Characterization of Water Quality Parameters of Groundwater in Fluoride Endemic Zones of Mahendergarh District, Haryana

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DOI: 10.29322/IJSRP.16.01.2026.p16911
https://dx.doi.org/10.29322/IJSRP.16.01.2026.p16911

Paper Received Date: 15th November 2025
Paper Acceptance Date: 26th December 2025
Paper Publication Date: 6th January 2026

Abstract

Groundwater quality in semi-arid regions is increasingly threatened by both natural processes and anthropogenic activities, with fluoride contamination emerging as a major concern for public health and agriculture. The present study investigates seasonal variations in groundwater quality across forty sampling sites in Mahendergarh district, Haryana, during pre- and post monsoon periods. Physicochemical parameters including pH, turbidity, electrical conductivity, total hardness, total dissolved solids, alkalinity, major ions, and biological indicators were analyzed following APHA protocols and compared with WHO and BIS standards. Water Quality Index (WQI) and hydrochemical indices such as Sodium Adsorption Ratio (SAR), Residual Sodium Carbonate (RSC) and percent sodium (%Na) were calculated to evaluate drinking and irrigation suitability. Results revealed widespread non compliance, with fluoride concentrations ranging from 1.13 to 6.38 mg/L, exceeding permissible limits in several villages. Elevated hardness, turbidity and critically low dissolved oxygen (<3 mg/L) further compromised water quality. Seasonal dilution during monsoon improved certain parameters, yet post monsoon rebound highlighted persistent contamination. Hydrochemical indices indicated risks of sodicity and reduced soil permeability, rendering groundwater marginal to unsuitable for irrigation in many locations. The findings underscore the urgent need for defluoridation, continuous monitoring and site-specific management strategies to safeguard public health and ensure sustainable water resource utilization.

Keywords: Groundwater quality, Fluoride contamination, Mahendergarh district, Water Quality Index (WQI), Hydrochemical indices, Irrigation suitability, Public health

1. Introduction

Water is universally recognized as the most vital natural resource, sustaining life, ecosystems, and socio economic development. It constitutes nearly three-quarters of the Earth’s surface and is indispensable for agriculture, industry, energy generation, domestic use,

ISSN 2250-3153
and ecological balance (El Moll, 2023). However, the rapid pace of industrialization, urbanization and agricultural intensification has increasingly compromised water quality worldwide. Groundwater, in particular, has emerged as a critical source of drinking and irrigation water in semi arid regions, yet it is highly vulnerable to contamination from both anthropogenic and geogenic factors (Priyan, 2021). In India, groundwater accounts for more than 60% of irrigation and nearly 80% of drinking water supply (Saha and Ray, 2018). The overexploitation of aquifers, coupled with inadequate waste management practices, has led to deterioration in water quality (Akhtar et al., 2021). Among the various contaminants, fluoride occupies a unique position due to its dual role while trace amounts are beneficial for dental health; excessive concentrations pose severe risks, including dental and skeletal fluorosis (Ahmad et al., 2022). The World Health Organization (WHO) recommends fluoride levels in drinking water to remain around 1.0 mg/L, yet concentrations in many Indian states far exceed this limit (Ali et al., 2016). Epidemiological surveys estimate that endemic fluorosis affects more than 67 million people across 20 states, making it one of the most widespread water-related health problems in the country (Khanam et al., 2022).

Mahendergarh district in southern Haryana exemplifies this challenge. Characterized by semi arid climate, sandy soils and alkaline lithology, the region is geologically predisposed to fluoride mobilization (Patel et al., 2023). Groundwater is the primary source of drinking and irrigation water and its quality directly influences public health and agricultural productivity (Abanyie et al., 2023). Reports from the district indicate high prevalence of dental and skeletal fluorosis, alongside other waterborne diseases such as diarrhea, jaundice and anemia. These health burdens underscore the urgent need for systematic evaluation of groundwater quality. Water Quality Index (WQI) has emerged as a robust tool for integrating multiple physicochemical parameters into a single composite score, thereby simplifying the assessment of water suitability for human consumption (Chidiac et al., 2023). Similarly, hydrochemical indices such as Sodium Adsorption Ratio (SAR), Residual Sodium Carbonate (RSC) and percent sodium (%Na) provide critical insights into irrigation suitability. Together, these indices enable comprehensive evaluation of groundwater for both domestic and agricultural purposes (Abbas et al., 2025).

The present study aims to assess the physicochemical characteristics and fluoride concentration of groundwater in Mahendergarh district, Haryana, across pre and post monsoon seasons. By comparing observed values with WHO, BIS standards and calculating WQI and hydrochemical indices, the research seeks to determine the suitability of groundwater for drinking and irrigation. Furthermore, the study intends to highlight the health implications of fluoride contamination and propose management strategies for sustainable water resource utilization (Uddin et al., 2023). This investigation not only contributes to scientific understanding of groundwater chemistry in fluoride prone regions but also provides actionable data for policymakers, health authorities and local communities.

2. Study area

2.1 Geographical Location and Boundaries

Mahendergarh district is situated in the southern part of Haryana state, India, covering an area of approximately 1,899 km². Geographically, it lies between latitudes 27°47′–28°26′ N and longitudes 75°56′–76°51′ E. The district shares boundaries with Bhiwani, Charkhi Dadri and Rohtak districts to the north; Rewari district and Alwar district of Rajasthan to the east; Jaipur, Alwar, and Sikar districts of Rajasthan to the south; Jhunjhunu and Sikar districts of Rajasthan to the west. Narnaul town serves as the administrative headquarters. The district is strategically located along the Aravalli mountain range, which influences its geomorphology and groundwater characteristics. According to the 2025 Census, Mahendergarh has population of 11.22 lakh**,** with approximately 5.88 lakh males and 5.34 lakh females.

2.2 Climate and Soil Characteristics

The district experiences a semi arid climate with extreme seasonal variations. Summer temperatures often rise above 42°C while winter temperatures may drop to around 6°C. Annual rainfall averages 550 mm, with the majority received during the monsoon season (July-September). The region is prone to droughts due to irregular rainfall distribution and high evapotranspiration rates. Soils in Mahendergarh are predominantly sandy with frequent sand dunes observed across the landscape (Chaudhari et al., 2024). The texture is coarse with low organic matter and poor water holding capacity. These soil characteristics combined with high alkalinity, contribute to the mobilization of fluoride and other ions into groundwater (Li et al., 2020). The semi arid climate and sandy soils thus play a critical role in determining both the recharge potential and chemical composition of aquifers.

