Groundwater Quality Assessment in Fluoride Affected Regions of Mahendergarh District, Haryana: A Review of Physicochemical Parameters and Public Health Implications

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Abstract

Groundwater is the primary source of drinking and irrigation water in semi-arid regions where annual rainfall is limited to 400–500 mm and summer temperatures often exceed 45°C. In Haryana's Mahendergarh District, more than 90% of the rural population depends entirely on groundwater, making water quality a major public health concern. Literature reveals that fluoride contamination is widespread, with reported concentrations ranging from 0.08 to 6.6 mg/L, of which 63% exceed the WHO guideline of 1.5 mg/L and 85% surpass the BIS limit of 1.0 mg/L. Hydro geochemical conditions such as alkaline pH (7.5–8.5), elevated bicarbonate levels (> 300 mg/L), and high sodium concentrations promote the dissolution of fluorite and apatite, leading to increased fluoride mobility. Co-contaminants, including nitrate levels above 45–50 mg/L and TDS frequently exceeding 1500 mg/L, further degrade groundwater suitability. The health consequences are significant, with high incidences of dental and skeletal fluorosis reported among children and adults. Although defluoridation technologies such as the Nalgonda process (80–90% removal), activated alumina (90–95% removal) and reverse osmosis (> 95%) show potential, their widespread adoption remains limited by cost and maintenance challenges. These findings highlight the urgent need for integrated, community centered groundwater management strategies in fluoride-affected semi arid regions.

Keywords: Groundwater contamination, Fluoride toxicity, Hydro geochemistry, physicochemical parameters, Mahendergarh District, Public health

1. Introduction

Groundwater represents one of the most vital natural resources for sustaining life and livelihoods in semi-arid regions. The groundwater serves as the primary source of drinking water, irrigation and industrial use, in areas where surface water availability is limited due to erratic rainfall and high evapotranspiration rates (Priyan, 2021). Semi-arid landscapes such as those found in parts of

Haryana are characterized by prolonged dry seasons limited perennial rivers and a high dependency on aquifers to meet domestic and agricultural demands (Ahamad at el., 2023). The reliance on groundwater in these regions is further intensified by the increasing pressure of population growth, urbanization and agricultural intensification (Paria at el., 2021). Unlike surface water, groundwater is often perceived as a more reliable and resilient source, buffered against short-term climatic fluctuations. However, this perception can be misleading, as aquifers in semi-arid zones are highly vulnerable to over-extraction and contamination (Khatri at el., 2024).

The physicochemical quality of groundwater directly influences its suitability for human consumption and agricultural use. Parameters such as pH, electrical conductivity, total dissolved solids, and hardness are critical indicators of water quality and deviations from permissible limits can pose significant health and environmental risks (Kalevandi at el., 2024). In particular, naturally occurring geogenic contaminants such as fluoride have emerged as a major concern in semi-arid aquifers where geological formations often contain fluoride bearing minerals. Thus groundwater quality assessment in semi-arid regions is not merely a scientific exercise but a public health necessity. It provides the evidence base for sustainable water management policy interventions and community awareness programs aimed at safeguarding both human health and agricultural productivity (Makanda at el., 2022). Fluoride contamination in groundwater is a well documented global phenomenon affecting millions of people across diverse geographies. While fluoride in trace amounts (around 0.5–1.0 mg/L) is beneficial for dental health excessive concentrations can lead to severe health disorders, most notably dental and skeletal fluorosis (Lubojanski at el., 2023). The World Health Organization (WHO) has set the permissible limit of fluoride in drinking water at 1.5 mg/L, beyond which adverse health effects become increasingly evident (WHO, 2022). Globally, regions in Africa, China and parts of the Middle East have reported endemic fluorosis linked to groundwater consumption. In India, fluoride contamination is widespread with more than 20 states reporting concentrations above the permissible limit. The problem is particularly acute in the arid and semi-arid belts of Rajasthan, Gujarat, Andhra Pradesh, and Haryana where geological formations rich in fluorine bearing minerals contribute to elevated groundwater fluoride levels. At the regional level, Haryana has emerged as one of the critical states grappling with fluoride contamination (Gupta at el., 2024). The semi arid districts, including Mahendergarh, Rewari and Bhiwani are recognized hotspots where groundwater fluoride concentrations often exceed safe thresholds. The health burden in these regions is substantial with dental and skeletal fluorosis affecting large segments of the rural population (Srivastava and Flora, 2020). Children are especially vulnerable as prolonged exposure during developmental stages leads to irreversible damage (Ghosh at el., 2024).

The issue of fluoride contamination is not limited to health impacts alone; it also carries socioeconomic implications. Communities in affected regions face reduced productivity, increased healthcare costs, and diminished quality of life (Bieliaieva and Zabolotna, 2023). Addressing fluoride contamination, therefore, requires a multidisciplinary approach that integrates hydrogeology, chemistry, epidemiology, and public health policy. Mahendergarh District, located in the southwestern part of Haryana, represents a critical case study for groundwater quality assessment due to its unique hydro geological and socioeconomic context (Kumari at el., 2024). The district lies within the semi arid zone, characterized by low rainfall, high dependence on groundwater, and limited surface water resources. The aquifers in Mahendergarh are predominantly composed of alluvial and hard rock formations, many of which contain fluoride bearing minerals such as fluorite and apatite (Beg at el., 2023).

