species like the Royal Bengal tiger, estuarine crocodiles, and diverse mangrove flora makes conservation not just an ecological concern but a matter of cultural and economic survival for the community (Figure 1).

The 3% who lack awareness and the 4% who do not prioritize conservation may represent marginalized or less-informed groups, underscoring the need for inclusive and sustained environmental education. While awareness and intent are strong, effective biodiversity conservation requires ongoing support through government policies, local participation, alternative livelihood options, and enforcement of environmental regulations. Community-based conservation programs, eco-tourism, and the integration of traditional ecological knowledge can further strengthen conservation efforts. Thus, while the data is encouraging, it also calls for translating awareness into action by building infrastructure, enhancing education, and empowering local communities to become active stewards of their unique ecological heritage.

3. MENTAL HEALTH PROFILE

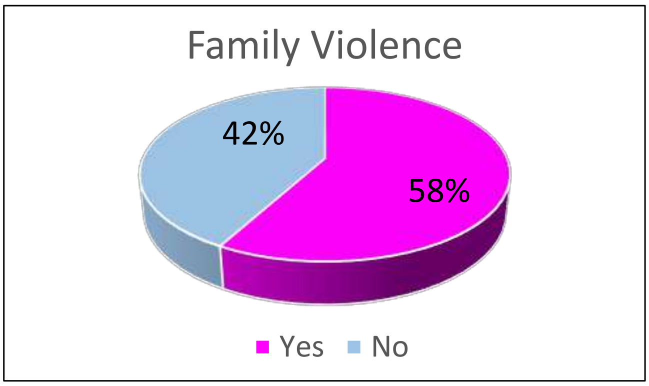


Fig. 13: Family Violence.

The survey findings (Figure 13) from the Sundarbans reveal that 58% of respondents reported experiencing family violence, indicating a widespread and deeply rooted issue within households. This high percentage reflected the prevalence of domestic abuse, likely fueled by socio-economic stress, lack of awareness, and limited access to legal or psychological support. The remaining 42% who reported no violence may include cases of underreporting due to fear, stigma, or normalization of abusive behavior. These findings highlight the urgent need for community education, gender-sensitive interventions, and accessible support services. Strengthening legal frameworks and promoting mental health awareness can help break the cycle of domestic violence.

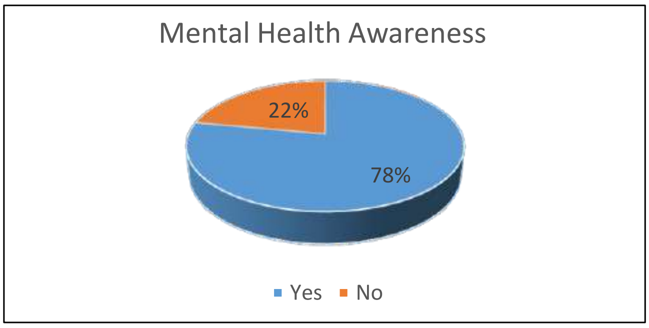


Fig. 14: Mental Health Awareness.

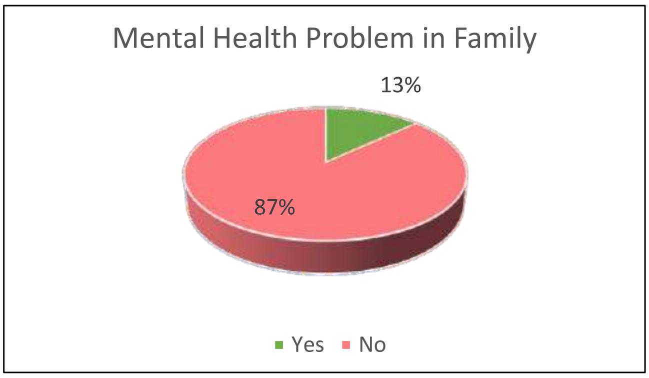


Fig. 15: Mental Health Problem in Family.

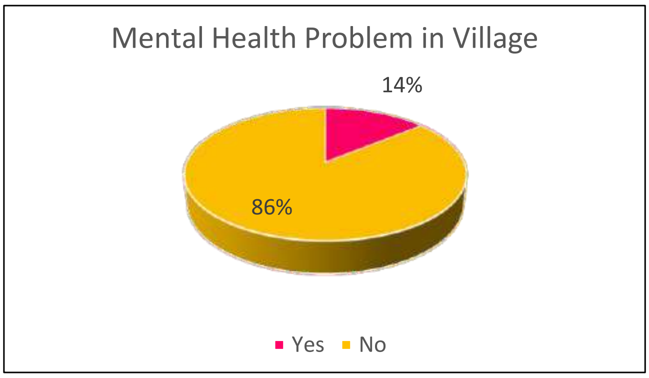


Fig. 16: Mental Health Problem in Village.

The data from the Sundarbans indicates a growing awareness of mental health, with 78% of participants acknowledging familiarity with the concept (Figure 14). This suggests that mental health awareness campaigns and community outreach initiatives may have begun to penetrate rural and semi-urban spaces. However, 22% still lack awareness, highlighting the need for continued efforts to educate and inform. Interestingly, while awareness is relatively high, only 13% reported mental health issues within their families and 14% within their villages. In contrast, a large majority; 87% and 86%, respectively (Figures 15 &16) denied the presence of mental health problems either in their family or community. This discrepancy suggests that, despite growing awareness, significant stigma, fear of social judgment, or lack of understanding regarding symptoms and conditions may prevent individuals from acknowledging or reporting mental health concerns.

In rural and marginalized regions like the Sundarbans, mental health remains a sensitive and often misunderstood topic. Traditional beliefs, limited access to professional mental health services, and a focus on survival in a climate-vulnerable environment may push mental health to the margins of public discourse. As a result, mental health problems often remain hidden, unrecognized, or untreated. The gap between awareness and reported mental health problems raises important questions. Individuals may recognize mental health as a concept but are reluctant or unable to identify or disclose mental health struggles within their communities or homes. Cultural perceptions, fear of judgment, and lack of accessible mental health services may further suppress open discussion. Therefore, while awareness is a crucial first step, it must be accompanied by de-stigmatization, community dialogue, and practical access to mental health care. In regions like the Sundarbans, integrating mental health support with existing health and social services is essential for long-term well-being.

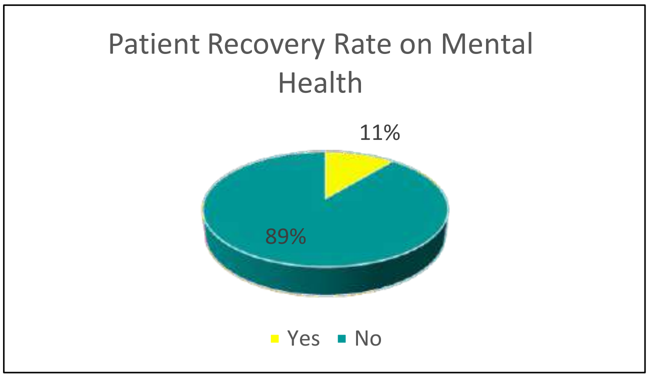


Fig. 17: Patient Recovery Rate on Mental Health.

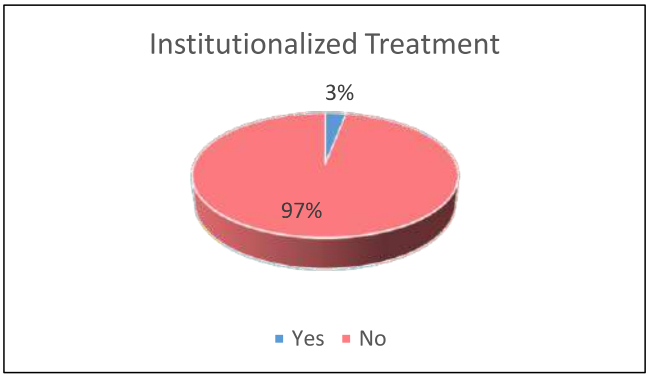


Fig. 18: Institutionalized Treatment.

The survey findings from the Sundarbans reveal a deeply concerning mental health and healthcare scenario. Only 11% of respondents reported patient recovery from mental health conditions, while a staggering 89% observed no improvement (Figure 17). This low recovery rate is closely tied to the lack of access to appropriate treatment and ongoing care. Institutionalized mental health treatment is virtually absent in the region, with only 3% of respondents having access to such services, while 97% reported no institutional care availability (Figure 18).

Most alarming is the finding that 100% of participants reported no opportunity to formally report mental health issues. This lack of a reporting mechanism not only reflects systemic neglect but also reinforces the stigma and silence surrounding mental illness in rural communities. Without access to professionals or safe channels for disclosure, individuals suffer in isolation, worsening their conditions over time.

Adding to the crisis is the lack of basic healthcare infrastructure—there are no affordable or accessible medical facilities within a 2 km radius, making even the most basic health needs difficult to address. This geographic inaccessibility is further compounded by poor transport infrastructure, with 83% of participants rating transportation quality as bad. In a region prone to floods, cyclones, and climate-related disruptions, poor transport severely limits access to emergency care, regular treatment, and follow-up visits, especially for vulnerable populations like the elderly, women, people with disabilities, and children.

This combination of poor recovery rates, limited institutional care, absence of reporting systems, lack of nearby healthcare, and inadequate transport highlights a severe public health crisis. These findings underscore an urgent need for systemic intervention in the Sundarbans. Community-based mental health programs, mobile medical units, improved road and transport networks, and integration of mental health services into existing primary healthcare structures are essential. Training local health workers to identify and support mental health issues, creating safe and confidential reporting systems, and raising awareness can gradually improve outcomes. Moreover, establishing an affordable and accessible healthcare infrastructure must be prioritized to ensure early diagnosis, continuous treatment, and recovery. Without such efforts, the region will continue to face a silent and growing mental health crisis with long-term social and economic consequences.

Table 1: Summarized results of the key findings from the Sundarbans survey.

Category	**Findings**
Marital Status	91% married, 5% unmarried, 5% widow/widower
Education Level graduates, 3% postgraduates	53% below Class VIII, 21% Class VIII–X, 7% XI–XII, 16%
Educational Infrastructure	No primary schools, high schools, or colleges within 2 km
Transport Facilities	83% rated transport quality as bad
Mental Health Recovery	11% reported recovery, 89% no recovery
Institutional Mental Health Care	3% accessed treatment, 97% did not
Mental Health Reporting	100% said no opportunity to report issues
Healthcare Access	No affordable or nearby medical facilities within 2 km

**Source: Compiled by the authors.*

Table 1 gives a summary of the core results of the survey. The data highlights critical development challenges in the Sundarbans, particularly in education, healthcare, mental health, and infrastructure. Despite a largely settled population, educational attainment is low, primarily due to the lack of nearby schools and poor transport facilities. Mental health care is almost nonexistent, with low recovery rates and no access to institutional treatment or reporting mechanisms. Similarly, healthcare access is severely limited by both distance and affordability. The findings call for urgent, integrated interventions that address education, transport, healthcare access, and mental health services. Establishing local schools and clinics, mobile healthcare units, training community health workers, and improving transport connectivity are essential. Culturally sensitive awareness programs must also be launched to break stigma around mental health and promote inclusive and sustainable development in the region.

Observations from the survey

Our survey indicated that most of the local residents from both districts are aware of ecological health as well as mental health, mental issues and mental well-being. However, while they were open about responding to personal, ecological and environmental issues, most seem to be visibly uncomfortable in responding to specific questions related to mental health issues. Although the majority of people, when surveyed, mentioned that they have very little knowledge about any mental health issues in their families or villages currently or in the recent past, outside the survey, they do mention their familiarity with mental issues. The taboo associated with being labelled or diagnosed as someone undergoing mental illness-related treatment in the region could be one possible factor for their reluctance to participate in the survey effectively. Mental disorders or mental ailments and related diseases recorded in the survey include: Anxiety disorders, Depression, Post Traumatic Stress Disorders (PTSD), Eating Disorders, Schizophrenia, Bipolar disorder, Neurodevelopmental disorder, Disruptive behaviour and Social disorder.

The Sundarbans locality as a whole is grossly unsuitable for human settlements due to the difficult geography of the region. Inclement weather, frequent cyclones, heavy rainfall, extensive human-animal conflicts, poor sanitation, health and hygiene, poor infrastructure, lack of year-long agricultural opportunity, unorganized and scattered cottage industries, rampant unemployment, socio-political disability, social, domestic and gender violence, local criminal activities (such as socio-political threats, physical and mental abuses, robbery, theft, rape, prostitution, dowry related crime, kidnapping, and occasional riots on grounds of religious divisions and intolerance) (Kumar, 2012; Das et al., 2016). Due to lack of local employment opportunities, a large number of daily wage male workers, as well as females working as domestic help, housemaids, factory workers, nurses, attendants, health caregivers, receptionists, sales agents, sex workers, etc., visit Kolkata on a daily basis. The separation of mother and child and other close family members due to employment purposes remains for a considerable period of time. The constant social as well as financial crisis looms large among local residents, both male and female, directly or indirectly impacting their mental and physical health quite seriously.

The recent financial supports provided by the West Bengal Government under various female-centric schemes have empowered the female residents to some extent. It has made them economically independent of their male family members. Although basic healthcare facilities are available but treatments for mental illness are referred to major government hospitals in Kolkata. Acute financial crises, unemployment opportunities, illiteracy and abject poverty have forced many female residents representing different age groups of the region into various petty crimes and prostitution for easy money. Trafficking of girls has been reported to be quite high in the Sundarbans region.

The rapid degradation of the mangrove forest over the past few decades has impacted the ecology of the region negatively. It has impacted both the ecology and economy of the region (Bahadur et al, 2010, 2018). The extensive erosion of the river banks and poor quality of dam construction, rampant corruption, illegal activities (such as encroachment of forested areas, destruction of highly fragile mangrove forest (Kumar, 2012), over harvesting of fishes and their spawns, changing agricultural lands to fisheries such as pisciculture, crab and oyster farming, shrimp and pearl culture has been destroying the local ecosystem drastically with little or no conservation efforts to protect the local environment (Banerjee et al., 2012).