2.3 Hydro geological Features Influencing Groundwater

Mahendergarh district is influenced by the Aravalli range which consists of crystalline rocks and alkaline lithology. These geological formations are known to release fluoride ions into groundwater through weathering and leaching processes. The aquifers are primarily unconfined to semi confined with groundwater occurring at shallow to moderate depths (Orecchia et al., 2022). Seasonal fluctuations in the water table are common with depletion observed during pre monsoon months due to over extraction for agriculture and domestic use. Groundwater quality is further affected by the interaction of recharge water with soil and rock minerals. The presence of carbonate and bicarbonate ions, coupled with high sodium concentrations, alters the hydrochemical balance, often leading to elevated values of Residual Sodium Carbonate (RSC) and Sodium Adsorption Ratio (SAR) (Abbas et al., 2025). These parameters directly influence the suitability of groundwater for irrigation. In addition, the semi-arid climate restricts natural dilution processes, causing persistent high concentrations of fluoride in many parts of the district.

3. Materials and Method

3.1 Sampling Strategy

Groundwater samples were collected from tube wells and hand pumps located across different villages of Mahendergarh district. To capture seasonal variations, sampling was carried out during pre monsoon (May-June) and post-monsoon (October-November) periods. Each sample was collected in clean, sterilized polyethylene containers (2 L capacity), sealed immediately to prevent contamination and transported to the laboratory under controlled conditions. On site measurements (temperature, pH, EC, turbidity) were recorded at the time of collection to minimize changes during storage.

3.2 Physicochemical parameters analyzed

The physico-chemical parameters of the collected water samples were analyzed following the standard procedures recommended by the American Public Health Association (APHA, 2017). All instruments were calibrated prior to use, and measurements were performed either in situ or under controlled laboratory conditions to ensure accuracy and reproducibility.

ISSN 2250-3153

Temperature: Water temperature was recorded at the sampling site using a calibrated centigrade thermometer (Jennson Deluxe, range 0–110 °C). Readings were taken after allowing the thermometer to stabilize for 2-3 minutes in the sample.

pH: The hydrogen ion concentration was determined using a digital micro pH meter (Systronics make). For field measurements, a portable pH scan meter (Eutech Cybernetics, Model pH Scan) was employed. The instrument was calibrated at 25 °C using buffer solutions of pH 4.0 and 7.0, in accordance with APHA method 4500:B.

Electrical Conductivity (EC): Electrical conductivity was measured directly using a conductivity meter (Systronics make). Field measurements were carried out with a portable TDS/EC meter (Eutech Cybernetics, Model TDS Scan-1). Calibration was performed using 0.1 N KCl solutions and results were expressed in millimhos per centimeter (mmho/cm).

Turbidity: Turbidity was determined using a Nephelo meter standardized with a 40 NTU suspension. The instrument was adjusted to 100 units, where each division corresponded to 0.4 NTU. Samples with turbidity exceeding 40 NTU were diluted appropriately, and the final turbidity was calculated as:

Turbidity, NTU= Nephelo meter reading x 0.4 x dilution factor

Dissolved Oxygen (DO): DO was measured using the Winkler titration method. Samples were fixed immediately at the site to prevent oxygen exchange, and titration was carried out with sodium thiosulfate solution using starch as an indicator.

Biochemical Oxygen Demand (BOD): BOD was determined by incubating samples at 20 °C for five days, followed by measurement of residual DO. The difference between initial and final DO was used to calculate BOD, with seed correction applied where necessary.

Chemical Oxygen Demand (COD): COD was estimated using the dichromate reflux method. Samples were digested with potassium dichromate in acidic medium, and excess dichromate was titrated with ferrous ammonium sulfate (FAS). COD values were expressed in mg/L.

Hardness and Alkalinity: Total hardness was measured by EDTA titration, expressed as mg/L $CaCO_3$. Total alkalinity was determined by titration with standard acid to phenolphthalein and methyl orange endpoints, also expressed as mg/L $CaCO_3$.

Major ions: Concentrations of Ca2+, Mg2+, Na+, K+, Cl−, $SO^2{}_4$−, Fe2+, NO3−, and F− were analyzed using standard titrimetric and spectro photometric methods. Results were reported in mg/L and converted to milli equivalents per liter (meq/L) for irrigation quality indices.

4. Results

4.1 Physicochemical characteristics of groundwater samples

The groundwater samples analyzed across forty sites revealed marked variation in physicochemical characteristics when compared with WHO and BIS standards. Biochemical Oxygen Demand (BOD) values at several sites exceeded 5 mg/L, indicating significant organic pollution, although neither WHO nor BIS prescribe explicit limits for BOD in drinking water; such elevated levels nonetheless suggest unsuitability for potable use. Chemical Oxygen Demand (COD) values were consistently higher than BOD, with peaks above 20 mg/L, reflecting the presence of chemically oxidizable pollutants from anthropogenic sources, again without direct limits in WHO or BIS guidelines but clearly indicative of contamination. Dissolved Oxygen (DO) concentrations showed an inverse relationship with

BOD and COD, with multiple sites recording values below 4 mg/L, which falls short of the recommended minimum of 5 mg/L set by both WHO and BIS for safe drinking water.