This geological predisposition, combined with intensive groundwater extraction for agriculture and domestic use, has exacerbated the problem of fluoride contamination. Several surveys and scientific investigations have consistently reported fluoride concentrations in Mahendergarh groundwater exceeding the permissible limits set by WHO and the Bureau of Indian Standards (BIS). Villages across the district have documented cases of dental and skeletal fluorosis, highlighting the urgent need for systematic assessment and intervention (Srivastava and Flora, 2020). The public health implications are profound, as the majority of the rural population relies exclusively on groundwater for drinking and cooking purposes (Carrard at el., 2019). Focusing on Mahendergarh is also justified from a policy and management perspective. Haryana has initiated several water quality monitoring and mitigation programs, yet localized assessments remain limited. A comprehensive review of physicochemical parameters in Mahendergarh can provide valuable insights into the spatial distribution of fluoride, correlations with other water quality indicators and potential sources of contamination (Sidhu at el., 2025). Such evidence is crucial for designing targeted interventions, including defluoridation technologies, rainwater harvesting and community awareness campaigns.

2. Geographical and Climatic Characteristics

Geographical features such as rock type, soil composition and aquifer depth strongly influence groundwater chemistry. Regions rich in granitic or volcanic rocks often show higher natural fluoride levels. The structure of the terrain also affects water flow, recharge rates, and mineral dissolution.

2.1 Location, physiography and climatic regime of Mahendergarh

Mahendergarh District is located in the southwestern part of Haryana, India, between latitudes 27°48′N to 28°36′N and longitudes 75°56′E to 76°51′E. It covers an area of approximately 1,899 km² and lies within the semi-arid tract of the state. Physiographically the district represents a transitional zone between the alluvial plains of Haryana and the rocky outcrops of the Aravalli range. The terrain is characterized by undulating plains, scattered rocky ridges and shallow depressions, which influence both surface drainage and groundwater recharge (Letz at el., 2021). The climatic regime of Mahendergarh is predominantly semi-arid, marked by hot summers, cool winters and erratic rainfall. Average annual precipitation ranges between 400–500 mm, with nearly 80–85% of rainfall concentrated in the monsoon months (Swami, 2021).

High evapotranspiration rates, often exceeding rainfall, contribute to chronic water scarcity. The district experiences extreme seasonal variability, with summer temperatures frequently rising above 45°C, while winter temperatures may drop below 5°C (Goparaju and Ahmad, 2019). This climatic stress, combined with limited surface water resources, has made groundwater the principal source of water for domestic, agricultural, and industrial needs (Priyan, 2021).

2.2 Hydro geological framework and aquifer typology

The hydro geological setting of Mahendergarh is governed by a combination of alluvial deposits and hard rock formations. The aquifers are predominantly unconfined to semi confined, with depths varying according to physiographic zones. In the plains, aquifers are composed of sand, silt, and clay layers, which provide moderate storage and transmissivity (Walraevens et al., 2025). In contrast, the Aravalli hills and adjoining rocky terrains host fractured quartzite and granite aquifers, where groundwater occurs in secondary porosities created by joints, fractures and weathered zones (Pradhan et al., 2022). Recharge to aquifers is limited due to low rainfall and high runoff in sloping terrains. Infiltration is further constrained by the presence of hard rock formations, resulting in shallow water tables in some areas and deeper aquifers in others (Lachassagne et al., 2021). Hydro chemical investigations have revealed the presence of fluoride bearing minerals such as fluorite and apatite in the geological strata, which contribute to elevated fluoride concentrations in groundwater. Intensive groundwater extraction for irrigation has also altered the hydro geological balance, lowering water tables and enhancing mineral dissolution processes. The aquifer typology of Mahendergarh thus reflects a dual system: alluvial aquifers with relatively higher yields but vulnerability to quality deterioration and hard rock aquifers with limited yields but significant geogenic contamination potential (Sahoo et al., 2025). This framework underscores the importance of systematic groundwater quality assessment, particularly in relation to fluoride mobilization and its implications for public health (Jamakala et al., 2025).

3. **Socioeconomic Context**

Socioeconomic factors greatly shape how communities experience and manage fluoride contamination. Low-income populations often rely on untreated groundwater, increasing their exposure to high fluoride levels. Limited infrastructure and resources can hinder access to safe drinking water.

3.1 Demographic Dependence on Groundwater Resources

Mahendergarh District is predominantly rural with the popular of its population residing in villages that rely almost exclusively on groundwater for drinking, cooking and sanitation. The absence of perennial rivers and limited surface water storage infrastructure has made groundwater the principal source of potable water (Priyan, 2021). Public supply schemes are largely dependent on bore wells and hand pumps, which tap aquifers of varying depths. This dependence is not merely a matter of convenience but a necessity dictated by the semi-arid climate and physiographic constraints of the region (Agnew and Anderson, 2024).

The demographic reliance on groundwater has heightened vulnerability to water quality issues, particularly fluoride contamination (Araya et al., 2022). Health surveys in the district have documented widespread cases of dental and skeletal fluorosis, underscoring the direct link between groundwater quality and public health outcomes. Children and economically disadvantaged groups are disproportionately affected, as they lack access to treated or alternative water sources. Thus, demographic dependence on groundwater in Mahendergarh represents both a lifeline and a critical public health challenge (Mahto, 2024).