The unprecedented population pressure of the region has been putting strain on scanty available local natural resources, such as major and minor forest products, which are depleting the vulnerable local mangrove forests, biodiversity and wildlife (Das et al., 2016). The indiscriminate use and application of synthetic chemical fertilizers and pesticides by local farmers are being deposited as residues on the soil (Banerjee et al., 2012). With rain and irrigation, these chemicals are percolating ground water table and polluting local freshwater resources (like lakes, ponds, ditches, dams, marshes and bogs), causing eutrophication, growth of cyanobacteria and growth of aquatic weeds destabilizing and irreplaceably damaging the highly fragile local freshwater aquatic ecosystem (Frankhauser et al., 2022). The estuaries (marine) ecosystem rich in biodiversity is also being impacted by such repeated, detrimental anthropogenic activities (Côté and Darling, 2010).

Possible Solutions and Way Forward

Better Infrastructure: Improved roadways, bridges, and transport facilities can enhance trade and mobility (Bhowmick, 2024).

Sustainable Agriculture and Fisheries: Promoting salt-resistant crops and better fishing techniques can boost income (Côté and Darling, 2010; Islam and Chuenpagdee, 2013; Didar-Ul Islam et al., 2018).

Eco-Tourism and Handicrafts: Encouraging eco-friendly tourism and local handicrafts can generate employment (Bahadur et al, 2010, 2018).

Climate Resilience Planning: Construction of embankments, better housing, and freshwater management systems can help mitigate climate-related issues (Barnett, 2007; Côté and Darling, 2010).

Education and Skill Development: Vocational training and digital education can empower the youth and reduce migration (Das et al., 2016; Deutsch, 2020).

Conclusion

In conclusion, the ecological fragility of the Sundarbans profoundly impacts residents' mental health, manifesting in increased anxiety, depression, and trauma-related disorders. Addressing these challenges requires integrated approaches combining environmental conservation with accessible mental health support and strong community engagement. Sustainable interventions can enhance resilience, improve well-being, and ensure the long-term health of both the ecosystem and its vulnerable human populations.

The Sundarbans community shows strong environmental and biodiversity awareness, yet faces critical gaps in education, healthcare, and mental health support. While 95–97% are environmentally aware, only 11% report mental health recovery, with no systems to report concerns and minimal access to treatment. Education remains limited, with most not studying beyond class VIII and no nearby schools. The absence of affordable healthcare and a high rate of family violence further worsen conditions. Despite these hardships, the community shows resilience through its mental health awareness, environmental awareness and cultural attachment to nature.

A holistic, community-based approach focusing on education, accessible healthcare, mental health services, better infrastructure, climate resilience planning, and socio-cultural empowerment is essential for improving the quality of life and fostering sustainable development in the Sundarbans.

Future Recommendations

The Sundarbans region, spread across India and Bangladesh (Anita et al., 2010; Aziz and Paul, 2015; Didar-Ul Islam et al., 2018; Patra and Basu, 2021; Sahana et al., 2021), faces significant socio-economic and educational challenges (Islam et al., 2015; Rudra and Chattopadhyay, 2019; Patra and Basu, 2021; Sahana et al., 2021; Ghosh and Roy, 2022) due to its geographical remoteness, frequent natural disasters, poor infrastructure, and lack of access to quality education and healthcare (Hommeland Murphy, 2013; Ghosh and Dutta, 2024). These combined efforts can create a resilient and self-sufficient Sundarbans (Paul and Chatterjee, 2019; Patra and Basu, 2021; Sahana et al., 2021), improving the quality of life for its residents. Here are some strategies to uplift the region:

1. Economic Development Strategies

a. Sustainable Livelihood

Eco-Tourism: Promote responsible tourism to create jobs while conserving the fragile ecosystem (Patra and Basu, 2021; Sahana et al., 2021; Ghosh and Roy, 2022).

Honey and Handicrafts: Train locals in sustainable honey collection, handicrafts, and cottage industries (Basu and Cetzal-Ix, 2018a, b; Patra and Basu, 2021).

Aquaculture and Agriculture: Introduce climate-resilient crops and modern fishery techniques (Hitz and Smith, 2004).

Mangrove-Based Livelihoods: Encourage sustainable mangrove-based livelihoods like crab farming (Hommel and Murphy, 2013).

b. **Infrastructure Development**

Better Connectivity: Improve road and river transport to integrate Sundarbans with urban markets (Patra and Basu, 2021; Sahana et al., 2021; Ghosh and Roy, 2022).

Electrification and Renewable Energy: Promote solar and wind energy to address electricity shortages (Hommel and Murphy, 2013).

Cyclone Shelters and Embankments: Strengthen disaster resilience through better infrastructure (Hitz and Smith, 2004; Paul and Chatterjee, 2019; Patra and Basu, 2021; Sahana et al., 2021).

2. **Educational Development Strategies**

a. **Improving Access to Education**

Mobile Schools and Boat Schools: To reach remote villages where conventional schools are unfeasible (Srivastava et al., 2010; Sahana et al., 2021; Patra and Basu, 2021; Ghosh and Dutta, 2024).

Community Learning Centers: Set up centers with digital learning tools and local teachers (Patra and Basu, 2021; Sahana et al., 2021).

Midday Meal and Incentive Schemes: Encourage school attendance through nutritional support (Anita et al., 2010; Srinivasan, 2012).

b. **Skill Development and Higher Education**

Vocational Training: Establish training centers in fishing, tourism, handicrafts, and technology (Anita et al., 2010; Soora et al., 2013).

Scholarships and Digital Education: Provide financial aid and online learning opportunities (Hjerpe and Linnér, 2010; Uddin et al., 2013).

3. **Health and Social Welfare**

Telemedicine and Mobile Health Clinics: Address the lack of healthcare facilities (Hjerpe and Linnér, 2010; Patra and Basu, 2021; Ghosh and Dutta, 2024).

Women Empowerment Programs: Promote self-help groups (SHGs) for financial independence (Guiteras, 2009; Patra and Basu, 2021; Ghosh and Dutta, 2024).

Disaster Preparedness Training: Educate communities about cyclone preparedness (Chowdhury and Brahma, 2019; Patra and Basu, 2021; Ghosh and Dutta, 2024).

4. **Environmental Conservation**

Mangrove Reforestation: To combat erosion and protect biodiversity (Kumar, 2012; Hommel and Murphy, 2013).

Sustainable Fishing and Farming Practices: Introduce eco-friendly methods (Hjerpe and Linnér, 2010; Rudraand Chattopadhyay, 2019).

5. **Government and NGO Collaboration**

Public-Private Partnerships: Engage NGOs and private sector investments in education and healthcare (Hjerpe and Linnér, 2010).

Microfinance and Cooperative Models: Support small businesses through accessible credit (Anita et al., 2010; Rudra and Chattopadhyay, 2019).

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PHOTOCATALYTIC DEGRADATION OF INDUSTRIAL DYE POLLUTANTS USING METAL OXIDE NANOPARTICLES

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ABSTRACT

Industrial dye pollutants represent one of the most persistent classes of organic contaminants in water systems. Conventional treatment methods often fail to completely eliminate these harmful compounds due to their complex aromatic structures and resistance to biodegradation. Photocatalysis using metal oxide nanoparticles has emerged as an eco-friendly, cost-effective, and highly efficient method for the degradation of dye pollutants under light irradiation. This research paper reviews the fundamental principles of photocatalysis, the synthesis and properties of metal oxide nanoparticles (such as TiO_2, ZnO, and Fe_2O_3), mechanisms influencing photo catalytic efficiency, challenges, and future perspectives. Emphasis is placed on recent advancements in enhancing photocatalytic performance and the potential for real-world wastewater treatment.

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Keywords: Photocatalysis, Industrial dyes, Metal oxide nanoparticles, TiO_2, ZnO, Wastewater treatment.

Introduction

Industrialization has significantly contributed to economic growth, but it has also intensified environmental pollution, particularly water contamination caused by industrial effluents. Among the various pollutants discharged into aquatic environments, synthetic dyes released from industries such as textile, leather, paper, plastic, pharmaceutical, and food processing represent a major environmental concern. These compounds are specifically engineered to possess high chemical stability, strong color intensity, and resistance to light and washing conditions. While these characteristics are desirable for industrial applications, they also make dyes highly persistent in natural water systems and difficult to degrade through conventional treatment methods (Ong et al., 2018; Kumar et al., 2020). Even at very low concentrations, dye pollutants can severely impact aquatic ecosystems. The presence of coloured effluents in water bodies reduces light penetration, thereby interfering with photosynthetic activity of aquatic plants and microorganisms. In addition, many dye compounds and their transformation products exhibit toxic, mutagenic, or carcinogenic properties that can pose serious threats to human health and environmental sustainability (Singh et al., 2023; Zhao et al., 2021). A large number of dyes are produced globally each year, and a considerable fraction of these substances eventually enters wastewater streams during manufacturing and dyeing processes. Among the different classes of dyes, azo dyes, anthraquinone dyes, and triphenylmethane dyes are the most widely utilized in industrial applications. Azo dyes are particularly dominant, accounting for more than sixty percent of the global dye market. These dyes contain one or more azo (–N=N–) functional groups, which contribute to their structural stability and resistance to degradation. Under certain environmental or biological conditions, however, azo dyes may undergo reductive cleavage, forming aromatic amines that are recognized as hazardous and potentially carcinogenic compounds

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(Sharma & Dutta, 2022). Traditional wastewater treatment methods, including sedimentation, filtration, adsorption, and biological treatment, are commonly employed to remove contaminants from industrial effluents. However, these approaches often fail to completely eliminate complex dye molecules due to their stable aromatic structures and resistance to microbial degradation. Biological treatment systems, in particular, are often ineffective because many synthetic dyes are non-biodegradable and can inhibit microbial activity (Chen et al., 2024). Various physicochemical methods have been developed to improve dye removal efficiency, including coagulation–flocculation, membrane filtration, activated carbon adsorption, and chemical oxidation processes. Despite their effectiveness in certain applications, these techniques suffer from several drawbacks. Adsorption-based methods merely transfer pollutants from the liquid phase to a solid phase, creating additional challenges related to secondary waste management. Membrane filtration systems are often costly and susceptible to fouling, while chemical oxidation methods may generate toxic by-products and require substantial chemical inputs (Ahmed et al., 2014; Wang et al., 2018). In recent years, Advanced Oxidation Processes (AOPs) have emerged as promising alternatives for the treatment of dye-contaminated wastewater. These technologies are based on the generation of highly reactive species, particularly hydroxyl radicals (OH), which possess extremely strong oxidation potential. Hydroxyl radicals are capable of non-selectively oxidizing a wide range of organic pollutants, ultimately converting them into harmless products such as carbon dioxide, water, and inorganic ions (Kumar et al., 2020). Among the various AOP techniques, semiconductor photocatalysis has attracted considerable attention due to its operational simplicity, high degradation efficiency, and potential to utilize solar radiation as a sustainable energy source. In photocatalytic processes, a semiconductor material absorbs photons with energy equal to or greater than its band gap. This excitation promotes electrons from the valence band to the conduction band, leaving behind positively charged holes in the valence band.

These photogenerated electron–hole pairs migrate to the catalyst surface, where they participate in redox reactions that generate reactive oxygen species such as hydroxyl radicals and superoxide radicals. These reactive species attack dye molecules and gradually break them down into simpler, non-toxic compounds (Pelaez et al., 2016; Li et al., 2019). Metal oxide nanoparticles have been extensively investigated as photocatalysts because of their favourable physicochemical properties, including chemical stability, strong oxidative potential, and large surface area. Among them, titanium dioxide (TiO_2) is one of the most widely studied photocatalytic materials due to its low toxicity, cost-effectiveness, and high photocatalytic activity. However, the relatively wide band gap of TiO_2 restricts its activity mainly to ultraviolet light. To overcome this limitation and improve visible light utilization, other metal oxide materials such as zinc oxide (ZnO), iron (III) oxide (Fe_2O_3), and tungsten oxide (WO_3) have also been explored for photocatalytic applications (Ong et al., 2018; Zhao et al., 2021). The nanoscale structure of these materials plays an essential role in enhancing photocatalytic efficiency. Nanoparticles provide a significantly larger surface-to-volume ratio compared to bulk materials, which increases the number of active catalytic sites available for dye adsorption and degradation.

Moreover, reduced particle size shortens the migration distance for photogenerated charge carriers, thereby minimizing electron–hole recombination and improving overall photocatalytic performance (Singh et al., 2023). Various synthesis methods, including sol–gel techniques, hydrothermal synthesis, co-precipitation, and green synthesis approaches, have been developed to control the size, morphology, and surface characteristics of metal oxide nanoparticles. These strategies allow researchers to optimize photocatalytic activity for environmental remediation applications. Despite significant progress in photocatalytic wastewater treatment, several challenges remain. Rapid recombination of photogenerated charge carriers can reduce photocatalytic efficiency, and the recovery of nanoparticles from treated water can be difficult in practical systems. To address these limitations, researchers have proposed several strategies such as metal or non-metal doping, formation of semiconductor heterojunctions, and immobilization of photocatalysts onto solid substrates (Chen et al., 2024). Overall, photocatalytic degradation using metal oxide nanoparticles represents a promising and environmentally sustainable approach for the treatment of dye-contaminated industrial wastewater. By utilizing light energy to generate powerful oxidizing species, photocatalysis enables the efficient breakdown of persistent dye molecules into harmless products. Continued research in nanomaterial engineering, catalyst design, and reactor development is expected to further improve the efficiency and scalability of this technology for large-scale wastewater treatment applications.

Industrial Dye Pollutants: Types and Environmental Impact

Classification of Dyes

Synthetic dyes used in industrial processes can be classified according to their chemical structure, application method, and chromophore groups. These dyes are extensively utilized in industries such as textiles, leather processing, plastics, pharmaceuticals, and paper manufacturing due to their strong colouring ability and chemical stability. However, these same characteristics make them persistent environmental pollutants when discharged into aquatic systems (Kumar et al., 2020; Zhao et al., 2021).