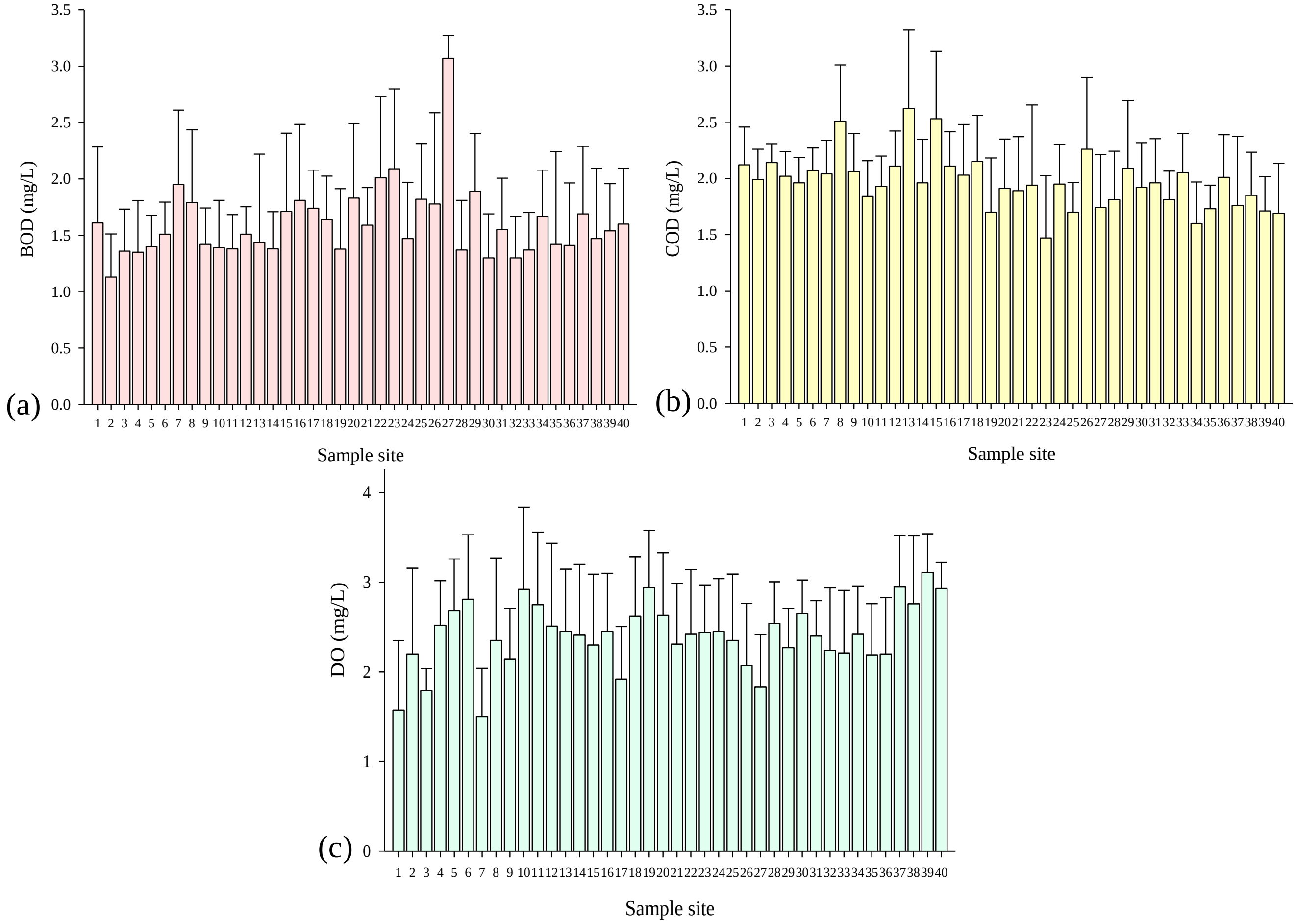

Fig.1: The groundwater samples collected from forty sites were analyzed for Biochemical Oxygen Demand (BOD), Chemical Oxygen Demand (COD), and Dissolved Oxygen (DO). The results are presented in Figure a–c.

This depletion of oxygen highlights impaired self purification capacity and potential ecological stress. Overall, the comparison demonstrates that several sites fail to comply with international and national standards, underscoring the influence of organic and chemical pollution on groundwater quality and the urgent need for remediation and stricter monitoring.

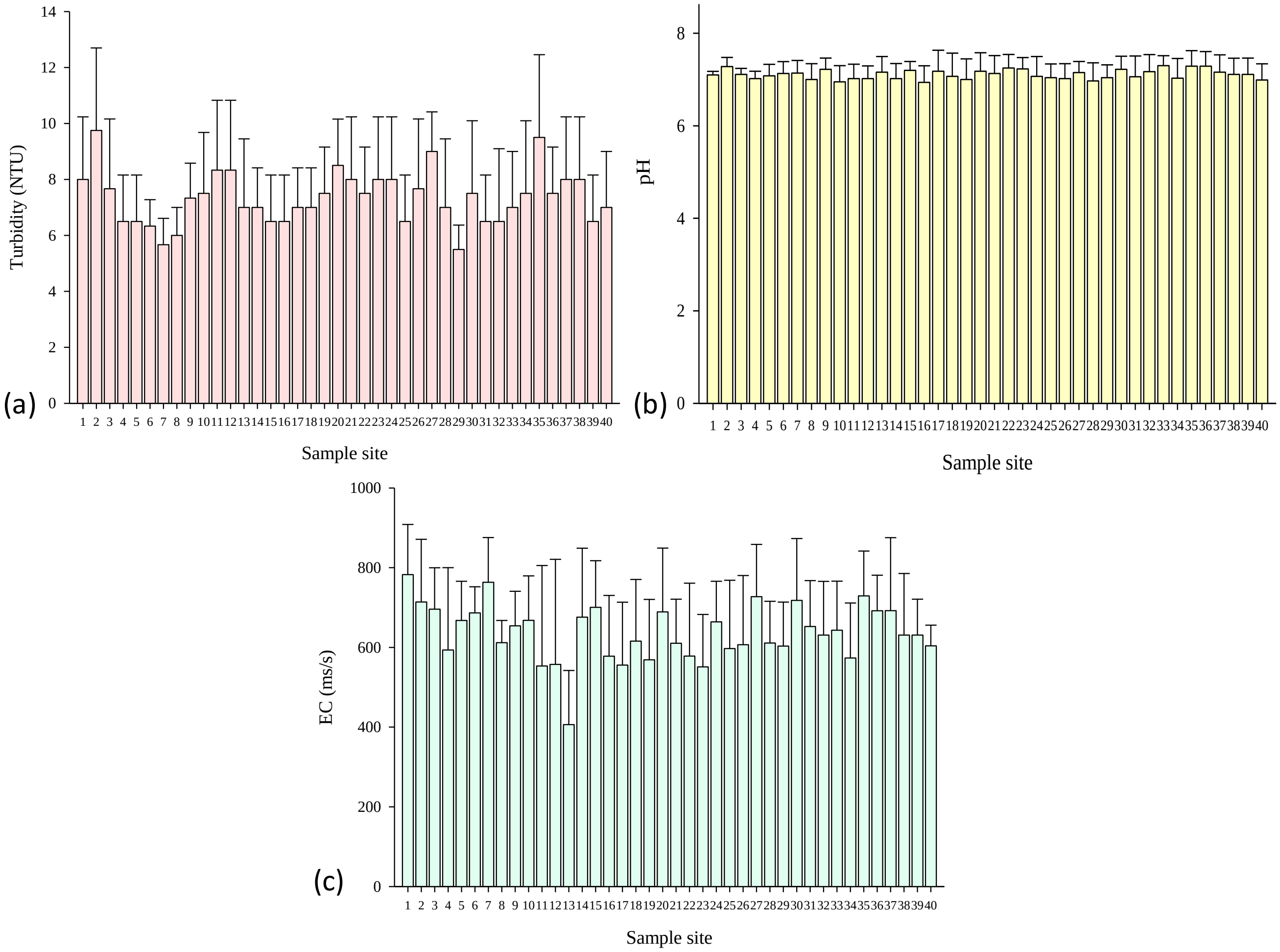

Fig.2: The groundwater samples collected from forty sites were analyzed for Turbidity, pH and Electrical Conductivity. The results are presented in Figure a–c.