3.2 Agricultural and domestic utilization patterns

Agriculture forms the backbone of Mahendergarh’s economy and groundwater serves as the primary source of irrigation. Tube wells and bore wells are extensively used to cultivate crops such as wheat, mustard, bajra and pulses. The semi-arid climate necessitates irrigation even for traditionally rain fed crops, thereby increasing pressure on aquifers. Over extraction of groundwater has not only lowered water tables but also intensified the mobilization of fluoride and other dissolved salts into the groundwater system (Al Sabti et al., 2023). Domestic utilization of groundwater is equally significant, with households depending on it for drinking, cooking and sanitation. The lack of centralized water treatment facilities means that most communities consume untreated groundwater directly from bore wells or hand pumps (Tura and Demeku, 2025). This practice has contributed to the widespread prevalence of fluorosis and other waterborne health issues. The dual role of groundwater in sustaining both agriculture and domestic needs highlights its critical importance, while simultaneously exposing the population to significant health risks due to poor water quality (Shaikh and Birajdar, 2024).

4. Groundwater Quality and Fluoride Contamination

Groundwater quality depends on the geological formations, recharge conditions, and human activities that influence the chemical composition of water **(Fig: 1).** in many regions, natural weathering of rocks and minerals affects the overall purity and usability of groundwater.

4.1 Geogenic and anthropogenic sources of fluoride in aquifers

Fluoride contamination in groundwater is primarily geogenic in origin, arising from the dissolution of fluoride bearing minerals such as fluorite, apatite and biotite present in the geological strata (Al Sabti et al., 2023).

Fig-1: Different Causes of Groundwater Pollution from Natural and Human Activities

In Mahendergarh District, the semi arid setting and the presence of Aravalli rock formations enhance the likelihood of fluoride mobilization through prolonged water rock interaction. The weathering of granitic and gneissic rocks, coupled with alkaline conditions, facilitates the release of fluoride ions into aquifers. Anthropogenic activities further aggravate fluoride levels. Intensive groundwater extraction for irrigation accelerates mineral dissolution by lowering water tables and increasing residence time (Wei et al., 2024). Agricultural practices, including the use of phosphate fertilizers, contribute indirectly to fluoride enrichment. Industrial effluents and improper waste disposal may also introduce fluoride into shallow aquifers, compounding the geogenic load (Dawoud and Al Hassan, 2025). Thus, both natural and human induced processes act synergistically to elevate fluoride concentrations in groundwater.

4.2 Spatial distribution and temporal variability of fluoride concentrations

The distribution of fluoride in Mahendergarh groundwater is spatially heterogeneous, with certain villages and blocks consistently reporting concentrations above the permissible limit of 1.5 mg/L set by the World Health Organization (Sidhu et al., 2025). Hotspot regions are typically located near hard rock aquifers of the Aravalli range, where geogenic sources dominate. In contrast, alluvial plains exhibit moderate fluoride levels but remain vulnerable due to over extraction and anthropogenic inputs. Temporal variability is influenced by seasonal recharge patterns. During monsoon months, dilution effects may lower fluoride concentrations, whereas in pre monsoon periods, reduced recharge and higher evaporation intensify contamination (Sultana, 2025). Long term monitoring has revealed a gradual increase in fluoride levels over the past decades, reflecting both declining water tables and cumulative geochemical processes. This variability underscores the need for continuous surveillance and localized interventions.

4.3 Hydrogeochemical processes influencing fluoride mobilization

Fluoride mobilization in aquifers is governed by a complex interplay of hydro geochemical processes. Alkaline pH and high bicarbonate concentrations enhance fluoride solubility by promoting the dissolution of fluorite and related minerals. Elevated sodium levels, resulting from ion exchange reactions, further increase fluoride mobility by reducing calcium concentrations, which otherwise precipitate fluoride as CaF_2 (Zhu et al., 2025). Evaporation in semi-arid climates intensifies solute concentration, while prolonged residence time of groundwater in fractured rock systems facilitates water rock interaction **(Table 1).** Over extraction of groundwater alters hydraulic gradients, exposing deeper strata and accelerating mineral dissolution. Anthropogenic inputs, such as fertilizers, may modify aquifer chemistry, indirectly influencing fluoride mobilization (Kamruzzaman et al., 2025). Collectively, these processes explain the persistence and escalation of fluoride contamination in Mahendergarh aquifers.

Table: 1 Summary of Fluoride Contamination in Groundwater

Aspect	Details	Typical Values/Patterns	Implications	References
Geogenic Sources	Dissolution of fluoride-bearing minerals (fluorite, apatite, biotite) in Aravalli formations	Fluoride >1.5 mg/L common in hard rock aquifers	Natural geology predisposes aquifers to contamination	Chaudhuri et al., (2024)
Anthropogenic Inputs	Over-extraction, phosphate fertilizers, industrial effluents	Intensifies fluoride mobilization	Human activities exacerbate natural contamination	Mariappan Santhi et al., (2024)
Spatial Distribution	Hotspots in rocky terrains; moderate levels in alluvial plains	0.03–9.9 mg/L reported	Uneven contamination across villages	Haidery et al., (2025)
Temporal Variability	Seasonal dilution during monsoon; concentration in pre-monsoon	Higher fluoride in pre-monsoon samples	Seasonal monitoring essential	Ahmed et al., (2022)
Hydrogeochemical Processes	Alkaline pH, Na^+–Ca^{2+} ion exchange,	High Na^+, low Ca^{2+} favor mobilization	Sustains contamination over	Islam et al., (2024)

	evaporation, long residence time		decades	
Public Health Effects	Dental and skeletal fluorosis; systemic impacts	Prevalence high among children and rural communities	Significant health burden	Ghosh et al., (2024)
Standards	WHO permissible limit: 1.5 mg/L; BIS limit: 1.0–1.5 mg/L	Many samples exceed limits	Unsafe for drinking without treatment	WHO Guidelines (2017); BIS Standards (2020)
Mitigation Measures	Defluoridation (Nalgonda, RO, activated alumina); rainwater harvesting	Effective but limited adoption	Requires policy + community participation	Rani et al., (2024)
Geogenic Sources	Dissolution of fluoride-bearing minerals (fluorite, apatite, biotite) in Aravalli formations	Fluoride >1.5 mg/L common in hard rock aquifers	Natural geology predisposes aquifers to contamination	Chaudhuri et al., (2024)