One of the most widely used groups of industrial dyes is azo dyes, which contain one or more azo (–N=N–) linkages connecting aromatic rings. These dyes are known for their structural stability and ability to produce a wide variety of color. Azo dyes represent the largest class of synthetic dyes and account for more than sixty percent of the global dye production (Sharma & Dutta, 2022). A common example of this class is Congo Red, which is widely used in textile dyeing.

Another important category includes anthraquinone dyes, which are derived from the anthraquinone chemical structure. These dyes are widely used because of their excellent light stability and bright coloration. Reactive Blue 19 is a well-known anthraquinone dye frequently applied in textile processing industries.

Triphenylmethane dyes constitute another class of synthetic dyes characterized by a central carbon atom bonded to three aromatic rings. These dyes are commonly used for colouring textiles, paper, and leather products. Malachite Green is a widely recognized example of this group and has been historically used in textile and aquaculture applications, although concerns about toxicity have limited its usage in many regions.

Additionally, phthalocyanine dyes are extensively used to produce blue and green shades in textile and printing industries. These dyes are metal-complex compounds known for their strong chemical stability and resistance to degradation. Due to their stable aromatic structures and synthetic origin, many of these dyes are difficult to remove from wastewater using conventional treatment methods (Singh et al., 2023).

Environmental and Health Hazards

The discharge of untreated or inadequately treated dye-containing effluents into water bodies poses serious environmental and public health concerns. Even small quantities of dye pollutants can significantly alter the optical properties of water, reduce light penetration and interfering with photosynthesis in aquatic plants and algae. This disruption can negatively affect primary productivity and disturb the ecological balance of aquatic ecosystems (Ong et al., 2018). Furthermore, dye effluents may modify important physicochemical properties of water, including pH levels, chemical oxygen demand (COD), and dissolved oxygen content. These changes can create unfavourable conditions for aquatic organisms and lead to biodiversity loss in affected ecosystems (Chen et al., 2024). Another critical concern associated with industrial dyes is their potential toxicity and carcinogenicity. Some dye compounds and their degradation intermediates can produce harmful aromatic amines that are known to exhibit mutagenic and carcinogenic properties. Exposure to such compounds may pose risks to human health through contaminated drinking water, food chains, or occupational exposure in industrial settings (Sharma & Dutta, 2022). The molecular structures of many synthetic dyes contain complex aromatic rings and heterocyclic components, which contribute to their high chemical stability and resistance to biological degradation. As a result, conventional biological treatment processes often fail to completely eliminate these pollutants from wastewater. This limitation has led to increasing interest in advanced treatment technologies, particularly advanced oxidation processes and photocatalytic methods, for the effective degradation and mineralization of dye pollutants (Kumar et al., 2020; Singh et al., 2023).

Review of Literature

Significant research efforts have been devoted to the development of efficient technologies for the removal of dye pollutants from industrial wastewater. Among the various treatment methods, photocatalytic degradation using semiconductor metal oxide nanoparticles has emerged as a promising approach due to its ability to completely mineralize organic contaminants into harmless end products such as carbon dioxide and water. In recent years, numerous studies have explored the photocatalytic performance of different semiconductor materials for dye degradation, focusing on improving catalyst efficiency, stability, and visible-light activity (Kumar et al., 2020; Zhao et al., 2021). Titanium dioxide (TiO_2) is one of the most extensively investigated semiconductor photocatalysts for environmental remediation.

The widespread use of TiO_2 is mainly attributed to its strong oxidative potential, high chemical stability, low toxicity, and cost-effectiveness. When exposed to ultraviolet radiation, TiO_2 generates electron–hole pairs that initiate oxidation–reduction reactions leading to the degradation of organic dye molecules. Among the different crystalline phases of $TiO_2$the anabases phase generally exhibits higher photocatalytic activity due to its larger surface area and improved charge carrier mobility (Pelaez et al., 2016). Despite these advantages, the practical application of TiO_2 is restricted by its relatively wide band gap (~3.2 eV), which limits its photoactivity primarily to the ultraviolet region of the electromagnetic spectrum. Since ultraviolet light accounts for only a small fraction of solar radiation, considerable research has been directed toward modifying TiO_2 to enhance its visible-light response. Various strategies such as metal doping, non-metal doping, and formation of semiconductor heterojunctions have been developed to improve photocatalytic efficiency and reduce electron–hole recombination (Li et al., 2019; Kumar et al., 2020). Zinc oxide (ZnO) nanoparticles have also been widely studied as photocatalysts for dye degradation due to their similar band gap to TiO_2 and higher electron mobility, which can enhance charge transfer during photocatalytic reactions. Several studies have demonstrated the successful degradation of dyes such as methylene blue, rhodamine B, and methyl orange using ZnO-based nanostructures under ultraviolet or solar irradiation (Ong et al., 2018). However, ZnO suffers from photo-corrosion and structural instability under prolonged illumination, which can reduce its catalytic durability and limit large-scale applications. Another semiconductor material that has attracted attention is **iron** (III) oxide (Fe_2O_3), particularly due to its relatively narrow band gap (~2.1 eV) and ability to absorb visible light.

Hematite-based photocatalysts have shown promising results in the degradation of various dye pollutants under solar irradiation. Nevertheless, the photo catalytic efficiency of Fe_2O_3 is often hindered by the rapid recombination of photogenerated electron–hole pairs, which reduces the number of reactive species available for pollutant degradation (Sharma & Dutta, 2022). The formation of semiconductor heterojunctions can significantly enhance photocatalytic performance by promoting effective separation of photogenerated charge carriers and extending light absorption into the visible region. Composite systems such as TiO_2/ZnO, ZnO/Fe_3O_3, and TiO_2-based nanocomposites have demonstrated improved photocatalytic efficiency compared to single-component catalysts (Singh et al., 2023).

Controlling nanoparticle size, shape, and surface properties can increase the available active sites for dye adsorption and enhance interaction between the catalyst surface and pollutant molecules. Advanced synthesis methods including sol–gel processes, hydrothermal techniques, co-precipitation, and green synthesis approaches have been employed to produce highly efficient photocatalysts with tailored structural characteristics (Chen et al., 2024). Recent studies also highlight the importance of surface modification and catalyst immobilization to improve photocatalyst recovery and reuse in wastewater treatment systems. Immobilized photocatalytic materials can reduce the challenges associated with nanoparticle separation while maintaining high degradation efficiency. Photocatalysis, a subclass of AOPs, has been extensively explored for dye degradation due to its environmental compatibility and efficiency. Zinc oxide (ZnO) nanoparticles have also attracted significant attention as an alternative photocatalyst.

ZnO possesses a band gap similar to TiO_2 but offers higher electron mobility and comparable photocatalytic efficiency. Ouyang et al. (2017) reported effective degradation of methylene blue and other dyes using ZnO nanostructures. However, ZnO suffers from photo corrosion under prolonged irradiation, which limits its long-term application. Iron oxide (Fe_2O_3) has been investigated due to its narrower band gap (~2.1 eV) and ability to absorb visible light. Studies by Sara tale et al. (2011) highlighted the potential of Fe_2O_3 based photo catalysts for dye degradation under solar irradiation, though rapid electron–hole recombination remains a challenge. To address this issue, heterojunction systems and composite photocatalysts have been developed. Zhang et al. (2010) reported that TiO_2-based heterostructure photo catalysts significantly improve charge separation and degradation efficiency.

Photocatalysis: Fundamentals

Photocatalysis is an advanced oxidation process in which semiconductor materials utilize light energy to initiate chemical reactions capable of degrading organic pollutants. In this process, when a semiconductor photocatalyst is exposed to light with energy equal to or greater than its band gap, electrons present in the valence band are excited to the conduction band. This excitation leaves behind positively charged holes in the valence band, generating electron–hole (e^-–H^+) pairs. These charge carriers participate in redox reactions at the surface of the photocatalyst, resulting in the formation of highly reactive oxidative species capable of decomposing organic contaminants present in wastewater (Kumar et al., 2020; Zhao et al., 2021).

The photocatalytic degradation process is widely considered an effective and environmentally sustainable technique for wastewater treatment because it can completely mineralize complex organic compounds into harmless products such as carbon dioxide and water. Compared with conventional treatment methods, photocatalysis offers advantages including minimal chemical consumption, utilization of solar energy, and the ability to degrade a broad range of pollutants (Singh et al., 2023).

Mechanism of Photocatalytic Dye Degradation

The photocatalytic degradation of dye molecules occurs through a series of photochemical and oxidation–reduction reactions initiated by light irradiation. When photons strike the surface of a semiconductor photocatalyst, electrons are excited from the valence band to the conduction band, producing electron–hole pairs. The fundamental reactions involved in photocatalytic dye degradation can be summarized as follows:

1. Light irradiation excites electrons from the valence band to the conduction band of the semiconductor, producing electrons and holes.
2. The photogenerated holes react with water molecules or hydroxide ions to generate highly reactive hydroxyl radicals (OH).
3. Simultaneously, the excited electrons interact with dissolved oxygen molecules to form superoxide radicals (O_2^-).
4. These reactive oxygen species attack dye molecules and break down their complex molecular structures into smaller intermediate compounds.
5. Continued oxidation eventually converts these intermediates into stable mineralized products such as carbon dioxide, water, and inorganic ions.

The simplified reaction mechanism can be expressed as:

Semiconductor + $h\nu \rightarrow e^-$ (CB) + H^+ (VB)

$H^+ + H_2O \rightarrow \bullet OH$

$e^- + O_2 \rightarrow O2^- \bullet$

$\bullet OH / O2^- + \text{Dye} \rightarrow$ Mineralized Products

The efficiency of photocatalytic degradation is influenced by several factors including light absorption capacity, charge carrier separation efficiency, surface area of the catalyst, and chemical stability of the photocatalyst (Li et al., 2019; Chen et al., 2024).

Metal Oxide Nanoparticles in Photocatalysis

Metal oxide nanoparticles have gained significant attention as photocatalysts due to their unique physicochemical properties, including high surface area, strong oxidative ability, and chemical stability. The nanoscale structure of these materials enhances photocatalytic performance by increasing the number of active surface sites and improving interaction between the catalyst and pollutant molecules (Sharma & Dutta, 2022). Among various semiconductor materials, titanium dioxide (TiO_2), zinc oxide (ZnO), and iron oxide (Fe_2O_3) are the most extensively studied photocatalysts for environmental remediation applications.

Titanium Dioxide (TiO_2)

Titanium dioxide is one of the most widely investigated semiconductor photocatalysts due to its excellent chemical stability, strong oxidizing ability, low toxicity, and relatively low cost. These properties make TiO_2 highly suitable for environmental purification applications, particularly in the degradation of organic pollutants in wastewater (Pelaez et al., 2016). TiO_2 exists in three primary crystalline phases: anatase, rutile, and brookite. Among these phases, anatase generally exhibits the highest photocatalytic activity due to its larger surface area, higher adsorption capacity, and improved separation of photogenerated electron–hole pairs. Despite these advantages, TiO_2 suffers from certain limitations. Its relatively wide band gap of approximately 3.2 eV restricts its photoactivity mainly to the ultraviolet region of the electromagnetic spectrum, which constitutes only a small portion of solar radiation. Furthermore, rapid recombination of photogenerated electrons and holes reduces photocatalytic efficiency. To address these challenges, various modification strategies have been explored, including metal doping, non-metal doping, heterojunction formation, and coupling with carbon-based materials to extend its activity into the visible-light region (Kumar et al., 2020; Singh et al., 2023).

Zinc Oxide (ZnO)

Zinc oxide is another important semiconductor photocatalyst widely investigated for dye degradation. ZnO possesses a band gap similar to TiO_2 (~3.2 eV) but offers advantages such as higher electron mobility and efficient charge transport, which can enhance photocatalytic performance (Ong et al., 2018). ZnO nanoparticles are attractive for photocatalytic applications because they are abundant, inexpensive, and capable of generating high quantum efficiency under ultraviolet irradiation. Several studies have reported successful degradation of organic dyes such as methylene blue, rhodamine B, and methyl orange using ZnO-based nanomaterial's. However, ZnO also faces certain limitations, particularly photo-corrosion in aqueous environments under prolonged illumination, which can affect catalyst stability. To overcome these issues, researchers have investigated surface modification techniques and nanostructured morphologies such as nanorods, nanosheets, and nanoflowers to enhance visible-light absorption and improve photocatalytic activity (Zhao et al., 2021).

Iron Oxide (Fe_2O_3)

Iron oxide, particularly - Fe_2O_3 (hematite), has attracted interest as a photocatalyst due to its relatively narrow band gap of approximately 2.1 eV, enabling it to absorb visible light effectively. Additionally, iron oxide is environmentally friendly, abundant, and cost-effective, making it a promising candidate for large-scale wastewater treatment applications (Sharma & Dutta, 2022). Nevertheless, Fe_2O_3 suffers from several drawbacks, including low electrical conductivity and rapid recombination of photogenerated charge carriers, which can reduce photocatalytic efficiency. To address these limitations, Fe_2O_3 is often combined with other semiconductor materials or doped with suitable elements to enhance charge separation and improve catalytic performance.

Other Metal Oxides

In addition to TiO_2, ZnO, and Fe_2O_3, several other metal oxide semiconductors have been explored for photocatalytic degradation of pollutants. Materials such as tungsten oxide (WO_3), copper oxide (CuO), and nickel oxide (NiO) have shown promising photocatalytic activity under specific experimental conditions. These materials are often used in composite systems or heterojunction structures to improve visible-light absorption and enhance photocatalytic efficiency.

Enhancing Photocatalytic Efficiency

Although semiconductor photo catalysts such as TiO_2, ZnO, and Fe_2O_3have demonstrated promising capabilities in the degradation of dye pollutants, their practical performance is often limited by factors such as rapid recombination of photogenerated charge carriers, limited visible-light absorption, and low surface activity. To overcome these limitations, several modification strategies have been developed to enhance photocatalytic efficiency and improve pollutant degradation performance (Kumar et al., 2020; Singh et al., 2023).