The groundwater samples analyzed across forty sites were further evaluated for turbidity, pH and electrical conductivity (EC), revealing notable spatial variability. Turbidity values ranged from below 1 NTU to peaks approaching 14 NTU, with several sites exceeding the BIS permissible limit of 5 NTU for drinking water, indicating the presence of suspended particles and potential microbial contamination. pH values across the sites fluctuated between approximately 6.2 and 8.0, remaining largely within the acceptable range of 6.5-8.5 as prescribed by both WHO and BIS standards, suggesting that the groundwater is neither strongly acidic nor alkaline. Electrical conductivity values showed wide variation, with some sites exceeding 1000 mS/s, which may reflect elevated levels of dissolved salts and ions. Although BIS does not specify a direct limit for EC, high conductivity is often associated with poor palatability and potential health risks due to excessive mineral content. The presence of error bars across all parameters indicates measurement variability, possibly due to seasonal influences or sampling inconsistencies. Overall, the data suggest that while pH remains within safe limits, turbidity and EC exceed recommended thresholds at multiple locations, highlighting the need for targeted water treatment and quality assurance measures.

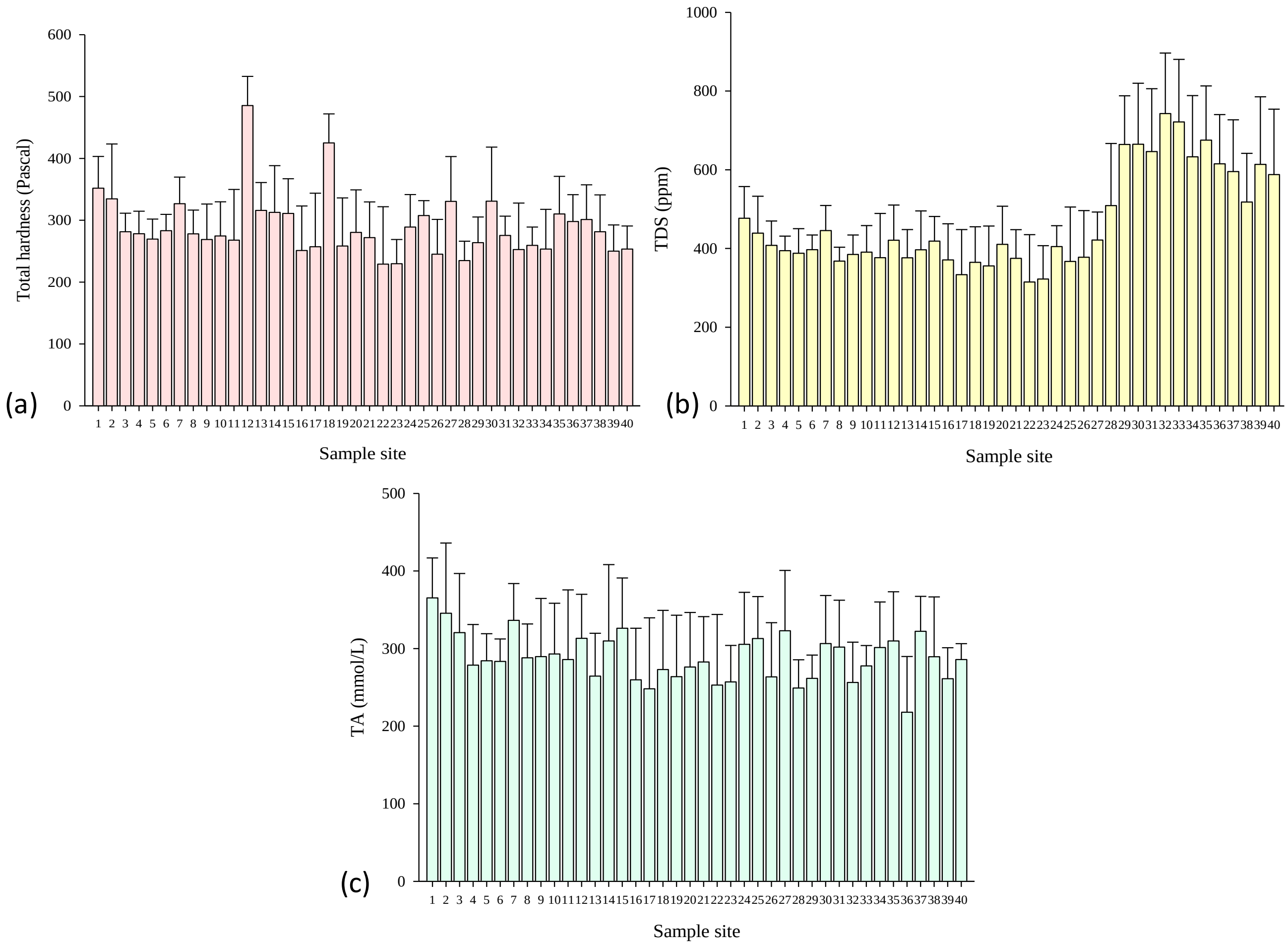

Fig. 3: The groundwater samples collected from forty sites were analyzed for Hardness, Total Dissolved Solids and Total Alkalinity. The results are presented in Figure a–c.

The groundwater samples collected from forty sites were assessed for total hardness, total dissolved solids (TDS), and total alkalinity (TA), revealing distinct spatial patterns and deviations from recommended standards. Total hardness values ranged from approximately 200 to 500 Pascal, with several sites exceeding the BIS permissible limit of 300 mg/L (equivalent to ~300 Pascal), indicating the presence of high concentrations of calcium and magnesium salts that may affect water palatability and scaling potential. TDS levels varied widely, with values spanning from 200 to nearly 900 ppm; notably, sites beyond sample 28 showed a marked increase. According to WHO and BIS guidelines, TDS levels up to 500 ppm are considered acceptable, while values between 500–1000 ppm fall under the permissible limit in the absence of an alternative source. Thus, samples exceeding 500 ppm may pose aesthetic and health concerns. Total alkalinity values ranged from 200 to 400 mmol/L, with several sites approaching or exceeding the BIS acceptable limit of 200 mg/L as $CaCO_3$ (approximately 200 mmol/L), suggesting buffering capacity against pH fluctuations but also potential interference with disinfection processes. The presence of error bars across all parameters reflects measurement variability, possibly due to seasonal or sampling inconsistencies. Overall, the data indicate that while some sites remain within safe limits, a significant proportion exhibit elevated hardness, TDS and alkalinity, warranting further investigation and potential treatment interventions to ensure compliance with drinking water standards.