5. Physicochemical Characterization of Groundwater

Groundwater quality is primarily governed by its physicochemical attributes, which reflect both natural geochemical processes and anthropogenic influences. The following parameters are widely recognized as fundamental indicators of potability and suitability for domestic, agricultural and industrial use:

5.1 Assessment of major water quality parameters

Groundwater quality is governed by several key physicochemical parameters. PH values between 6.5–8.5 are optimal as extremes may enhance corrosivity or mobilize toxic metals (Dawoud and Al Hassan, 2025). Electrical conductivity (EC) and total dissolved solids (TDS**)** reflect ionic strength and salinity elevated levels indicate excessive dissolved salts, impairing irrigation and drinking suitability. Hardness**,** derived from calcium and magnesium, affects domestic usability, with concentrations above 300 mg/L causing scaling and reduced soap efficiency (Takada et al., 2023). Alkalinity, mainly due to bicarbonates and carbonates, stabilizes pH but excessive levels influence taste and industrial applications. Chloride serves as a marker of salinity intrusion and contamination, with values above 250 mg/L imparting a salty taste and corroding pipelines (Gakwel, 2023). Sulphate**,** often from mineral dissolution or effluents, can cause scaling and gastrointestinal effects when exceeding 400 mg/L (Shukri et al., 2025). Nitrate, largely from agricultural runoff and sewage, poses serious health risks, particularly infant methemoglobinemia when concentrations surpass 45 mg/L.

5.2 Correlation analysis between fluoride and other physicochemical indicators

Fluoride concentration in groundwater is strongly influenced by aquifer geochemistry and hydro chemical conditions. Elevated pH and alkalinity often promote fluoride mobilization by enhancing the dissolution of fluorite and fluorapatite minerals. Electrical conductivity (EC) and total dissolved solids (TDS) show positive associations with fluoride, reflecting prolonged water–rock interaction and higher ionic strength (Nagaraj and Masilamani, 2023). Conversely, hardness and calcium frequently exhibit inverse relationships, as calcium precipitation reduces co precipitation of fluoride, thereby increasing its concentration in solution **(Table 2).**

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In some regions, nitrate and chloride contamination from agricultural or sewage sources has been observed alongside elevated fluoride, though such correlations are site specific (Patel et al., 2023).

Table: 2 Comparison with Bureau of Indian Standards (BIS) and World Health Organization (WHO) guidelines

Parameter	BIS Permissible Limit (IS 10500:2012, reaffirmed 2023)	WHO Guideline Value (4th ed., 2022 reaffirmed 2023)	Health/Utility Implications	Notes/Observations	Recent Findings (2023–2025)	References
pH	6.5–8.5	6.5–8.5	Acceptable taste, corrosion control	Standards aligned	Neutral to alkaline pH reported in most Indian aquifers; extremes linked to metal mobilization	Gantayat and Elumalai, (2024)
EC	3000 µS/cm (desirable <1500)	Not specified	Indicator of salinity	BIS provides threshold; WHO lacks specific value	Elevated EC (>2000 µS/cm) observed in arid zones of Haryana and Rajasthan	Tanwer et al., (2023)
TDS	500 mg/L (acceptable up to 2000)	1000 mg/L	Taste, scaling, health effects	BIS stricter at desirable level	CGWB 2023 data show >1500 mg/L in semi-arid belts	https://cgwb.gov.in/cgwbpnm/public/uploads/documents/17363272771910393216file.pdf
Hardness	200 mg/L (acceptable up to 600)	500 mg/L	Scaling, domestic usability	BIS more stringent	High hardness (>400 mg/L) reported in western India aquifers	Jodhani et al., (2025)
Alkalinity	200 mg/L (acceptable up to 600)	Not specified	Buffering capacity	BIS sets limit; WHO does not	Elevated alkalinity (>300 mg/L) linked to fluoride mobilization in Punjab (2024 study)	Khan et al., (2025)

Chloride	250 mg/L (acceptable up to 1000)	250 mg/L	Taste, corrosion	Standards aligned	Salinity intrusion noted in coastal aquifers; >500 mg/L in Gujarat	Bhagat et al., (2021)
Sulphate	200 mg/L (acceptable up to 400)	500 mg/L	Gastrointestinal effects	BIS stricter	Elevated sulphate (>400 mg/L) in industrial belts of Odisha	Ahmed, (2023)
Nitrate	45 mg/L	50 mg/L	Infant methemoglobine mia	Nearly aligned	Southern India study (2025) reported nitrate >80 mg/L with fluoride co contamination	Ritu et al., (2025)
Fluoride	1.0 mg/L (acceptable up to 1.5)	1.5 mg/L	Dental caries (<1.0), fluorosis (>1.5)	BIS lower desirable limit due to endemic fluorosis	Haryana (2025) and Southern India (2025) studies confirm >2.0 mg/L in several aquifers	Prasad et al., (2025)

6. **Public Health Implications of Fluoride Exposure**

Fluoride exposure has important public health implications because its effects vary with concentration. At optimal levels, fluoride strengthens tooth enamel and helps prevent dental caries, especially in children. However, prolonged exposure to high levels can lead to dental fluorosis, causing staining and mottling of teeth.