Doping and Sensitization

One of the most widely used approaches for improving photocatalytic activity involves doping semiconductor photocatalysts with metal or non-metal elements. Doping introduces defect sites within the semiconductor lattice, which can modify the electronic structure of the material and reduce its band gap energy. As a result, the photocatalyst becomes capable of absorbing visible light more effectively, thereby improving solar energy utilization (Li et al., 2019). Transition metals such as iron (Fe), chromium (Cr), and copper (Cu) have been commonly used as dopants to enhance charge carrier separation and extend the absorption spectrum of semiconductor photocatalysts. Similarly, non-metal dopants including nitrogen (N), sulphur (S), and carbon (C) have also been reported to improve visible-light photocatalytic activity by altering the electronic band structure of metal oxides (Zhao et al., 2021). Another effective strategy is sensitization, in which semiconductor photocatalysts are combined with dye molecules or narrow band-gap semiconductors such as cadmium sulphide (CdS). Sensitization enables improved photon absorption and facilitates the transfer of excited electrons from the sensitizer to the semiconductor catalyst, thereby enhancing photocatalytic efficiency under visible-light irradiation (Sharma & Dutta, 2022).

Heterojunction Formation

The formation of heterojunction photocatalysts has emerged as an important method for improving photocatalytic performance. Heterojunction structures are formed by combining two or more semiconductor materials with different band gap energies. This configuration promotes efficient separation of photogenerated electron–hole pairs by providing favorable charge transfer pathways between the semiconductor components (Chen et al., 2024). Composite systems such as TiO_2–ZnO, TiO_2–graphene, ZnO– Fe_2O_3, and TiO_2–g-C_3N_4 have shown significantly improved photocatalytic performance compared to single semiconductor systems. The enhanced performance is primarily attributed to reduced recombination rates of charge carriers and improved light absorption properties (Singh et al., 2023).

Surface Area and Morphology Control

Another critical factor influencing photocatalytic performance is the surface area and morphology of the catalyst material. Nanostructured photocatalysts provide a larger surface-to-volume ratio compared to bulk materials, allowing more active sites for pollutant adsorption and catalytic reactions. Various nanostructures such as nanotubes, nanorods, nanowires, nanosheets, and mesoporous structures have been developed to optimize photocatalytic performance. These nanostructures improve light absorption, enhance mass transfer, and increase the number of accessible reactive sites on the catalyst surface (Kumar et al., 2020). Additionally, controlling particle size and surface characteristics can significantly influence the adsorption of dye molecules, which is a critical step in the photocatalytic degradation process.

Light-Harvesting Strategies

Improving the light-harvesting ability of photocatalysts is another important approach to enhance photocatalytic efficiency. One promising strategy involves incorporating plasmonic metal nanoparticles, such as silver (Ag) and gold (Au), into semiconductor photocatalysts. These nanoparticles exhibit localized surface plasmon resonance (LSPR), a phenomenon in which conduction electrons oscillate collectively when exposed to visible light. This effect enhances light absorption and promotes efficient charge transfer between the metal nanoparticles and the semiconductor photocatalyst, resulting in improved photocatalytic activity under visible-light irradiation (Li et al., 2019; Chen et al., 2024).

Photocatalytic Degradation of Specific Dyes

Numerous studies have demonstrated the effectiveness of photocatalytic processes in degrading different classes of dye pollutants present in industrial wastewater. The degradation efficiency depends on the type of dye, photocatalyst material, and reaction conditions such as light intensity, catalyst concentration, and pH.

Azo Dyes

Studies consistently show effective degradation of azo dyes (e.g., Congo Red, Acid Orange 7) using TiO_2 and ZnO under UV and visible irradiation. These systems achieve high decolorization and mineralization efficiencies within hours (Chaudhuri & Majumder, 2006). Azo dyes represent the largest group of synthetic dyes used in industrial applications. Due to the presence of azo bonds (–N=N–) connecting aromatic rings, these dyes exhibit high chemical stability and resistance to biological degradation. Recent studies have reported efficient photocatalytic degradation of azo dyes such as Congo Red, Acid Orange 7, and Methyl Orange using semiconductor photo catalysts including TiO_2 and ZnO nanoparticles. These photocatalytic systems have demonstrated high decolorization rates and effective mineralization of dye molecules under ultraviolet and visible-light irradiation (Kumar et al., 2020; Singh et al., 2023).

Reactive Dyes

Reactive dyes are widely used in textile industries due to their strong bonding with fabric fibres and excellent colour stability. However, these dyes are highly resistant to conventional wastewater treatment processes. Recent research indicates that modified or doped TiO_2 photo catalysts can effectively degrade reactive dyes such as Reactive Black 5 and Reactive Blue 19 under visible-light irradiation. These systems have shown promising potential for solar-driven wastewater treatment technologies (Zhao et al., 2021).

Triphenylmethane Dyes

Triphenylmethane dyes such as Malachite Green and Crystal Violet are commonly used in textile dyeing and aquaculture applications. However, these dyes are known to exhibit toxic and carcinogenic properties. Recent studies have demonstrated that Fe_2O_3-based composite photo catalysts and semiconductor heterostructures can effectively degrade triphenylmethane dyes under visible-light irradiation. The improved degradation efficiency is largely attributed to enhanced light absorption and improved charge carrier separation achieved through band gap engineering and composite catalyst design (Sharma & Dutta, 2022; Chen et al., 2024).

Methodology

Materials Used

All chemicals used in this study were of analytical grade and were used without further purification. Methylene blue (MB) dye was selected as a model organic pollutant because it is widely used in textile industries and frequently detected in industrial wastewater (Kumar et al., 2020; Singh et al., 2023).

The following materials and equipment were used during the experimental investigation:

- Model dye pollutant: Methylene Blue (MB)
- Photocatalyst: Titanium dioxide (TiO_2) nanoparticles
- Light source: Ultraviolet lamp (365 nm wavelength)
- Solvent: Distilled water
- Mixing device: Magnetic stirrer
- Analytical instrument: UV–Visible spectrophotometer

Titanium dioxide nanoparticles were selected due to their high photocatalytic activity, chemical stability, low toxicity, and strong oxidizing ability, which make them suitable for environmental remediation applications (Pelaez et al., 2016; Ong et al., 2018).

Preparation of Dye Solution

A stock solution of methylene blue (10 mg L^{-1}) was prepared by dissolving an accurately measured quantity of dye in distilled water. The solution was thoroughly mixed to ensure complete dissolution. From this stock solution, working solutions of the required concentration were prepared through dilution with distilled water. The prepared dye solution was stored in dark containers to prevent any photodegradation prior to the experimental analysis (Li et al., 2019).

Photocatalytic Experiment

The photocatalytic degradation experiments were carried out using a batch reactor system under ultraviolet irradiation.

Initially, 100 mL of methylene blue solution was transferred into a clean glass beaker. Subsequently, TiO_2 nanoparticles were added at a concentration of 0.1 g L^{-1} to the dye solution. The suspension was then placed on a magnetic stirrer and mixed continuously in the dark for approximately 30 minutes to establish adsorption–desorption equilibrium between the dye molecules and the catalyst surface.

After achieving equilibrium, the suspension was exposed to UV irradiation (365 nm) to initiate the photocatalytic reaction. During the degradation process, small aliquots of the reaction mixture were collected at predetermined time intervals of 0, 20, 40, 60, 80, and 100 minutes.

The collected samples were immediately centrifuged to separate TiO_2 particles from the solution before spectroscopic analysis. Continuous stirring was maintained throughout the experiment to ensure homogeneous dispersion of catalyst particles and uniform exposure to the light source (Zhao et al., 2021; Chen et al., 2024).

Analytical Method

The concentration of methylene blue during the photocatalytic degradation process was monitored using a UV–Visible spectrophotometer. The absorbance of the dye solution was measured at its characteristic maximum absorption wavelength (max = 664 nm), which corresponds to the electronic transition of methylene blue molecules.

The degradation efficiency of the dye was evaluated by monitoring the decrease in absorbance over time. According to the Beer–Lambert law, absorbance is directly proportional to dye concentration, allowing the determination of degradation efficiency through spectroscopic measurements (Ahmed et al., 2014; Kumar et al., 2020).

The photocatalytic degradation efficiency was calculated using the following equation:

$$\boldsymbol{Degradation}\,(\%) = \frac{\boldsymbol{A_0 - A_t}}{\boldsymbol{A_0}} \times \mathbf{100}$$

where:
= *C0* initial dye concentration
= *Ct* dye concentration at time *t*

This method provides a reliable approach for evaluating the effectiveness of photocatalysts in degrading organic dye pollutants in aqueous solutions (Singh et al., 2023).

Results and Discussion

Effect of Irradiation Time

The photocatalytic degradation efficiency of methylene blue was evaluated by monitoring the variation in absorbance at different irradiation times under ultraviolet light. A gradual reduction in the absorbance intensity of the dye solution was observed as the irradiation time increased, indicating the progressive breakdown of dye molecules in the presence of the TiO_2 photocatalyst. Initially, the degradation rate was relatively slow during the first few minutes of irradiation due to the establishment of adsorption equilibrium between the dye molecules and the catalyst surface. As irradiation continued, the degradation rate increased significantly due to the generation of reactive oxygen species responsible for oxidative degradation of the dye molecules. The maximum degradation efficiency was observed after 100 minutes of UV exposure, demonstrating the effectiveness of TiO_2 nanoparticles in degrading methylene blue in aqueous solution. Similar trends have been reported in recent studies, where photocatalytic degradation efficiency increases with prolonged irradiation time due to continuous formation of reactive radicals (Kumar et al., 2020; Singh et al., 2023).

Photocatalytic Mechanism

The photocatalytic degradation of organic dyes using semiconductor materials is primarily governed by the generation of electron–hole pairs upon exposure to light with energy equal to or greater than the band gap of the photocatalyst. When TiO_2 nanoparticles are exposed to ultraviolet irradiation, electrons from the valence band become excited and move to the conduction band, leaving behind positively charged holes in the valence band. These charge carriers participate in a series of redox reactions on the catalyst surface.

The photogenerated holes react with water molecules or hydroxide ions present in the solution to produce hydroxyl radicals (OH), which are highly reactive oxidizing agents. Simultaneously, the excited electrons react with dissolved oxygen molecules to produce superoxide radicals (O). These reactive oxygen species attack dye molecules, breaking down complex aromatic structures and eventually converting them into smaller inorganic molecules such as carbon dioxide and water (Pelaez et al., 2016; Chen et al., 2024).

This photocatalytic process leads to complete mineralization of dye pollutants, making it an environmentally sustainable technique for wastewater treatment.

Comparison with Control Experiment

To confirm the role of the photocatalyst in the degradation process, a control experiment was conducted under identical experimental conditions but without the addition of TiO_2 nanoparticles. The results revealed that only negligible degradation of methylene blue occurred under UV irradiation alone, indicating that photolysis was not sufficient to degrade the dye effectively. In contrast, the presence of TiO_2 significantly enhanced dye degradation due to its ability to generate reactive oxygen species under UV illumination. These findings confirm that TiO_2 acts as an active photocatalyst, accelerating the oxidation reactions responsible for dye degradation. Similar observations have been reported in recent photocatalytic studies involving semiconductor nanomaterials for wastewater treatment (Li et al., 2019; Zhao et al., 2021).

Table 1: Properties of Common Metal Oxide Nanoparticles.

Metal Oxide	Band Gap (eV)	Light Response	Advantages	Limitations
TiO_2	~3.2	UV	Chemically stable, non-toxic, widely available	Limited visible light activity
ZnO	~3.2	UV	High electron mobility and strong photocatalytic efficiency	Susceptible to photocorrosion
Fe_2O_3	~2.1	Visible	Low cost and good visible light absorption	Rapid electron–hole recombination

Recent research has shown that combining these metal oxides into heterostructure nanocomposites can significantly improve photocatalytic performance by enhancing charge separation and extending light absorption into the visible region (Singh et al., 2023; Chen et al., 2024).

Table 2: Reported Photocatalytic Degradation of Industrial Dyes.

Dye	Photocatalyst	Light Source	Degradation (%)
Congo Red	TiO_2	UV	95
Reactive Black 5	N-doped TiO^2	Visible	88
Malachite Green	Fe_2O_3 composite	Visible	90

These studies demonstrate that modified or composite photocatalysts exhibit improved photocatalytic efficiency compared to pure metal oxides, particularly under visible light irradiation. Advances in nanomaterial engineering, including doping, heterojunction formation, and surface modification, have significantly improved photocatalytic degradation performance for industrial dye pollutants (Kumar et al., 2020; Zhao et al., 2021).

10. Calculation

10.1 Percentage Degradation Calculation

The efficiency of photocatalytic degradation of methylene blue was determined by monitoring the reduction in dye concentration during ultraviolet irradiation. The concentration change was evaluated using absorbance measurements obtained from a UV–Visible spectrophotometer at the characteristic wavelength of 664 nm, which corresponds to the maximum absorption peak of methylene blue. Since absorbance is directly proportional to dye concentration according to the Beer–Lambert law, the percentage degradation of the dye can be calculated using the following equation (Kumar et al., 2020; Singh et al., 2023):

$$\boldsymbol{Degradation}\,(\%) = \frac{\boldsymbol{A_0 - A_t}}{\boldsymbol{A_0}} \times \mathbf{100}$$

Where:

(A_0) = Initial absorbance

(A_t) = Absorbance at time (t)

Example Calculation:

- $(A_0 = 1.00)$
- $(A_{(100)} = 0.15)$

$$\boldsymbol{Degradation}\,(\%) = \frac{\mathbf{1.00-0.15}}{\mathbf{1.00}} \times \mathbf{100} = 85\%$$

The results indicate that approximately 85% of methylene blue dye was degraded after 100 minutes of UV irradiation in the presence of TiO_2 nanoparticles. This level of degradation is consistent with previously reported photo catalytic efficiencies for TiO_2 based systems under ultraviolet light (Pelaez et al., 2016; Zhao et al., 2021).