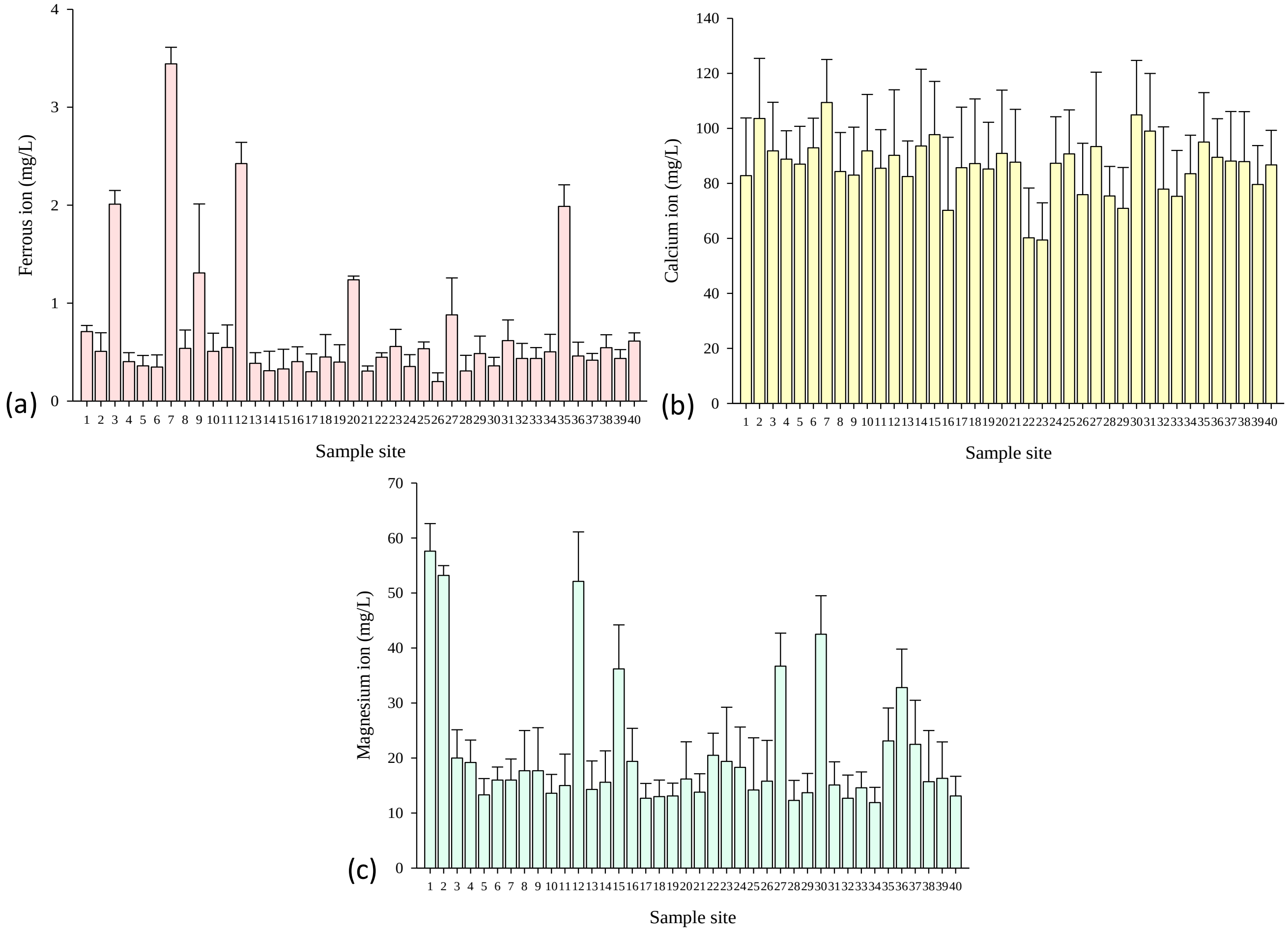

Fig. 4: The groundwater samples collected from forty sites were analyzed for ferrous, calcium and magnesium ion concentrations. The results are presented in Figure a–c.

The groundwater samples collected from forty sites were analyzed for ferrous, calcium, and magnesium ion concentrations, revealing site-specific variations and potential deviations from drinking water standards. Ferrous ion concentrations showed marked variability, with elevated levels observed at sample sites 6, 8, 11, 20 and 34. According to BIS (IS 10500:2012), the acceptable limit for iron in drinking water is 0.3 mg/L; values exceeding this threshold may impart taste, staining, and health concerns. Calcium ion concentrations were relatively consistent across sites, ranging between 80 and 120 mg/L. While BIS permits up to 75 mg/L as the desirable limit and 200 mg/L as the permissible limit in the absence of an alternative source, the observed values fall within acceptable bounds, though some sites approach the upper margin. Magnesium ion concentrations varied more widely, with higher values recorded at sites 1, 2, 3, and 11. BIS recommends a desirable limit of 30 mg/L and a permissible limit of 100 mg/L for magnesium; thus, elevated levels may contribute to hardness and potential laxative effects. The presence of error bars across all graphs indicates measurement uncertainty, possibly due to sampling conditions or temporal fluctuations. Overall, the data suggest that while calcium remains largely within safe limits, ferrous and magnesium concentrations exceed recommended thresholds at several sites, necessitating targeted water quality management and treatment interventions.