6.1 Physiological Effects of Chronic Fluoride Ingestion

Dental fluorosis- is the chronic ingestion of fluoride beyond permissible limits leads to hypo mineralization of dental enamel. Clinically, this manifests as mottling, discoloration and pitting of teeth. The severity correlates with both concentration and duration of exposure, with children being particularly vulnerable during the developmental stages of dentition (CHI, 2023).

Skeletal fluorosis- is prolonged exposure results in excessive fluoride deposition in bone tissue, causing osteo sclerosis, joint stiffness and restricted mobility **(Fig: 2)**. Advanced stages are characterized by deformities of the spine and long bones, with radiological evidence of increased bone density. The condition is often irreversible and imposes long term disability (Augusto et al., 2022).

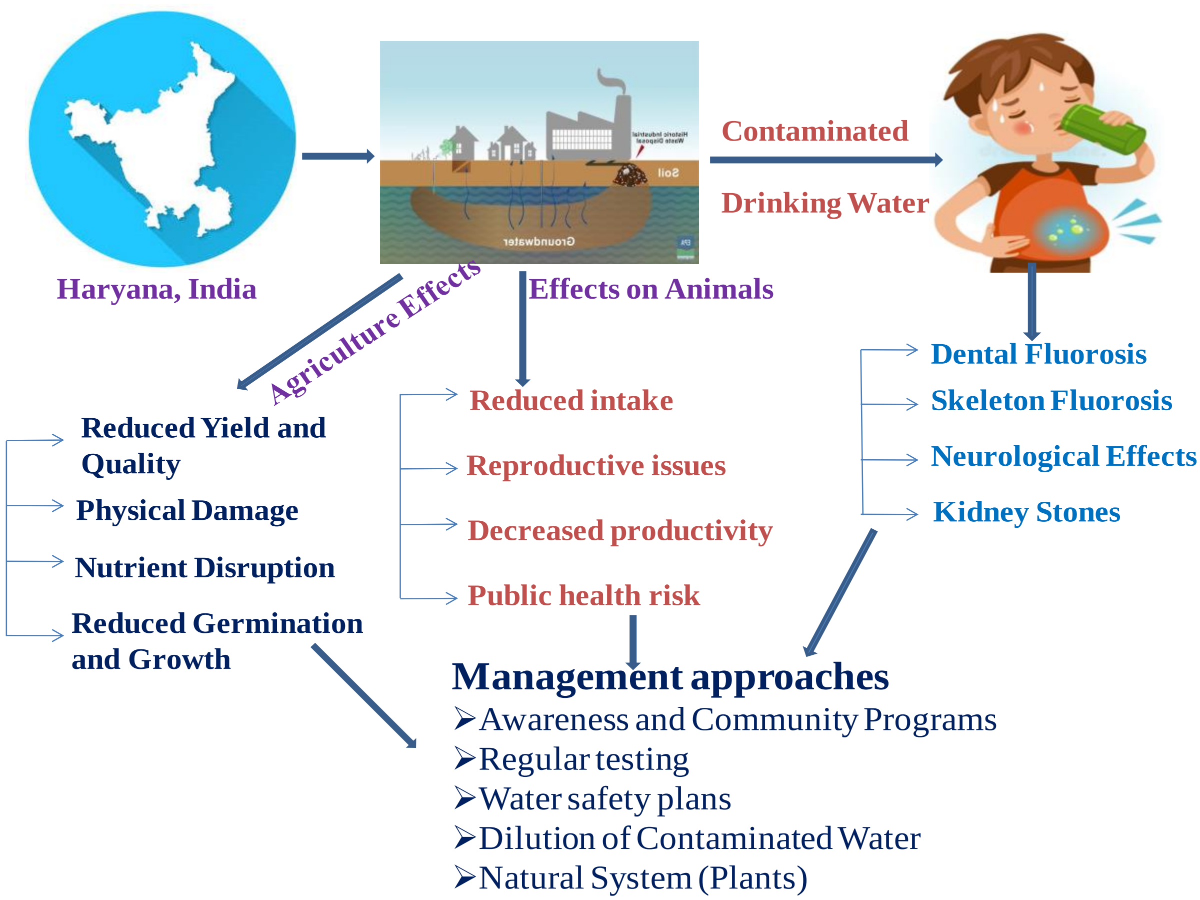

Fig: 2 Effects of Contaminated Groundwater on Agriculture, Animals and Human Health

Systemic manifestations - Beyond dental and skeletal effects, fluoride toxicity has been associated with neurological deficits (impaired cognition, reduced IQ in children), reproductive dysfunctions (altered fertility indices), and metabolic disturbances including thyroid dysfunction and impaired glucose tolerance. These systemic effects highlight fluoride's potential as a multisystem toxicant (Sotili et al., 2025).