10.2 Graph Data (for Plotting)

Table: Absorbance vs Time

Table 2: Reported Photocatalytic Degradation of Industrial Dyes.

Time (min)	Absorbance
0	1.00
20	0.78
40	0.56
60	0.38
80	0.24
100	0.15

Graph Description

The graphical representation of absorbance versus irradiation time illustrates a steady decline in absorbance intensity throughout the experiment. This decreasing trend indicates that the concentration of methylene blue gradually decreases as the photocatalytic reaction proceeds. The reduction in absorbance is attributed to the formation of reactive oxygen species such as hydroxyl radicals (•OH) and superoxide radicals (O2•-) generated on the surface of TiO_2 nanoparticles under ultraviolet irradiation. These highly reactive species attack dye molecules and break down complex organic structures into simpler compounds, ultimately leading to mineralization (Chen et al., 2024; Singh et al., 2023). The observed degradation pattern confirms that photo catalytic oxidation using TiO_2 nanoparticles is an effective approach for the treatment of dye-containing wastewater.

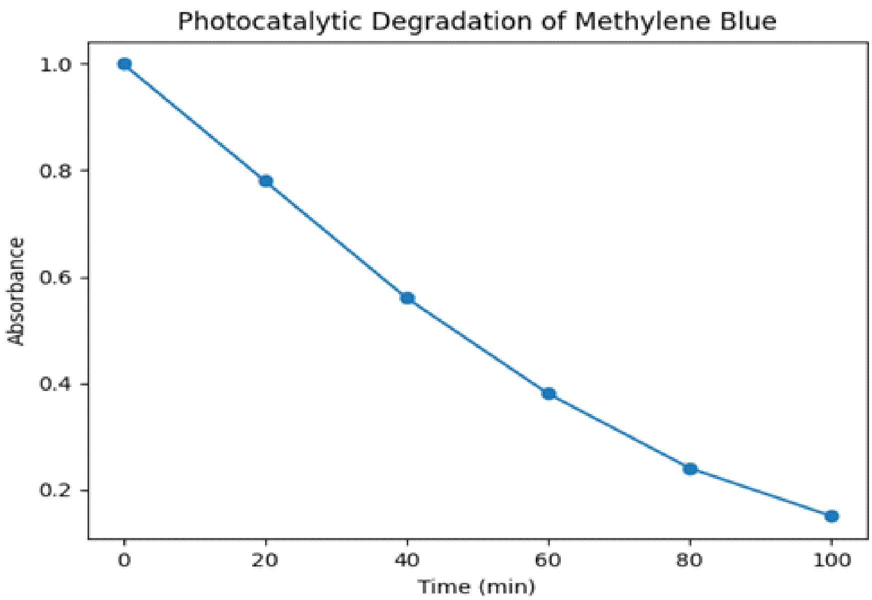

Fig. 1: Plot of *Absorbance vs Irradiation Time* The graph shows a decreasing trend, indicating increased photocatalytic degradation with time.

Challenges and Limitations

Although photocatalytic degradation using metal oxide nanoparticles has demonstrated considerable potential for the treatment of dye-contaminated wastewater, several technical and practical limitations still hinder its widespread industrial implementation.

Catalyst Recovery and Stability.

One of the primary challenges associated with nanoparticle-based photocatalysts is the difficulty in recovering catalyst particles after treatment. Since nanoparticles are typically dispersed in aqueous solutions to maximize catalytic activity, separating them from treated water can be complex and time-consuming. In addition, repeated usage may lead to catalyst deactivation due to agglomeration, surface fouling, or structural changes. To address these issues, recent research has focused on immobilizing photocatalysts on solid supports, incorporating magnetic components for easy separation, or developing recyclable catalyst systems (Singh et al., 2023; Chen et al., 2024).

Visible Light Activation

Many widely studied metal oxide photocatalysts, particularly titanium dioxide (TiO_2) and zinc oxide (ZnO), exhibit relatively wide band gaps and are therefore mainly activated under ultraviolet irradiation. However, ultraviolet radiation represents only a small fraction of the solar spectrum. Although strategies such as metal or non-metal doping, heterojunction formation, and surface modification have been proposed to extend photocatalytic activity into the visible region, achieving high efficiency under natural sunlight remains a significant research challenge (Kumar et al., 2020; Zhao et al., 2021).

Economic and Scale-up Issues

The transition of photocatalytic technologies from laboratory experiments to industrial-scale applications requires overcoming several economic and engineering barriers. These include cost-effective synthesis of nanomaterials, long-term catalyst stability, reactor design optimization, and integration with existing wastewater treatment infrastructures. Large-scale photocatalytic systems must also ensure efficient light distribution, adequate mass transfer, and sustainable energy consumption in order to be practically viable (Li et al., 2019).

Toxicity of Nanoparticles

Another important consideration is the potential environmental impact of nanoparticle release into aquatic ecosystems. Although many metal oxides are considered relatively safe, uncontrolled release of nanoparticles could pose risks to aquatic organisms and human health. Therefore, further research is needed to evaluate the toxicity, bioaccumulation potential, and environmental fate of nanomaterials, ensuring that photocatalytic technologies remain environmentally sustainable (Ahmed et al., 2014; Chen et al., 2024).

Future Perspectives

Future research directions include:

Future developments in photocatalytic wastewater treatment are expected to focus on improving catalyst efficiency, sustainability, and scalability. Several promising research directions include:

- Design of advanced heterojunction photocatalysts with improved charge separation and extended light absorption.
- Development of solar-driven photocatalytic reactors capable of treating real industrial wastewater under natural sunlight.
- Integration of hybrid treatment systems, combining photocatalysis with biological, adsorption, or membrane-based processes to enhance overall treatment efficiency.
- Adoption of green synthesis techniques, such as plant extract-mediated nanoparticle production, which reduce the use of hazardous chemicals and minimize environmental impact.

These innovations have the potential to significantly improve the practical applicability of photocatalytic systems for large-scale wastewater treatment applications (Singh et al., 2023; Chen et al., 2024).

Conclusion

The rapid growth of industrial activities, particularly in sectors such as textiles, leather processing, pharmaceuticals, and dye manufacturing, has resulted in the large-scale discharge of coloured effluents into natural water bodies. These synthetic dyes are chemically stable, resistant to bio-degradation, and often toxic to living organisms, posing serious threats to aquatic ecosystems and human health. Traditional wastewater treatment techniques, including adsorption, coagulation –flocculation, and biological treatment, often fail to completely remove dye pollutants. In many cases, these methods merely transfer contaminants from one phase to another without achieving complete degradation. Consequently, the development of advanced and environmentally sustainable treatment technologies has become increasingly important. Among the emerging technologies, photocatalytic degradation using metal oxide nanoparticles has gained significant attention due to its efficiency and environmental compatibility.

This process relies on semiconductor photocatalysis, where light irradiation activates a catalyst and generates reactive oxygen species capable of oxidizing complex organic pollutants. When semiconductor materials absorb photons with energy equal to or greater than their band gap, electron–hole pairs are generated. These charge carriers participate in oxidation and reduction reactions on the catalyst surface, producing highly reactive species such as hydroxyl radicals and superoxide radicals. These radicals attack dye molecules, break down their chromophore structures, and ultimately convert them into simpler inorganic products such as carbon dioxide and water. Among various photocatalytic materials, metal oxide nanoparticles have demonstrated excellent performance due to their high surface area, tuneable electronic properties, and chemical stability. Titanium dioxide remains one of the most widely investigated photocatalysts because of its low toxicity, affordability, and strong oxidative capability.

However, its limited response to visible light has encouraged the exploration of alternative materials such as zinc oxide (ZnO), iron oxide (Fe_2O_3), and tungsten oxide (WO_3), which exhibit improved light absorption properties. The nanoscale structure of these materials significantly enhances photocatalytic performance. Smaller particle sizes provide a larger surface-to-volume ratio, increasing the number of active sites available for pollutant adsorption and degradation. Additionally, reduced diffusion distances for charge carriers help minimize electron–hole recombination, which is one of the major factors limiting photocatalytic efficiency. Recent advances in synthesis techniques—including sol–gel processes, hydrothermal methods, co-precipitation, and environmentally friendly green synthesis approaches—have enabled better control over nanoparticle size, morphology, crystallinity, and surface characteristics.

These improvements have contributed to higher degradation efficiencies and enhanced catalyst stability. Experimental studies have also shown that photocatalytic performance is strongly influenced by operational parameters such as catalyst concentration, initial dye concentration, pH of the solution, irradiation intensity, and reaction time. Optimization of these parameters plays a crucial role in achieving maximum degradation efficiency. Many studies have reported that dye degradation follows pseudo-first-order kinetics, consistent with the Langmuir–Hinshelwood reaction model.

Despite its numerous advantages, photocatalytic wastewater treatment still faces several challenges. These include rapid recombination of charge carriers, difficulties in catalyst recovery, and the need for cost-effective large-scale reactor systems. To overcome these limitations, researchers are actively exploring strategies such as doping, heterojunction formation, surface modification, and catalyst immobilization. Another promising approach involves integrating photocatalysis with complementary treatment methods such as adsorption or biological processes, creating hybrid systems capable of improving overall treatment performance. Additionally, the use of solar radiation as a renewable energy source can significantly enhance the sustainability of photocatalytic technologies. Overall, photocatalytic degradation using metal oxide nanoparticles represents a powerful, environmentally friendly, and sustainable solution for the removal of industrial dye pollutants from wastewater. With continued advances in nanotechnology, materials engineering, and reactor design, this technology has strong potential to become a key component of future wastewater treatment systems. Continued research and development in this field will play an important role in protecting water resources and supporting sustainable industrial development.

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PHYTOREMEDIATION EFFICIENCY OF EMERGENT MACROPHYTES IN HORIZONTAL SUBSURFACE FLOW CONSTRUCTED WETLANDS: A COMPARATIVE ASSESSMENT OF SPECIES-SPECIFIC POLLUTANT REMOVAL CAPACITY

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Research Paper

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ABSTRACT

Constructed wetlands (CWs) utilizing macrophytes represent a sustainable and cost-effective approach for sewage treatment in developing regions. This pilot study evaluated the performance of selected macrophytes (*Typha latifolia*, *Phragmites australis*, and *Canna indica*) in a horizontal subsurface flow constructed wetland system for treating domestic sewage. The study was conducted over a 6-month period (March-August 2024) with a hydraulic retention time of 3 days. Water quality parameters including biochemical oxygen demand (BOD), chemical oxygen demand (COD), total suspended solids (TSS), total nitrogen (TN), total phosphorus (TP), and fecal coliforms were monitored bi-weekly. Results demonstrated significant removal efficiencies: BOD (82-89%), COD (76-84%), TSS (85-92%), TN (68-75%), and TP (71-79%). *Typha latifolia* exhibited the highest overall performance with superior nutrient uptake capacity and biomass production (2.8 kg/m^2). Plant growth rates and physiological responses were monitored to assess stress tolerance and adaptation. The findings suggest that macrophyte-based constructed wetlands can effectively treat domestic sewage, providing an eco-friendly alternative to conventional treatment systems, particularly suitable for small communities and rural areas with limited infrastructure.

No. of Pages: 5 **References: 14**

Keywords: Constructed wetlands, macrophytes, sewage treatment, phytoremediation, wastewater management, Typha latifolia.

Introduction

Global water scarcity and increasing pollution of freshwater resources have necessitated the development of sustainable wastewater treatment technologies (Vymazal, 2011). Conventional sewage treatment systems, while effective, require substantial capital investment, operational costs, and technical expertise, making them impractical for many developing regions and rural communities (Kadlec & Wallace, 2009). Constructed wetlands (CWs) have emerged as viable alternatives that combine ecological engineering principles with natural treatment processes to achieve efficient pollutant removal at reduced costs (Wu et al., 2015).

Constructed wetlands are engineered systems designed to simulate natural wetland ecosystems for wastewater treatment through physical, chemical, and biological processes (Brix, 1997). These systems utilize the synergistic interactions between substrates, microorganisms, and vegetation to remove contaminants from wastewater (Zhang et al., 2014). Among the various components, macrophytes play a crucial role in enhancing treatment efficiency through multiple mechanisms including direct nutrient uptake, oxygen transfer to the rhizosphere, providing surface area for microbial biofilms, and physical filtration (Vymazal, 2013).

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Macrophytes used in constructed wetlands are typically emergent species capable of tolerating waterlogged conditions and high pollutant concentrations (Tanner, 1996). Common species include *Typha* spp., *Phragmites australis*, *Scirpus* spp., and ornamental plants like *Canna* spp. (Greenway, 2005). The selection of appropriate plant species is critical for optimizing treatment performance and ensuring system sustainability under varying environmental conditions (Shelef et al., 2013).

Previous studies have demonstrated the effectiveness of macrophyte-based constructed wetlands for treating various types of wastewater, including domestic sewage, industrial effluents, and agricultural runoff (Vymazal & Kröpfelová, 2008; Stottmeister et al., 2003). However, most research has focused on temperate climates, and there remains a need for region-specific pilot studies to evaluate system performance under local environmental conditions and with indigenous or adapted plant species (Kivaisi, 2001).

The present study aims to evaluate the performance of three macrophyte species (*Typha latifolia*, *Phragmites australis*, and *Canna indica*) in a pilot-scale horizontal subsurface flow constructed wetland for treating domestic sewage. Specific objectives include: (1) assessing pollutant removal efficiency for key water quality parameters, (2) comparing the performance of different macrophyte species, (3) monitoring plant growth and biomass production, and (4) evaluating the feasibility of constructed wetlands as a decentralized sewage treatment option for small communities.

Materials and Methods

Study Site and Experimental Design

The pilot study was conducted at a rural wastewater treatment facility located in Maharashtra, India (19°N, 74°E) from March to August 2024. The climate is characterized as semi-arid with an average annual temperature of 25-28°C and rainfall of approximately 600 mm. The experimental setup consisted of nine horizontal subsurface flow (HSSF) constructed wetland units, each measuring 4 m × 2 m × 0.6 m (length × width × depth), arranged in a randomized block design with three replicates per treatment.