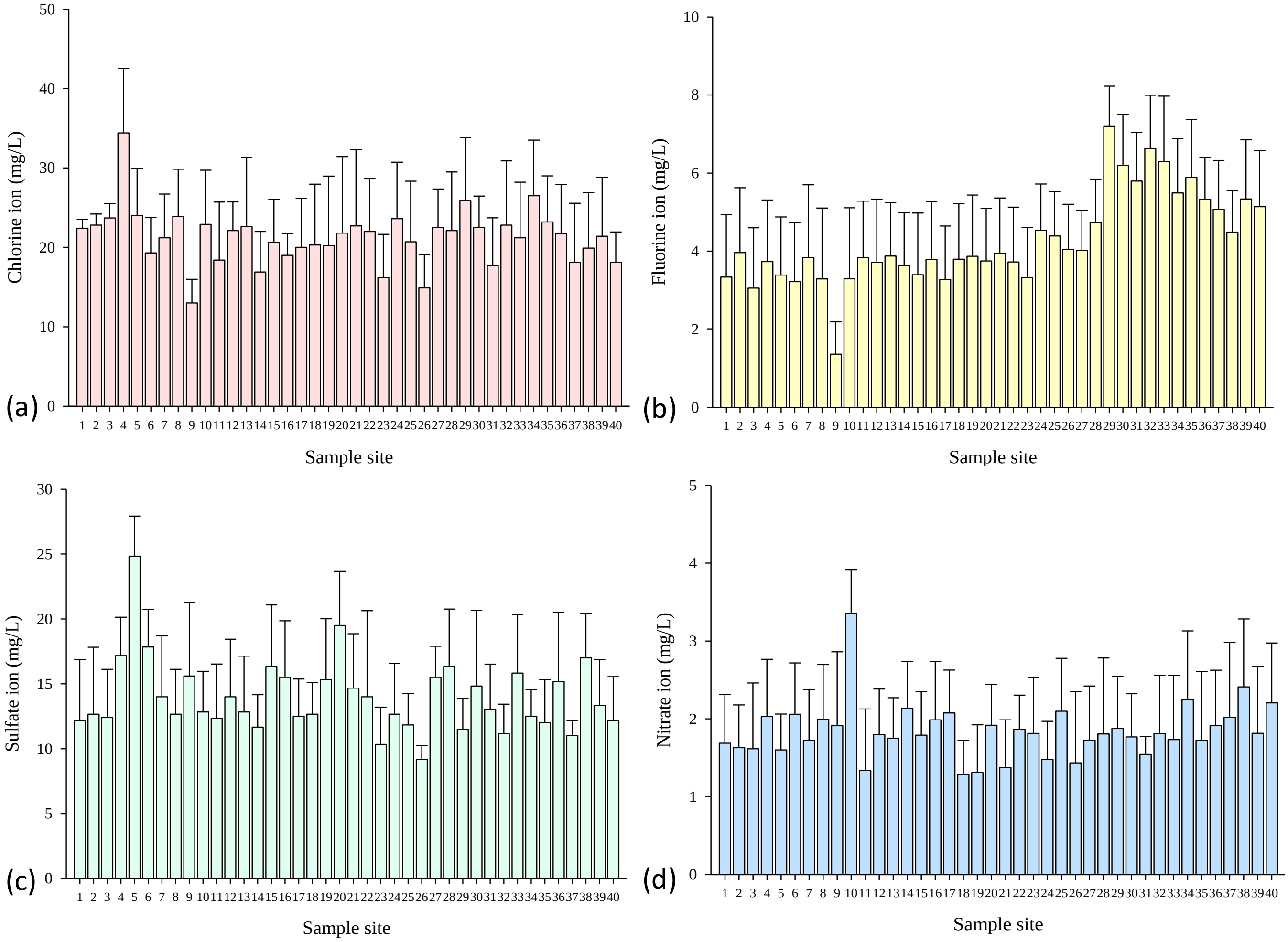

Fig. 5: The groundwater samples collected from forty sites were analyzed for chloride, fluoride, sulfate, and nitrate ion concentrations. The results are presented in Figure a–c.

The groundwater samples collected from forty sites were analyzed for chloride, fluoride, sulfate, and nitrate ion concentrations, revealing site-specific variations in compliance with WHO and BIS drinking water standards. Chloride levels ranged from negligible to approximately 50 mg/L, remaining well within the BIS acceptable limit of 250 mg/L, indicating no salinity-related concerns. Fluoride concentrations varied more prominently, with several sites approaching or exceeding 1.5 mg/L—the maximum permissible limit set by both WHO and BIS. Elevated fluoride levels pose risks of dental and skeletal fluorosis, particularly in regions with prolonged exposure. Sulfate concentrations remained below 30 mg/L across all sites, comfortably within the BIS acceptable limit of 200 mg/L, suggesting minimal risk of gastrointestinal effects or taste alteration. Nitrate levels were consistently low, with all sites recording values below 5 mg/L, far below the BIS permissible limit of 45 mg/L. This indicates minimal agricultural runoff or sewage infiltration. The presence of error bars across all graphs reflects measurement variability, possibly due to seasonal fluctuations or sampling inconsistencies. Overall, while chloride, sulfate, and nitrate levels remain within safe limits, fluoride concentrations exceed recommended thresholds at select sites, warranting targeted monitoring and potential defluoridation measures to ensure public health safety.

4.2 Seasonal variation in water quality parameters

The seasonal groundwater data from Mahendergarh and its surrounding villages reveal distinct temporal and spatial variations in physicochemical and biological parameters, many of which deviate from WHO and BIS drinking water standards. Across most locations, pH values remained within the acceptable range of 6.5–8.5, indicating neutral to mildly alkaline conditions. However, elevated fluoride concentrations were observed in Bigopur (up to 6.38 mg/L), Satnali (5.4 mg/L), and Nawana (3.51 mg/L), far exceeding the permissible limit of 1.5 mg/L, posing serious risks of fluorosis. Iron levels also surpassed the BIS threshold of 0.3 mg/L in Satnali (2.33 mg/L) and Bachhod (0.6 mg/L), suggesting geogenic contamination. Turbidity values exceeded the acceptable limit of 5 NTU in several locations, notably Satnali, Bhalkhi, and Koriawas, indicating suspended particulate matter and potential microbial presence. Total hardness values were consistently high, with Mahendergarh (380 mg/L), Budhwal (423 mg/L), and Ateli (353 mg/L) exceeding the desirable limit of 300 mg/L, reflecting elevated calcium and magnesium concentrations.