6.2 Epidemiological Evidence from Mahendergarh District

Singh and Mukherjee, (2015) earlier conducted a survey on fluoride levels were assessed using Hach field testing kits. Fluoride concentrations ranged from 0.08 to 6.6 mg/L (mean: 2.4 mg/L), with 63% of the samples exceeding the World Health Organization (WHO) drinking-water guideline of 1.5 mg/L and 85% surpassing the Bureau of Indian Standards (BIS) limit of 1 mg/L. The investigation also identified elevated nitrate concentrations, many of which were above WHO recommended limits. The dominant geochemical facies identified in the groundwater samples include Na–Cl–HCO_3 (26 samples), Na–Ca–Cl–HCO_3 (20 samples), Na–Cl

(14 samples), and Na–Ca–Mg–Cl–HCO_3 (11 samples). Across all 100 samples, sodium and bicarbonate were the major ionic components, which can enhance fluoride mobility by promoting the dissolution of fluorite. Thermodynamic relationships among calcium, fluoride and bicarbonate activities indicate that fluoride concentrations are primarily regulated by calcium ion activity. X-ray diffraction analyses of sediment samples further demonstrate that calcite and fluorite are the key solubility-controlling minerals governing the hydrogeochemical behavior of high-fluoride groundwater. Epidemiological studies reveal a high prevalence of dental and skeletal fluorosis among rural populations, particularly in villages reliant on deep aquifers (Xiang, 2024). Children and adolescents exhibit visible dental mottling, while adults frequently report musculoskeletal pain and restricted mobility. The burden is compounded by limited access to safe drinking water alternatives, making fluoride exposure a persistent public health challenge in the region (Mariappan Santhi et al., 2024).

6.3 Socioeconomic Burden and Quality of Life Impacts

The health consequences of fluoride exposure translate into significant socioeconomic costs. Affected individuals often experience reduced productivity due to chronic pain and disability, leading to economic hardship in agrarian communities. Educational attainment is hindered in children with dental fluorosis due to psychosocial stigma, while skeletal deformities limit employability in adults (Sanchez et al., 2024). Healthcare expenditures for managing fluorosis further strain household incomes. Collectively, these impacts diminish quality of life and perpetuate cycles of poverty, underscoring the urgent need for sustainable mitigation strategies (Prabhakar, 2025).

7. Mitigation and Management Strategies

Mitigation and management of fluoride contamination in groundwater require a multi-dimensional approach that combines technological interventions, policy frameworks and sustainable practices **(Fig: 2)**. Among the technological options, defluoridation techniques such as the Nalgonda process, activated alumina adsorption and reverse osmosis have been widely studied and applied.

7.1 Technological Interventions

Technological interventions for fluoride mitigation in groundwater have been extensively explored, with several methods demonstrating varying degrees of efficiency, feasibility and sustainability.

7.1.1 Defluoridation Techniques

Defluoridation remains the most widely adopted technological approach to mitigate fluoride contamination in drinking water. The Nalgonda process**,** developed in India, is a cost-effective method involving the addition of alum, lime and bleaching powder, followed by flocculation and sedimentation (Jamwal and Slathia, 2022). It has been extensively applied in rural settings due to its simplicity and scalability, though challenges such as sludge disposal and taste alteration persist. Activated alumina adsorption is another well established technique, offering high efficiency in fluoride removal; however, its performance is sensitive to pH and requires periodic regeneration, which can increase operational costs (Tolkou et al., 2021). Reverse osmosis (RO) has emerged as a modern solution, capable of removing fluoride along with other dissolved salts **(Table 3).** While RO ensures high-quality water output, its limitations include high energy demand, membrane fouling and the need for skilled maintenance, making it less feasible for low income communities. Comparative studies highlight that no single technique is universally optimal and selection depends on local water chemistry, economic feasibility and community acceptance (Gebre et al., 2021).

7.1.2 Alternative Water Supply Options

In regions where defluoridation technologies are impractical alternative water supply strategies are increasingly emphasized. Rainwater harvesting provides a fluoride-free source and has been promoted as a sustainable household-level intervention, particularly in semi-arid areas. Its success depends on adequate storage infrastructure and community participation. Blending methods**,** where high-fluoride groundwater is diluted with low fluoride surface water or treated water, are also practiced to achieve safe concentrations (Al Sabti et al., 2023). While blending is cost-effective, it requires reliable access to multiple water sources and careful monitoring to maintain permissible fluoride levels (Ahmad et al., 2022). These alternatives are often integrated with technological interventions to ensure long-term sustainability.

7.2 Policy and Governance Measures

Effective policy and governance are essential for managing fluoride contamination in drinking water. Governments must establish clear water-quality standards, regularly monitor groundwater sources and ensure timely reporting of contamination levels. Strong regulatory frameworks help protect communities from long term health risks.

7.2.1 Governmental Initiatives and Regulatory Frameworks in Haryana

The state of Haryana has implemented several initiatives to address fluoride contamination, recognizing its public health implications. Government programs have focused on the installation of community level defluoridation plants, promotion of rainwater harvesting structures and provision of piped water supply schemes in affected districts. Regulatory frameworks emphasize adherence to permissible fluoride limits as prescribed by the Bureau of Indian Standards (BIS) and World Health Organization (WHO) (Gao et al., 2021). However, challenges remain in ensuring consistent monitoring, maintenance of treatment plants and equitable distribution of safe water. Recent policy discussions highlight the need for stronger interdepartmental coordination and integration of water quality management into broader rural development schemes (Yu et al., 2024).

7.2.2 Community-Based Awareness and Participatory Approaches

Community engagement is increasingly recognized as a cornerstone of effective fluoride mitigation. Awareness campaigns focusing on the health risks of fluoride exposure and the importance of safe water practices have been shown to improve adoption of interventions. Participatory approaches, where local communities are involved in planning, operation and maintenance of defluoridation units or rainwater harvesting systems, enhance sustainability and accountability. Studies suggest that empowering women and local self-help groups can significantly improve the success of water management initiatives, as they are often primary stakeholders in household water use.