Constructed Wetland Configuration

Each wetland unit was constructed using reinforced concrete with a waterproof lining to prevent seepage. The substrate consisted of three layers: a bottom drainage layer of coarse gravel (20-30 mm diameter, 15 cm depth), a middle layer of medium gravel (10-15 mm diameter, 20 cm depth), and a top layer of fine gravel mixed with sand (5-10 mm diameter, 20 cm depth). The total substrate depth was 55 cm, with a water level maintained at 5 cm below the substrate surface. Inlet and outlet zones (40 cm each) consisted of coarse gravel to ensure uniform flow distribution and collection.

Macrophyte Selection and Establishment

Three macrophyte species were selected based on their documented wastewater treatment potential and local availability:

1. *Typha latifolia* L. (Common cattail) - emergent macrophyte, Typhaceae family
2. *Phragmites australis* (Cav.) Trin. ex Steud. (Common reed) - emergent macrophyte, Poaceae family
3. *Canna indica* L. (Indian shot) - emergent ornamental macrophyte, Cannaceae family

Uniform rhizomes or plantlets (n=25 per unit) were collected from established populations and transplanted into the wetland units in February 2024. A one-month establishment period was provided with reduced wastewater loading (50% of design load) before initiating the full-scale experiment. Three control units without vegetation were maintained for comparison.

Wastewater Characteristics and Loading

Domestic sewage from a nearby residential area (population ~500) was used as influent. The raw sewage was characterized by high organic content and nutrient concentrations typical of domestic wastewater. The wetland units were operated in continuous flow mode with a hydraulic retention time (HRT) of 3 days and an organic loading rate of 40 g BOD/m^2/day. Daily flow rate was maintained at 0.27 m^3/day per unit using flow meters.

Typical influent characteristics were: pH 7.2-7.8, BOD 180-240 mg/L, COD 320-450 mg/L, TSS 150-220 mg/L, TN 35-50 mg/L, TP 8-12 mg/L, and fecal coliforms 10 -10 MPN/100 mL.

Sampling and Analytical Methods

Water samples were collected bi-weekly from inlet and outlet points of each wetland unit using acid-washed polyethylene bottles. Samples were transported to the laboratory in ice boxes and analyzed within 24 hours following standard methods (APHA, 2017). The following parameters were measured:

- pH and temperature: measured in situ using a portable pH meter (Hanna Instruments)
- Dissolved oxygen (DO): measured using a DO meter (Hanna HI-9146)

- Biochemical oxygen demand (BOD5): 5-day incubation method (APHA 5210 B)
- Chemical oxygen demand (COD): closed reflux colorimetric method (APHA 5220 D)
- Total suspended solids (TSS): gravimetric method (APHA 2540 D)
- Total nitrogen (TN): Kjeldahl digestion followed by spectrophotometry (APHA 4500-N)
- Total phosphorus (TP): acid digestion followed by ascorbic acid method (APHA 4500-P)
- Fecal coliforms: membrane filtration technique (APHA 9222 D)

Plant Performance Monitoring

Plant growth parameters were measured monthly for 15 randomly selected plants per wetland unit:

- **Plant height:** measured from substrate surface to the highest leaf tip
- **Stem diameter:** measured at 5 cm above substrate surface using digital calipers
- **Leaf count:** total number of living leaves per plant
- **Biomass production:** aboveground biomass harvested at the end of the study, dried at 70°C for 48 hours, and weighed

Tissue samples from roots and shoots were collected at the study conclusion for nutrient content analysis (N, P, K) using standard digestion and spectrophotometric methods.

Statistical Analysis

Data were analyzed using SPSS version 26.0 (IBM Corp., Armonk, NY). Removal efficiencies were calculated as:

$$\text{Removal efficiency (\%)} = [(C_{in} - C_{out}) / C_{in}] \times 100$$

where Cin and Cout represent influent and effluent concentrations, respectively.

One-way analysis of variance (ANOVA) was performed to compare treatment efficiencies among different macrophyte species and control units, followed by Tukey's HSD post-hoc test for multiple comparisons. Pearson correlation analysis was used to examine relationships between plant growth parameters and pollutant removal rates. Statistical significance was set at $p < 0.05$.

Results

Water Quality Parameters and Removal Efficiency

The pilot-scale constructed wetlands demonstrated substantial removal of organic matter, nutrients, and fecal coliforms throughout the study period. Table 1 presents the mean influent and effluent concentrations along with removal efficiencies for different macrophyte treatments.

Table 1: Mean Water Quality Parameters and Removal Efficiencies in Constructed Wetlands.

Parameter	Influent Effluent (% Removal)	T. latifolia Effluent (% Removal)	P. australis Effluent (% Removal)	C. indica Effluent (% Removal)	Control
BOD (mg/L)	208 ± 28	23 ± 6 (89.0 ± 2.3)[a]	28±7 (86.5±2.8)[ab]	37±9 (82.2 ± 3.1)[b]	58 ± 12 (72.1 ± 4.2)[c]
COD (mg/L)	384 ± 52	62 ± 14 (83.9 ± 2.6)[a]	71 ± 16 (81.5±3.2)[ab]	92 ± 18 (76.0±3.7)[b]	124 ± 24 (67.7 ± 4.5)[c]
TSS (mg/L)	186 ± 34	15 ± 5 (91.9 ± 2.1)[a]	18 ± 6 (90.3 ± 2.4)[ab]	28 ± 8 (84.9 ± 3.0)[b]	42 ± 11 (77.4 ± 4.1)[c]
TN (mg/L)	42 ± 7	11 ± 3 (73.8 ± 3.4)[a]	12 ± 3 (71.4 ± 3.8)[ab]	14 ± 4 (66.7 ± 4.2)[b]	18 ± 5 (57.1 ± 5.1)[c]
TP (mg/L)	9.8 ± 1.6	2.1 ± 0.6 (78.6 ± 3.2)[a]	2.4 ± 0.7 (75.5 ± 3.6)[ab]	2.8 ± 0.8 (71.4 ± 4.0)[b]	3.6 ± 0.9 (63.3 ± 4.8)[c]
Fecal coliforms (log MPN /100mL)	6.2 ± 0.4	2.8 ± 0.5 (3.4 log reduction)[a]	3.0 ± 0.5 (3.2 log reduction)[a]	3.3 ± 0.6 (2.9 log reduction)[a]	4.1 ± 0.7 (2.1 log reduction)[a]

Note: Values represent means ± standard deviation (n = 12 sampling events × 3 replicates). Different superscript letters indicate statistically significant differences ($p < 0.05$) among treatments based on Tukey's HSD test.

Organic Matter Removal

All vegetated wetlands achieved high removal rates for both BOD and COD. *Typha latifolia* systems demonstrated the highest BOD removal efficiency (89.0 ± 2.3%), significantly outperforming control units (72.1 ± 4.2%, $p < 0.001$). The removal efficiency followed the order: *T. latifolia* > *P. australis* > *C. indica* > Control. Similar trends were observed for COD removal, with *T. latifolia* achieving 83.9% removal compared to 67.7% in unvegetated controls.

Suspended Solids Removal

TSS removal was highly efficient across all treatments, with vegetated systems achieving 85-92% removal. Both *T. latifolia* and *P. australis* performed comparably (91.9% and 90.3%, respectively; $p > 0.05$), significantly exceeding the performance of *C. indica* (84.9%) and control units (77.4%). The physical filtration capacity of the gravel substrate, enhanced by root system development, contributed to effective particle removal.

Discussion

Treatment Performance and Mechanisms

The pilot study demonstrated that macrophyte-based horizontal subsurface flow constructed wetlands can effectively treat domestic sewage, achieving removal efficiencies comparable to or exceeding conventional secondary treatment systems. The observed BOD removal rates (82-89%) align with previous studies reporting 75-95% removal in similar systems (Vymazal, 2011; Wu et al., 2015). The superior performance of vegetated systems compared to unvegetated controls confirms the critical role of macrophytes in enhancing treatment processes.

Multiple synergistic mechanisms contribute to pollutant removal in constructed wetlands. Organic matter degradation occurs primarily through aerobic and anaerobic microbial metabolism (Stottmeister et al., 2003). Macrophytes enhance this process by releasing oxygen through roots, creating oxidized microsites in the otherwise anaerobic substrate where aerobic bacteria can degrade organic compounds (Brix, 1997). The extensive root systems also provide large surface areas for biofilm development, increasing overall microbial activity.

Species-Specific Performance

Typha latifolia emerged as the superior species for wastewater treatment in this study, demonstrating highest removal efficiencies for all measured parameters except TSS, where performance was comparable to *P. australis*. Several factors contribute to *T. latifolia*'s enhanced performance. First, its vigorous growth and high biomass production (4.73 kg/m^2) indicate robust metabolic activity and nutrient uptake capacity. Second, Typha species are characterized by well-developed aerenchyma tissue facilitating efficient oxygen transport to roots, thereby enhancing rhizosphere oxidation and supporting aerobic microbial processes (Brix, 1997).

Conclusion

This pilot study demonstrates that macrophyte-based horizontal subsurface flow constructed wetlands provide effective treatment for domestic sewage, achieving substantial removal of organic matter, nutrients, and pathogens. *Typha latifolia* emerged as the optimal species, combining high treatment efficiency with robust growth and biomass production. The superior performance of vegetated systems compared to unvegetated controls confirms the essential role of macrophytes in enhancing treatment through multiple mechanisms including oxygen transfer, nutrient uptake, and biofilm support.
The study supports the feasibility and sustainability of constructed wetlands as decentralized wastewater treatment solutions, particularly for small communities and rural areas lacking conventional infrastructure. These systems offer ecological, economic, and social benefits including low capital and operating costs, minimal energy consumption, simple operation, aesthetic value, and potential for habitat creation. The findings provide valuable baseline data for designing and implementing constructed wetland systems in similar climatic and socioeconomic contexts.

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ASSESSMENT OF GROUNDWATER QUALITY FOR DRINKING PURPOSE IN SONIPAT BLOCK OF HARYANA

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ABSTRACT

The study area Sonipat block is located in Sonipat district of Haryana state between the latitudes 28.93^{0}N to 29.13^{0}N and longitudes 76.81^0 to 77.10^0 E and covers an area of 341.22 sq. km. Geologically alluvium and geomorphologically alluvial plain are present in the study area. The main objective of the study was to assess groundwater quality for drinking purpose in the study area. In the study area twenty six groundwater samples were collected in 250 ml double capped plastic bottles. Geo-coordinates of sample locations were noted with the help of mobile GPS. Chemical analysis of twenty six groundwater samples were done using Tamilnadu Water Supply and Drainage (TWAD) Board, Chennai prepared Field Water Testing kit for twelve chemical parameters viz. pH, alkalinity, hardness, chloride, total dissolved solids (TDS), fluoride, iron, nitrite, nitrate, ammonia, phosphate and residual chlorine. Results of groundwater samples analysis were compared with BIS (IS 10500:2012) drinking water standards to know groundwater quality for drinking purpose. The study shows that in the study area pH ranges 6.5 to 8.5, alkalinity 70 mg/l to 650 mg/l, hardness 100 mg/l to 620 mg/l,chloride 10 mg/l to 710 mg/l, TDS 252 mg/l to 1824 mg/l,fluoride nil to 5 mg/l, iron nil to 0.3 mg/l,ammonia nil to 5 mg/l,nitrite 0.5 mg/l to1 mg/l,nitrate 45 mg/l to 100 mg/l,phosphate nil to 1 mg/l, residual chlorine nil to 2 mg/l. The study is highly useful for planning and monitoring of groundwater for drinking purpose in the study area.

No. of Pages: 6 **References: 12**

Keywords: Groundwater, quality, drinking, Sonipat, Haryana.

INTRODUCTION

Water is a precious natural gift by the nature to the planet Earth. Earlier there was a balance between recharge and withdrawal of groundwater, hence, the groundwater depth was shallow and quality deterioration was mainly from natural sources. But in the present time, groundwater recharge is less and withdrawal is more which have resulted in decling of groundwater depth as well as quality deterioration is due to anthropogenic reseaons like using artificial manures and herbicides in agriculture and industrial wastes. The anthropogenic pollution of groundwater has made groundwater unsuitable for drinking purpose in many areas. Rajankar et al.(2009), Annapoorna and Janardhana (2015), Kumar et al. (2015), Punia et al. (2015), Deshpande and Patil (2016), Nagaraju et al.(2016), Nelly and Mutua (2016), Chaudhary and Satheeshkumar (2018), Khelif and Boudoukha (2018), Hanumantharao et al.(2019), Zhang et al. (2019) had done work on groundwater quality assessment for drinking purpose in many areas.

STUDY AREA

Sonipat block is located in Sonipat district, Haryana (Fig.1). The geo-coordinates of the study area are latitudes 28.93^{0}N to 29.13^0 N and longitudes 76.81^0 to 77.10^0 E and covers an area of 341.22 sq. km. Geologically alluvium and geomorphologically alluvial plain are present.

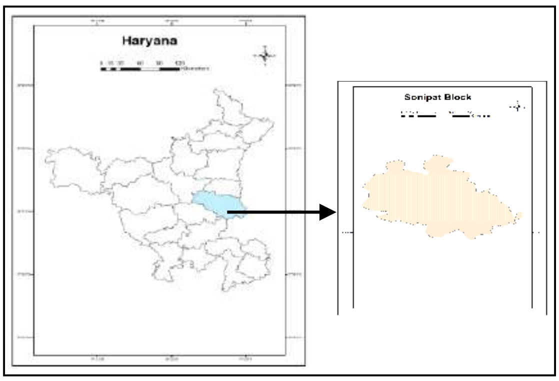

Fig.1: Location map of the study area.

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OBJECTIVE

The main objective was to assess groundwater quality for drinking purpose in the study area.