Table.1 Seasonal variations of ground water quality of Nangal Katha, Sigra, Kuski and Bachhod

Sr.No	Parameters	Nangal Katha			Sigra			Kuksi			Bachhod		
		Pre-Monsoon	During - Monsoon	Post - Monsoon	Pre-Monsoon	During - Monsoon	Post - Monsoon	Pre-Monsoon	During - Monsoon	Post - Monsoon	Pre-Monsoon	During - Monsoon	Post - Monsoon
1	pH	6.8	7.2	7.1	7.1	7.2	7	6.6	7	6.4	6.6	6.8	7.1
2	SO_4^{2-}	7.9	10.8	10.75	17.1	22.2	20.4	18.6	18.7	18.5	15	20	12
3	NO_3^-	3.2	4.8	3.5	5.15	5.87	5.09	5.72	6.5	5.26	2.36	3.1	2.16
4	Cl^-	27	32	34	20	23	24	89	75	80	18	22	21
5	F^-	4.3	4.41	4.38	3.26	3.2	3.32	2.3	2.18	2.26	1.48	1.54	1.6
6	Fe^+	0.27	0.25	0.16	0.38	0.28	0.35	0.23	0.24	0.25	0.5	0.4	0.6
7	Turbidity	5	7	5	5	7	5	7	9	5	7	5	5
8	Ca^{2+}	72	74	71	57	52	53	92	94	89	104	109	102
9	Mg^{2+}	28	17	15	21	25	27	21.5	20.5	24	25	22	28
10	TH	205	203	211	289	285	290	247	235	255	292	248	282
11	TDS	404	343	317	470	440	410	380	290	284	472	330	370
12	EC	435	423	412	511	534	523	545	555	560	765	755	757
13	TA	268	270	269	258	269	248	289	282	284	299	292	296
14	BOD	4.2	3.8	3.9	1.3	1.1	1.4	1.5	0.8	0.5	1	0.8	0.6
15	COD	1.8	1.6	1.5	2.3	2	1.9	1.8	1.6	1.8	2	1.6	1.8
16	DO	1.9	1.8	1.7	1.6	1.4	1.5	2.2	2.1	2	2.2	1.8	1.7

TDS levels were above the acceptable 500 ppm in Mahendergarh (530 ppm), Budhwal (590 ppm), and Ateli (595 ppm), indicating poor palatability and potential health concerns. Electrical conductivity values were highest in Mahendergarh (803 mS/s) and Bachhod (765 mS/s), suggesting high ionic content. Dissolved oxygen levels remained critically low across all sites and seasons, with values ranging from 1.2 to 2.9 mg/L, well below the recommended minimum of 5 mg/L, indicating oxygen depletion and poor self-purification capacity. Seasonal trends showed slight improvements during monsoon due to dilution effects, but post-monsoon concentrations often rebounded, underscoring persistent contamination. Overall, the data highlight widespread non-compliance with drinking water standards, particularly for fluoride, iron, turbidity, hardness, TDS, and DO, necessitating urgent site-specific interventions, defluoridation measures, and continuous monitoring to safeguard public health.

4.3 Fluoride concentration levels compared with WHO/BIS standards

The analysis of fluoride concentration levels across the groundwater samples shows clear seasonal and spatial variability, with several sites exceeding the permissible limits set by WHO and BIS standards. According to WHO and BIS (IS 10500:2012), the acceptable limit for fluoride in drinking water is 1.0–1.5 mg/L, with concentrations above 1.5 mg/L considered unsafe due to risks of dental and skeletal fluorosis.

In the dataset, Mahendergarh recorded values between 1.13–1.42 mg/L, which are close to or slightly above the permissible limit, indicating marginal non-compliance. Budhwal showed much higher concentrations, ranging from 3.41–4.3 mg/L, far exceeding the safe limit and posing significant health risks. Bigopur exhibited extreme values, with fluoride levels between 5.39-6.38 mg/L, representing severe contamination. Satnali also showed elevated concentrations, rising from 3.38 mg/L pre-monsoon to 5.4 mg/L post-monsoon, again well above the permissible threshold. Nawana recorded values between 2.55–3.51 mg/L, while Nangal Katha consistently reported fluoride levels around 4.3–4.41 mg/L, both exceeding the standard. In contrast, Bhalkhi remained within safe limits (0.22–0.32 mg/L), and Bachhod showed moderate but acceptable values (1.48–1.6 mg/L).

Overall, the comparison demonstrates that fluoride concentrations in several villages (Budhwal, Bigopur, Satnali, Nawana, Nangal Katha, Koriawas, and Mitarpura) are well above WHO/BIS standards, highlighting serious public health concerns. Only a few sites such as Bhalkhi and Bachhod remain compliant. This pattern underscores the urgent need for defluoridation measures, safe water supply alternatives and continuous monitoring to mitigate the risks of fluorosis in affected regions.

5. Discussion

The evaluation of groundwater quality across Mahendergarh and adjoining regions revealed significant spatial and seasonal variations in physicochemical and biological parameters. The Water Quality Index (WQI) values classified several sites within the "good" category, indicating compliance with most WHO and BIS standards, while others fell into "poor" or "unsuitable" categories due to elevated concentrations of fluoride, hardness, turbidity, and critically low dissolved oxygen. Such categorization underscores the heterogeneity of groundwater quality and highlights the need for site-specific management strategies.

Fluoride contamination was identified as one of the most pressing issues. Concentrations in villages such as Bigopur, Satnali, Nawana, and Nangal Katha exceeded the permissible limit of 1.5 mg/L, with values ranging between 3.4 and 6.4 mg/L. Prolonged consumption of such water is known to cause dental fluorosis, characterized by mottling and discoloration of teeth, and skeletal fluorosis, which manifests as joint stiffness, bone deformities, and chronic pain. These findings are consistent with earlier reports from Haryana and Rajasthan, where endemic fluorosis has been documented in rural populations dependent on groundwater. The persistence of high fluoride levels across seasons suggests a geogenic origin, likely linked to fluoride bearing minerals in the aquifer matrix, compounded by limited dilution during recharge.

Hydrochemical indices applied to assess irrigation suitability further revealed constraints on agricultural use. Elevated values of Sodium Adsorption Ratio (SAR), Residual Sodium Carbonate (RSC), and percent sodium (%Na) in several sites indicate risks of sodicity, reduced soil permeability and impaired crop productivity. High RSC values, particularly in areas with elevated alkalinity, suggest precipitation of calcium and magnesium, thereby increasing sodium hazard. Similarly, magnesium hazard values exceeding 50% in Budhwal and Nawana point to potential soil quality deterioration. These indices collectively emphasize that groundwater in many locations is marginal to unsuitable for irrigation without corrective measures such as gypsum application, blending with low salinity water, or adoption of salt tolerant crops.

Comparison with previous studies in Haryana and other Indian states reveals a consistent pattern of groundwater contamination. Investigations in Rajasthan and Andhra Pradesh have reported fluoride concentrations exceeding 5 mg/L, alongside elevated nitrate and salinity levels, leading to widespread health and agricultural challenges. The present findings align with these observations, confirming that groundwater quality issues in Mahendergarh are part of a broader regional problem affecting semi-arid states. Seasonal dilution during monsoon improved certain parameters such as TDS and EC, but post monsoon rebound in hardness and fluoride concentrations underscores the persistence of contamination and the limited resilience of aquifers.