Table: 3 Approaches for Fluoride Mitigation in Drinking Water: Efficiency, Costs and Limitations

Technique	Efficiency in Fluoride Removal	Cost Implications	Operational Requirements	Limitations	Suitability Context	Key Research Insights	References

Nalgonda Process	Moderate–high (up to ~80–90%)	Low (chemicals inexpensive)	Simple dosing, flocculation, sedimentation	Sludge disposal; taste alteration; residual aluminum	Rural/semi-urban community plants	Widely applied in India; effective for community-scale treatment but criticized for sludge management	Choubisa, (2023)
Activated Alumina	High (up to ~95%)	Moderate–high (due to regeneration)	Requires pH control; periodic regeneration	Declining efficiency over cycles; higher costs	Household/institutional point-of-use	Effective at small scale; regeneration with caustic soda needed; efficiency drops after repeated cycles	Mou and Chen, (2021)
Reverse Osmosis (RO)	Very high (>95%)	High (capital + O&M, energy)	Skilled operation; electricity; membrane care	Energy intensive; brine disposal challenges	Urban households, institutions	Provides high-quality water; brine disposal remains a major environmental concern	Pearson et al., (2021)
Rainwater Harvesting	Fluoride-free source	Low–moderate (depends on storage infrastructure)	Catchment hygiene; seasonal storage	Seasonal dependence; contamination risks	Semi-arid regions; household/community systems	Demonstrated success in fluoride-affected districts; requires community participation	KIPTOO, (2024)
Blending Methods	Variable (depends on dilution ratio)	Low (cost-effective)	Reliable access to multiple sources; monitoring	Requires sustained multi-source management	Areas with mixed sources available	Cost-effective but requires careful monitoring to maintain safe levels	Kumari et al., (2024)

8. Sustainable Water Management Approaches

Long-term mitigation requires integration of fluoride control into broader sustainable water management frameworks. This includes promoting conjunctive use of surface and groundwater, enhancing recharge through watershed management, and adopting circular economy principles to minimize resource wastage.

8.1 Integration of Circular Economy Principles

The integration of circular economy (CE) principles into water management represents a paradigm shift from linear resource use toward closed-loop systems that prioritize reuse, recycling and waste minimization. In fluoride affected regions, CE approaches can enhance sustainability by converting treatment by products into value-added materials, such as utilizing defluoridation sludge in construction or soil stabilization (Ahamed, 2023). Water reuse technologies, including decentralized wastewater treatment and grey water recycling, reduce dependence on contaminated groundwater while simultaneously conserving freshwater resources. Rainwater harvesting, when coupled with nutrient recovery systems, exemplifies CE by addressing both water scarcity and agricultural productivity. Literature emphasizes that successful CE adoption requires supportive governance structures, technological innovation, and community-level participation to ensure that interventions are both environmentally sound and socio-economically viable (Aiyetan, 2025).

8.2 Climate-Resilient Agricultural Practices

Agriculture is highly vulnerable to both water quality issues and climate variability, making climate-resilient practices essential for sustainable management. Strategies such as crop diversification, adoption of fluoride-tolerant cultivars, and integrated soil water management reduce the risk of fluoride accumulation in food crops while enhancing resilience to droughts and floods (Srivastav et al., 2021). Conservation agriculture techniques including minimal tillage, organic amendments, and mulching improve soil health and reduce reliance on contaminated groundwater. Precision irrigation methods, such as drip and sprinkler systems, optimize water use efficiency and minimize exposure to fluoride-laden aquifers. Agro forestry and watershed management further contribute to resilience by enhancing groundwater recharge, stabilizing ecosystems and buffering against climate extremes. The literature highlights that embedding these practices within participatory frameworks strengthens local adaptive capacity, ensuring that agricultural systems remain productive, safe, and sustainable under changing climatic conditions (Silici et al., 2021).

9. Challenges and Future Prospects

While considerable progress has been made in mitigating fluoride contamination through technological, policy and community based interventions, several persistent challenges continue to hinder sustainable outcomes. Conventional defluoridation methods such as the Nalgonda process and activated alumina, while effective, face operational constraints including sludge disposal, declining efficiency over repeated cycles, and sensitivity to water chemistry. Reverse osmosis systems provide high-quality water but remain energy-intensive and costly, limiting their accessibility in rural and low-income settings, while community defluoridation plants often suffer from poor maintenance, irregular chemical supply, and lack of trained personnel. Policy frameworks exist at both national and state levels, yet enforcement remains uneven, with inadequate monitoring and weak interdepartmental coordination. In regions such as Haryana, decentralized implementation has been slowed by bureaucratic bottlenecks and limited financial resources, while community participation is often constrained by low awareness, cultural preferences, and socio-economic disparities. Environmental pressures further complicate the situation, as over-extraction of groundwater and climate variability exacerbate fluoride mobilization and reduce the reliability of alternative sources such as rainwater harvesting.

Looking ahead, future strategies must emphasize integrated, adaptive, and sustainable approaches. Technological innovation will play a central role, with research focusing on low-cost, energy-efficient materials such as nano adsorbents and bio sorbents, as well as hybrid treatment systems that overcome current limitations. Smart monitoring tools using sensors and digital platforms are expected to enable real-time water quality assessment, improving transparency and accountability. Circular economy principles offer promising opportunities by valorizing treatment by-products, reusing wastewater, and promoting closed-loop water management systems that reduce environmental footprints. Climate-resilient agricultural practices, including crop diversification, precision irrigation, and watershed management, will be essential to ensure food and water security under changing climatic conditions. Strengthening policy enforcement, fostering inter sectoral coordination, and integrating water quality management into rural development programs will be critical, while public private partnerships can mobilize resources and expertise. Ultimately, the success of future interventions will depend on community empowerment, with emphasis on awareness campaigns, women's involvement, and local ownership of water management systems. Aligning fluoride mitigation with the United Nations Sustainable Development Goals, particularly SDG 6 on clean water and sanitation, will provide global visibility and funding opportunities, ensuring that mitigation efforts are not only technically effective but also socially equitable and environmentally sustainable.