MATERIALS AAND METHODOLOGY

In the study area twenty six groundwater samples were collected in 250 ml double capped plastic bottles. Geo-coordinates of sample locations were noted with the help of mobile GPS. Chemical analysis of twenty six groundwater samples were done using Tamilnadu Water Supply and Drainage (TWAD) Board, Chennai prepared Field Water Testing kit for twelve chemical parameters viz. pH, alkalinity, hardness, chloride, total dissolved solids (TDS), fluoride, iron, nitrite, nitrate, ammonia, phosphate and residual chlorine (Table 1). Results of groundwater samples analysis were compared with BIS drinking water standards (IS 10500:2012) (Table 2) to know groundwater quality for drinking purpose.

Table 1: Result of chemical analysis of groundwater samples.

S. No.	Sample Location	Latitude	Longitude	pH	Alkalinity (mg/l)	Hardness (mg/l)	Chloride (mg/l)	TDS (mg/l)	Fluoride (mg/l)	Iron (mg/l)	Ammonia (mg/l)	Nitrite (mg/l)	Nitrate (mg/l)	Phosphate (mg/l)	Residual Chlorine (mg/l)
1	Sandal Kalan	28.92	77.07	7.5	450	500	50	1200	0	0	0.5	0.5	100	0	0
2	Jatheri	28.96	77.06	8	450	620	10	1296	1.5	0	1	0.5	100	0	2
3	Rardhana	28.93	77.07	8	610	550	50	1452	0	0	0.5	0.5	75	0.5	0.2
4	Liiwan-1	28.97	77.05	7.5	650	350	270	1524	1.5	0	0.5	0.5	45	0	0
5	Bandpur	28.95	77.04	7	320	320	450	1308	3	0	0.5	0.5	45	0	0.5
6	Jagdishpur	28.97	77.03	7.5	520	180	50	900	1.5	0	0.5	0.5	45	0	0.2
7	Bayyanpur-1	29.01	76.97	6.5	250	520	640	1692	2	0	0.5	1	100	0	0
8	Barwasni-1	28.96	76.96	6.5	70	120	20	252	1	0	1	0.5	45	0	0
9	Kakroi	28.99	77.05	6.5	120	250	20	468	1.5	0	0.5	0.5	45	0	0
10	Garh Sahajanpur	28.95	77.04	7.5	550	100	80	876	5	0	0.5	1	100	0	0
11	Rardhana-2	29.01	76.96	7	130	130	40	360	0	0	0.5	0.5	45	0	0
12	Barwasni-2	28.96	77.08	7.5	480	620	420	1824	1.5	0	1	0.5	45	0	0.2
13	Bayyanpur-2	28.96	77.00	7.5	280	470	710	1752	2	0	1	0.5	45	1	0
14	Raipur-2	28.99	77.05	7.5	500	170	190	1032	3	0	0.5	0.5	45	0.5	0
15	Raipur-1	28.98	76.96	7.5	360	140	400	1080	3	0	0.5	0.5	45	1	0
16	Mehlana	29.01	76.96	7.5	100	120	30	300	3	0	0.5	0.5	45	0.5	0
17	Barwasni-3	29.01	76.96	7.5	120	370	20	612	1	0	0.5	1	100	0	0
18	Badhana	28.94	77.04	8	100	200	140	528	3	0.3	0.5	1	75	1	0
19	Jagdishpur-2	28.99	77.05	7	100	170	70	408	3	0	0.5	0.5	45	0	0
20	Fajilpur	28.99	77.05	8.5	520	340	120	1176	1.5	0	5	1	75	0	0
21	Liiwan-2	28.94	77.07	7.5	330	310	40	816	1.5	0	0	0.5	45	0	0
22	Pinana	29.06	76.83	8	450	430	120	1200	1.5	0	0.5	0.5	45	0	0
23	Jatheri-2	28.92	77.08	7	140	200	30	444	1	0.3	0.5	0.5	45	0	0
24	Rewali	29.01	77.06	7.5	180	200	100	576	1	0	0	0.5	45	0	0
25	Sahpur Turk	29.03	76.95	7	200	130	190	624	1.5	0	0	0.5	45	0	0
26	Hullaheri	28.92	77.07	7	300	270	160	876	1.5	0.3	0	0.5	45	0	0

Table 2: BIS drinking water standards (IS 10500:2012)

S. No.	Parameters	Potable		Non-Potable
		Desirable	Permissible	
1	pH	6.5 to 8.5	-	<6.5 and >8.5
2	Alkalinity (mg/l)	<200	200-600	>600
3	Total Hardness (mg/l)	<200	200-600	>600
4	Chloride (mg/l)	<250	250-1000	>1000
5	Total Dissolved Solids (TDS) (mg/l)	<500	500-2000	>2000
6	Fluoride (mg/l)	<1.0	1.0-1.5	>1.5
7	Iron (mg/l)	<0.3	-	>0.3
8	Ammonia (mg/l)	<0.5	-	>0.5
9	Nitrite (mg/l)	<1.0	-	>1.0
10	Nitrate (mg/l)	<45	-	>45
11	Phosphate (mg/l)	<1.0	-	>1.0
12	Residual Chlorine (mg/l)	<0.2	0.2-1.0	>1.0

RESULTS AND DISCUSSION

i. pH

In the study area pH ranges 6.5 to 8.5 (Table 1, Fig.2). As per BIS (IS 10500:2012) drinking water standards pH is desirable between 6.5 to 8.5 and non-potable if less than 6.5 and more than 8.5 (Table 2). pH is desirable in all the twenty six groundwater samples (Sandal Kalan, Jatheri, Rardhana, Liwan-1, Bandpur, Jagdishpur, Bayyanpur-1, Barwasni-1, Kakroi, Garh Sahajanpur, Rardhana-2, Barwasni-2, Bayyanpur-2, Raipur-2, Raipur-1, Mehlana, Barwasni-3, Badhana, Jagdishpur-2, Fajilpur, Liwan-2, Pinana, Jatheri-2, Rewali, Sahpur Turk, Hullaheri)..

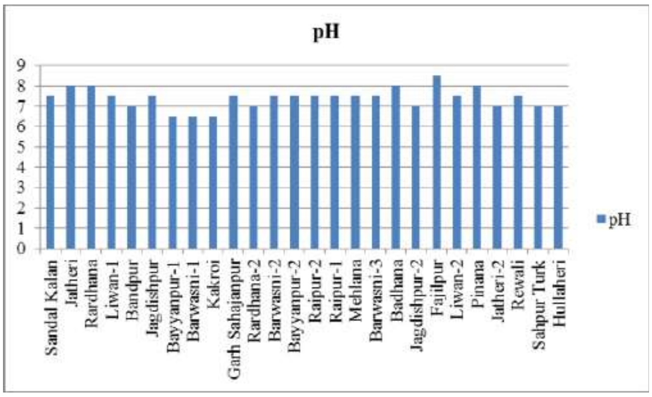

Fig.2: pH in groundwater samples.

ii. Alkalinity

In the study area alkalinity ranges 70 mg/l to 650 mg/l (Table 1, Fig.3). As per BIS (IS 10500:2012) drinking water standards alkalinity is desirable if less than 200 mg/l, permissible between 200 mg/l-600 mg/l and non-potable if more than 600 mg/l (Table 2). Alkalinity is desirable in nine groundwater samples (Barwasni-1, Kakroi, Rardhana-2, Mehlana, Barwasni-3, Badhana, Jagdishpur-2, Jatheri-2, Rewali), permissible in fifteen groundwater samples (Sandal Kalan, Jatheri, Bandpur, Jagdishpur, Bayyanpur-1, Garh Sahajanpur, Barwasni-2, Bayyanpur-2, Raipur-2, Raipur-1, Fajilpur, Liwan-2, Pinana, Sahpur Turk, Hullaheri) and non-potable in two groundwater samples (Randhana (610 mg/l), Liwan-1(650 mg/l)).

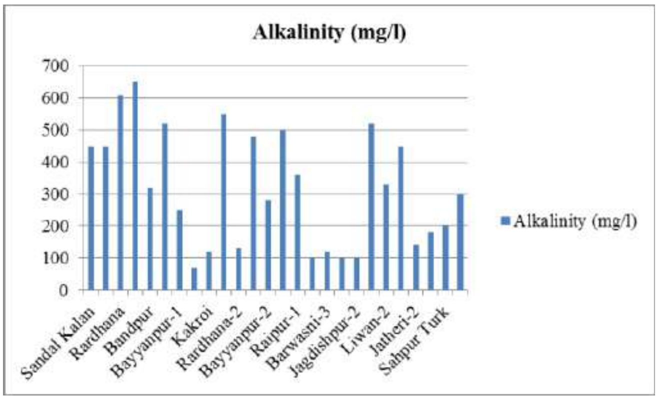

Fig. 3: Alkalinity in groundwater samples.

iii. Hardness

In the study area hardness ranges 100 mg/l to 620 mg/l (Table 1, Fig.4). As per BIS (IS 10500:2012) drinking water standards hardness is desirable if less than 200 mg/l, permissible between 200 mg/l - 600 mg/l and non-potable if more than 600 mg/l (Table 2). Hardness is desirable in nine groundwater samples **(**Jagdishpur, Barwasni-1, Garh Sahajanpur, Rardhana-2, Raipur-2, Raipur-1, Mehlana, Jagdishpur-2, Sahpur Turk), permissible in fifteen groundwater samples (Sandal Kalan, Rardhana, Liwan-1, Bandpur, Bayyanpur-1, Kakroi, Bayyanpur-2, Barwasni-3, Badhana, Fajilpur, Liwan-2, Pinana, Jatheri-2, Rewali, Hullaheri) and non-potable in two groundwater samples (Jatheri (620 mg/l), Barwasni-2 (620 mg/l).

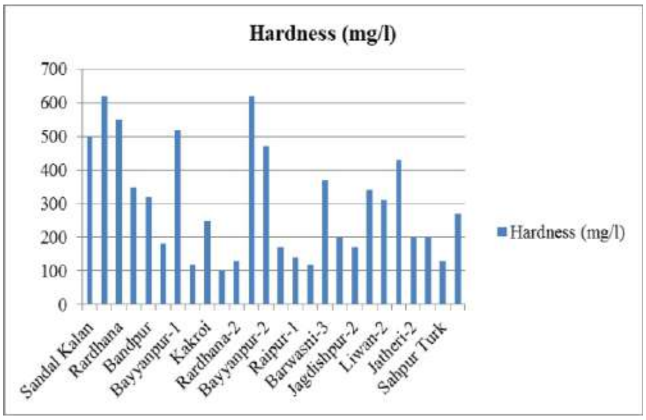

Fig. 4: Hardness in groundwater samples.

iv. Chloride

In the study area chloride ranges 10 mg/l to 710 mg/l (Table 1, Fig.5). As per BIS (IS 10500:2012) drinking water standards chloride is desirable if less than 250 mg/l, permissible between 250 mg/l - 1000 mg/l and non-potable if more than 1000 mg/l (Table 2). Chloride is desirable in twenty groundwater samples (Sandal Kalan, Jatheri, Rardhana, Jagdishpur, Barwasni-1, Kakroi, Garh Sahajanpur, Rardhana-2, Raipur-2, Mehlana, Barwasni-3, Badhana, Jagdishpur-2, Fajilpur, Liwan-2, Pinana, Jatheri-2, Rewali, Sahpur Turk, Hullaheri) and permissible in six groundwater samples (Liwan-1, Bandpur, Bayyanpur-1, Barwasni-2, Bayyanpur-2, Raipur-1).

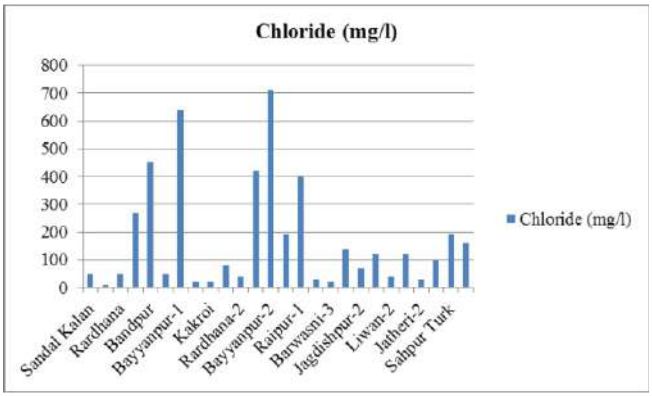

Fig. 5: Chloride in groundwater samples.

v. Total Dissolved Solids (TDS)

In the study area TDS ranges 252 mg/l to 1824 mg/l (Table 1, Fig.6). As per BIS (IS 10500:2012) drinking water standards TDS is desirable if less than 500 mg/l, permissible between 500 mg/l -2000 mg/l and non-potable if more than 2000 mg/l (Table 2). TDS is desirable in six groundwater samples (Barwasni-1, Kakroi, Rardhana-2, Mehlana, Jagdishpur-2, Jatheri-2) and permissible in twenty groundwater samples (Sandal Kalan, Jatheri, Rardhana, Liwan-1, Bandpur, Jagdishpur, Bayyanpur-1, Garh Sahajanpur, Barwasni-2, Bayyanpur-2, Raipur-2, Raipur-1, Barwasni-3, Badhana, Fajilpur, Liwan-2, Pinana, Rewali, Sahpur Turk, Hullaheri).