6. Conclusion and Recommendations

The present investigation into the seasonal variation of groundwater quality in Mahendergarh and surrounding villages demonstrates marked spatial and temporal heterogeneity in physicochemical and biological parameters. While pH values largely remained within the acceptable range prescribed by WHO and BIS standards, several critical parameters including fluoride, total hardness, turbidity, total dissolved solids, and dissolved oxygen exceeded permissible limits at multiple sites. Elevated fluoride concentrations in Bigopur, Satnali, Nawana, and Nangal Katha pose serious risks of dental and skeletal fluorosis, while high hardness and TDS values compromise palatability and long term health. Dissolved oxygen levels consistently below 5 mg/L across all seasons highlight impaired self purification capacity of groundwater. Hydrochemical indices further revealed constraints on irrigation suitability, with high SAR, RSC, and sodium percentages in several locations indicating risks of sodicity, reduced soil permeability and diminished crop productivity.

The findings are consistent with previous studies from Haryana, Rajasthan, and Andhra Pradesh, confirming that groundwater contamination in semi-arid regions is both geogenic and anthropogenic in origin and persists across seasons despite monsoonal dilution. The convergence of poor WQI scores, health hazards, and agricultural limitations underscores the urgent need for integrated management. Based on the results, it is recommended that defluoridation techniques such as activated alumina or the Nalgonda method be adopted in fluoride affected villages, and safe drinking water alternatives should be provided through piped supply or blending with low fluoride sources. Continuous monitoring of groundwater quality across seasons is essential to track changes and guide interventions. For irrigation, corrective measures such as gypsum application, blending of high salinity water with low salinity sources and adoption of salt tolerant crops should be promoted in areas with high SAR and RSC values. Community awareness programs are necessary to educate rural populations about the health risks of contaminated groundwater and the importance of safe water practices, while policy interventions at district and state levels should prioritize groundwater remediation and sustainable management to safeguard both public health and agricultural productivity.

CRediT authorship contribution statement

Neelam Bharti: Writing – original draft, Validation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Ravi Kumar Rana**: Editing, Visualization, Supervision.

Funding; Not applicable.

Declaration of competing interest

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

Acknowledgement

The authors are thankful to Baba Mastnath University, Rohtak, Haryana, India for providing infrastructural facility to conduct the research.

Data availability; all the data is provided with in the manuscript.

References

Abanyie, S. K., Apea, O. B., Abagale, S. A., Amuah, E. E. Y., & Sunkari, E. D. (2023). Sources and factors influencing groundwater quality and associated health implications: A review. *Emerging Contaminants*, *9*(2), 100207.

Abbas, M., Arshad, M., & Shahid, M. A. (2025). Spatiotemporal zoning of groundwater quality in Rechna Doab: analysis of Electrical Conductivity (EC), Sodium Adsorption Ratio (SAR), and Residual Sodium Carbonate (RSC) variability. *EQA-International Journal of Environmental Quality*, *68*, 37-49.

Abbas, M., Arshad, M., & Shahid, M. A. (2025). Spatiotemporal zoning of groundwater quality in Rechna Doab: analysis of Electrical Conductivity (EC), Sodium Adsorption Ratio (SAR), and Residual Sodium Carbonate (RSC) variability. *EQA-International Journal of Environmental Quality*, *68*, 37-49.

Ahmad, S., Singh, R., Arfin, T., & Neeti, K. (2022). Fluoride contamination, consequences and removal techniques in water: a review. *Environmental Science: Advances*, *1*(5), 620-661.

Akhtar, N., Syakir Ishak, M. I., Bhawani, S. A., & Umar, K. (2021). Various natural and anthropogenic factors responsible for water quality degradation: A review. *Water*, *13*(19), 2660.

Ali, S., Thakur, S. K., Sarkar, A., & Shekhar, S. (2016). Worldwide contamination of water by fluoride. *Environmental chemistry letters*, *14*(3), 291-315.

Chaudhari, S. K., Santra, P., Machiwal, D., Kumar, M., Singh, V. K., Reddy, K. S., & Kundu, S. (2024). Soil, Water, and Nutrient Management in Drylands. In *Managing Soil Drought* (pp. 85-131). CRC Press

Chidiac, S., El Najjar, P., Ouaini, N., El Rayess, Y., & El Azzi, D. (2023). A comprehensive review of water quality indices (WQIs): history, models, attempts and perspectives. *Reviews in Environmental Science and Bio/Technology*, *22*(2), 349-395.

El Moll, A. (2023). Water resources and climate change: regional, national and international perspective. In *Sustainable and circular management of resources and waste towards a green deal* (pp. 309-336). Elsevier.

Khanam, N., Singh, A. A., Singh, A. K., & Hamidi, M. K. (2022). Water quality characterization of industrial and municipal wastewater, issues, challenges, health effects, and control techniques. In *Recent Trends in Wastewater Treatment* (pp. 1-30). Cham: Springer International Publishing.

Li, J., Wang, Y., Zhu, C., Xue, X., Qian, K., Xie, X., & Wang, Y. (2020). Hydrogeochemical processes controlling the mobilization and enrichment of fluoride in groundwater of the North China Plain. *Science of the Total Environment*, *730*, 138877.

Orecchia, C., Giambastiani, B. M., Greggio, N., Campo, B., & Dinelli, E. (2022). Geochemical characterization of groundwater in the confined and unconfined aquifers of the Northern Italy. *Applied Sciences*, *12*(15), 7944.

Patel, A., Singh, A. K., Singh, R., Puthiyottil, N., & Rai, S. P. (2023). Fluoride Mobilization and Provenance Identification in Semi-arid Conditions: A Hydrochemical and Isotopic Approach. In *Surface and Groundwater Resources Development and Management in Semi-arid Region: Strategies and Solutions for Sustainable Water Management* (pp. 97-116). Cham: Springer International Publishing.

Priyan, K. (2021). Issues and challenges of groundwater and surface water management in semi-arid regions. *Groundwater resources development and planning in the semi-arid region*, 1-17.

Saha, D., & Ray, R. K. (2018). Groundwater resources of India: potential, challenges and management. In *Groundwater development and management: issues and challenges in South Asia* (pp. 19-42). Cham: Springer International Publishing.

Uddin, M. G., Diganta, M. T. M., Sajib, A. M., Hasan, M. A., Moniruzzaman, M., Rahman, A., ... & Moniruzzaman, M. (2023). Assessment of hydrogeochemistry in groundwater using water quality index model and indices approaches. *Heliyon*, *9*(9).