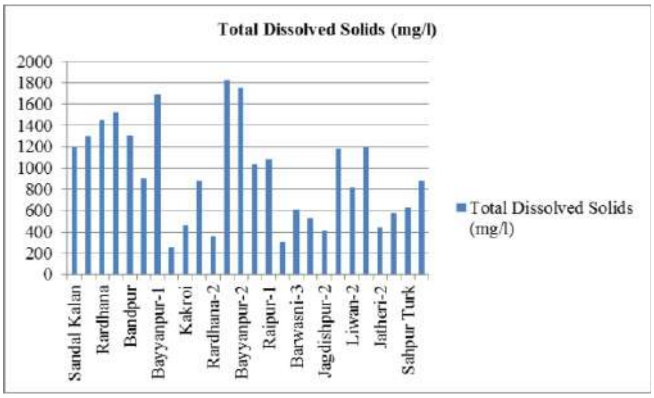

Fig. 6: TDS in groundwater samples.

vi. Fluoride

In the study area fluoride ranges nil to 5 mg/l (Table 1, Fig.7). As per BIS (IS 10500:2012) drinking water standards fluoride is desirable if less than 1.0 mg/l, permissible between 1.0 mg/l -1.5 mg/l and non-potable if more than 1.5 mg/l (Table 2). Fluoride is desirable in three groundwater samples (Sandal Kalan, Rardhana, Rardhana-2), permissible in fourteen groundwater samples (Jatheri, Liwan-1, Jagdishpur, Barwasni-1, Kakroi, Barwasni-2, Barwasni-3, Fajilpur, Liwan-2, Pinana, Jatheri-2, Rewali, Sahpur Turk, Hullaheri) and non-potable in nine groundwater samples (Bandepur (3 mg/l), Bayyanpur-1 (2 mg/l), Garh Sahajanpur (5 mg/l), Bayyanpur-2 (2 mg/l), Raipur-2 (3 mg/l), Raipur-1(3 mg/l), Mehlana (3 mg/l), Badhana (3 mg/l), Jagdishpur-2 (3 mg/l)).

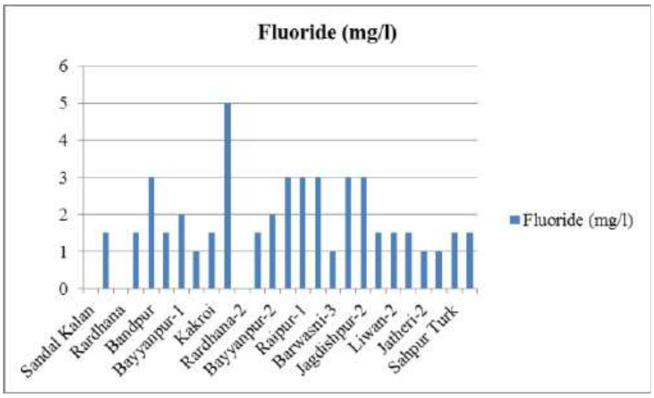

Fig. 7: Fluoride in groundwater samples.

vii. Iron

In the study area iron ranges nil to 0.3 mg/l (Table 1, Fig.8). As per BIS (IS 10500:2012) drinking water standards iron is desirable if less than 0.3mg/l and non-potable if more than 0.3 mg/l (Table 2). Iron is desirable in all the twenty six groundwater samples (Sandal Kalan, Jatheri, Rardhana, Liwan-1, Bandpur, Jagdishpur, Bayyanpur-1, Barwasni-1, Kakroi, Garh Sahajanpur, Rardhana-2, Barwasni-2, Bayyanpur-2, Raipur-2, Raipur-1, Mehlana, Barwasni-3, Badhana, Jagdishpur-2, Fajilpur, Liwan-2, Pinana, Jatheri-2, Rewali, Sahpur Turk, Hullaheri).

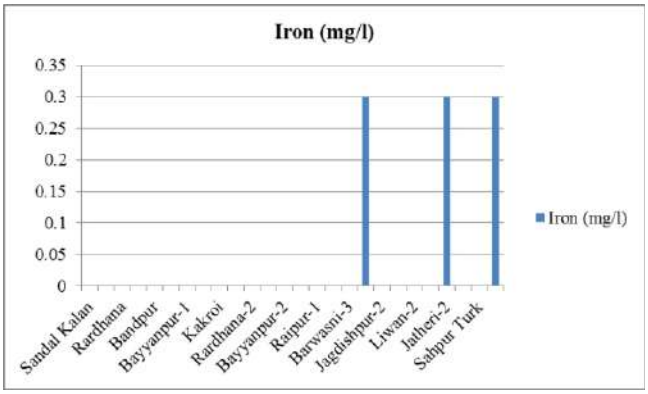

Fig. 8: Iron in groundwater samples.

viii. Ammonia

In the study area ammonia ranges nil to 5 mg/l (Table 1, Fig.9). As per BIS (IS 10500:2012) drinking water standards ammonia is desirable if less than 0.5 mg/l and non-potable if more than 0.5 mg/l (Table 2). Ammonia is desirable in twenty one groundwater samples (Sandal Kalan, Rardhana, Liwan-1, Bandpur, Jagdishpur, Bayyanpur-1, Kakroi, Garh Sahajanpur, Rardhana-2, Raipur-2, Raipur-1, Mehlana, Barwasni-3, Badhana, Jagdishpur-2, Liwan-2, Pinana, Jatheri-2, Rewali, Sahpur Turk, Hullaheri) and non-potable in five groundwater samples (Jatheri (1 mg/l), Barwasni-1(1mg/l), Barwasni-2 (1 mg/l), Bayyanpur-2 (1mg/l), Fajilpur (5 mg/l)).

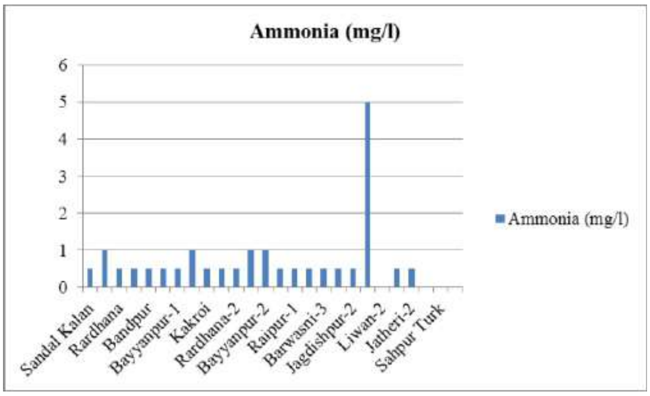

Fig. 9: Ammonia in groundwater samples.

ix. Nitrite

In the study area nitrite ranges 0.5 mg/l to1 mg/l (Table 1, Fig.10). As per BIS (IS 10500:2012) drinking water standards nitrite is desirable if less than 1.0 mg/l and non-potable if more than 1.0 mg/l (Table 2). Nitrite is desirable in all the twenty six groundwater samples (Sandal Kalan, Jatheri, Rardhana, Liwan-1, Bandpur, Jagdishpur, Bayyanpur-1, Barwasni-1, Kakroi, Garh Sahajanpur, Rardhana-2, Barwasni-2, Bayyanpur-2, Raipur-2, Raipur-1, Mehlana, Barwasni-3, Badhana, Jagdishpur-2, Fajilpur, Liwan-2, Pinana, Jatheri-2, Rewali, Sahpur Turk, Hullaheri).

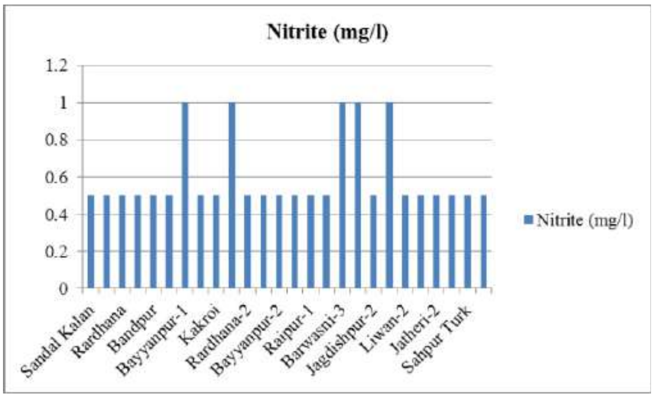

Fig. 10: Nitrite in groundwater samples.

x. Nitrate

In the study area nitrate ranges 45 mg/l to 100 mg/l (Table 1, Fig.11). As per BIS (IS 10500:2012) drinking water standards nitrate is desirable if less than 45 mg/l and non-potable if more than 45mg/l (Table 2). Nitrate is desirable in eighteen groundwater samples (Liwan-1, Bandpur, Jagdishpur, Barwasni-1, Kakroi, Rardhana-2, Barwasni-2, Bayyanpur-2, Raipur-2, Raipur-1, Mehlana, Jagdishpur-2, Liwan-2, Pinana, Jatheri-2, Rewali, Sahpur Turk, Hullaheri) and non-potable in eight groundwater samples (Sandal Kalan (100mg/l), Jatheri (100mg/l), Rardhana (75 mg/l), Bayyanpur-1 (100mg/l), Garh Sahajanpur (100mg/l), Barwasni-3 (75 mg/l), Badhana (75mg/l), Fajilpur (75 mg/l)).

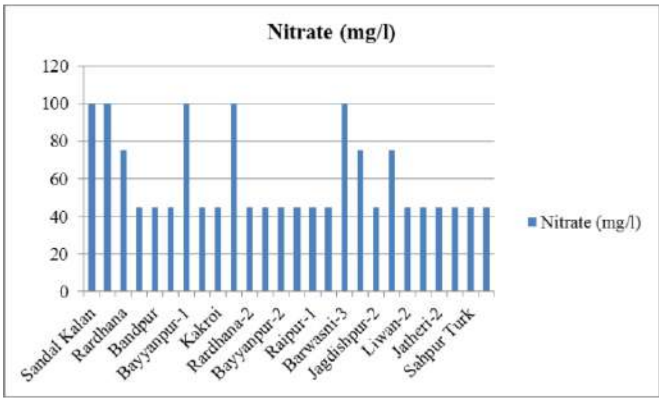

Fig. 11: Nitrate in groundwater samples.

xi. Phosphate

In the study area phosphate ranges nil to 1 mg/l(Table 1, Fig.12). As per BIS (IS 10500:2012) drinking standards phosphate is desirable if less than 1.0 mg/l and non-potable if more than 1.0 mg/l (Table 2). Phosphate is desirable in all the twenty six groundwater samples (Sandal Kalan, Jatheri, Rardhana, Liwan-1, Bandpur, Jagdishpur, Bayyanpur-1, Barwasni-1, Kakroi, Garh Sahajanpur, Rardhana-2, Barwasni-2, Bayyanpur-2, Raipur-2, Raipur-1, Mehlana, Barwasni-3, Badhana, Jagdishpur-2, Fajilpur, Liwan-2, Pinana, Jatheri-2, Rewali, Sahpur Turk, Hullaheri).

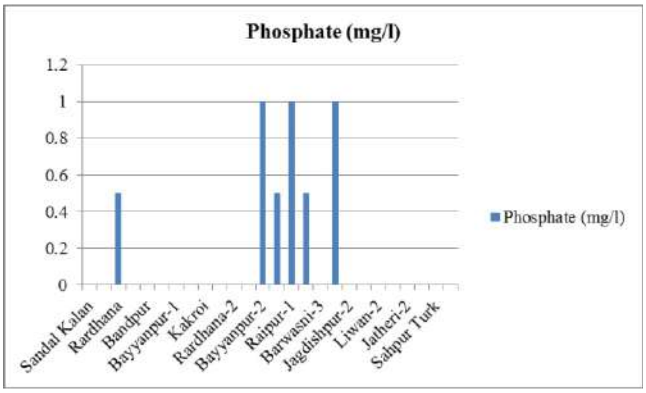

Fig. 12: Phosphate in groundwater samples.

xii. Residual Chlorine

In the study area residual chlorine ranges nil to 2 mg/l (Table 1, Fig.13). As per BIS (IS 10500:2012) drinking water standards residual chlorine is desirable if less than 0.2 mg/l, permissible between 0.2 mg/l-1 mg/l and non-potable if more than 1.0 mg/l (Table 2). Residual chlorine is desirable in twenty one groundwater samples (Sandal Kalan, Liwan-1, Bayyanpur-1, Barwasni-1, Kakroi, Garh Sahajanpur, Rardhana-2, Bayyanpur-2, Raipur-2, Raipur-1, Mehlana, Barwasni-3, Badhana, Jagdishpur-2, Fajilpur, Liwan-2, Pinana, Jatheri-2, Rewali, Sahpur Turk, Hullaheri), permissible in four groundwater samples (Rardhana, Bandpur, Jagdishpur, Barwasni-2) and non-potable in one groundwater sample (Jatheri (2 mg/l))..

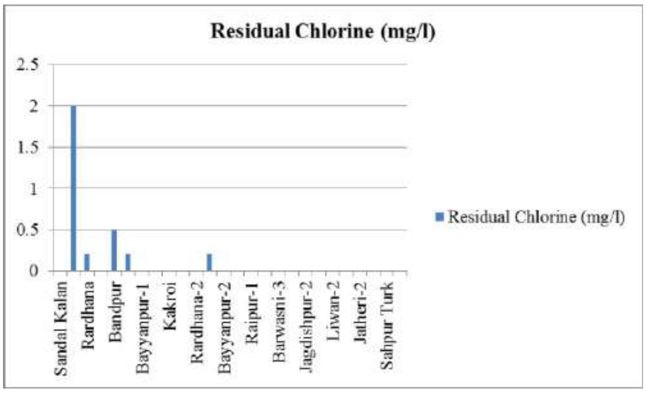

Fig. 13: Residual Chlorine in groundwater samples.

CONCLUSIONS

In the study area pH, iron, nitrite, phosphate are desirable in all the twenty six groundwater samples. Alkalinity is desirable in nine groundwater samples, permissible in fifteen groundwater samples and non-potable in two groundwater samples. Hardness is desirable in nine groundwater samples, permissible in fifteen groundwater samples and non-potable in two groundwater samples. Chloride is desirable in twenty groundwater samples and permissible in six groundwater samples. TDS is desirable in six groundwater samples and permissible in twenty groundwater samples. Fluoride is desirable in three groundwater samples, permissible in fourteen groundwater samples and non-potable in nine groundwater samples. Ammonia is desirable in twenty one groundwater samples and non-potable in five groundwater samples. Nitrate is desirable in eighteen groundwater samples and non-potable in eight groundwater samples. Residual Chlorine is desirable in twenty one groundwater samples, permissible in four groundwater samples and non-potable in one groundwater sample. The study is highly useful for planning and monitoring of groundwater for drinking purpose in the study area.

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