10. Conclusion

The fluoride contamination in groundwater remains a pressing environmental and public health challenge, particularly in regions such as Haryana where dependence on groundwater is high. Technological interventions including the Nalgonda process, activated alumina and reverse osmosis have demonstrated varying degrees of effectiveness, yet each is constrained by cost, operational feasibility, and sustainability concerns. Alternative water supply options such as rainwater harvesting and blending methods provide practical solutions, though their success depends on community participation and reliable infrastructure. Policy and governance measures have played a critical role in shaping mitigation strategies, but gaps in enforcement, monitoring, and long term maintenance continue to limit their impact. Sustainable water management approaches, especially those integrating circular economy principles and climate resilient agricultural practices, offer promising pathways to address fluoride contamination while ensuring ecological balance and socio economic equity.

The synthesis of literature underscores that no single strategy can provide a universal solution; rather, a multi-dimensional framework combining technological innovation, policy strengthening, and community empowerment is essential. Future directions must prioritize low cost, energy efficient technologies, participatory governance models, and alignment with global sustainability agendas such as the United Nations Sustainable Development Goals. By embedding fluoride mitigation within broader water security and climate resilience frameworks, it is possible to move toward solutions that are not only technically effective but also socially inclusive and environmentally sustainable.

CRediT authorship contribution statement

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

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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.

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References

Agnew, C., & Anderson, E. (2024). *Water resources in the arid realm*. Routledge.

Ahamad, F., Tyagi, S. K., Singh, M., & Sharma, A. K. (2023). Groundwater in arid and semi-arid regions of India: A review on the quality, management and challenges. *Groundwater in Arid and Semi-Arid Areas: Monitoring, Assessment, Modelling, and Management*, 11-52.

Ahamed, I. (2023). Removal of fluoride from groundwater using suitable adsorbents and management of generated waste.

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.

Ahmed, M. S., Bhuyan, P., Sarkar, S., & Hoque, R. R. (2022). Seven-year study of monsoonal rainwater chemistry over the mid-Brahmaputra plain, India: assessment of trends and source regions of soluble ions. *Environmental Science and Pollution Research*, *29*(17), 25276-25295.

Ahmed, T. (2023). *Water Quality Assessment of Household Drinking Water and Evaluation of Potential Human Health Risk–A Case of South Kantajhar Village, Rourkela, Odisha* (Doctoral dissertation, NATIONAL INSTITUTE OF TECHNOLOGY ROURKELA).

Aiyetan, A. O. (2025). Enhancing sustainable and resilient water infrastructure in South Africa in the face of climate change. *Urban Planning*, *10*.

Al Sabti, B., Samayamanthula, D. R., Dashti, F. M., & Sabarathinam, C. (2023). Fluoride in groundwater: distribution, sources, processes, analysis, and treatment techniques: a review. *Hydrogeochemistry of Aquatic Ecosystems*, 1-31.

Araya, D., Podgorski, J., Kumi, M., Mainoo, P. A., & Berg, M. (2022). Fluoride contamination of groundwater resources in Ghana: Country-wide hazard modeling and estimated population at risk. *Water Research*, *212*, 118083.

Augusto, A. C. D. L., Goes, P. C. K., Flores, D. V., Costa, M. A. F., Takahashi, M. S., Rodrigues, A. C., ... & Aihara, A. Y. (2022). Imaging review of normal and abnormal skeletal maturation. *Radiographics*, *42*(3), 861-879.

Beg, M. K., Kumar, N., Srivastava, S. K., & Carranza, E. J. M. (2023). Interpretation of fluoride groundwater contamination in Tamnar area, Raigarh, Chhattisgarh, India. *Earth*, *4*(3), 626-654.

Bhagat, C., Puri, M., Mohapatra, P. K., & Kumar, M. (2021). Imprints of seawater intrusion on groundwater quality and evolution in the coastal districts of south Gujarat, India. *Case Studies in Chemical and Environmental Engineering*, *3*, 100101.

Bieliaieva, O., & Zabolotna, A. (2023). Management of the Processes of Improving the Quality of Life in the Region. *Copernicus Political and Legal Studies*, *2*(4), 32-38.

Carrard, N., Foster, T., & Willetts, J. (2019). Groundwater as a source of drinking water in southeast Asia and the Pacific: A multi-country review of current reliance and resource concerns. *Water*, *11*(8), 1605.

Chaudhuri, R., Sahoo, S., Debsarkar, A., & Hazra, S. (2024). Fluoride contamination in groundwater—a review. *Geospatial Practices in Natural Resources Management*, 331-354.

CHI, D. L. (2023). Dental and Oral Health. *Burns' Pediatric Primary Care-E-Book: Burns' Pediatric Primary Care-E-Book*, *283*.

Choubisa, S. L. (2023). Nalgonda technique is an ideal technique for defluoridation of water: its use can prevent and control hydrofluorosis in humans in India. *Academic J Hydrology Water Res*, *1*(1), 15-21.

Dawoud, M. A., & Al Hassan, W. A. (2025). Groundwater Management and Treatment: A Resilient Source for Environmental Protection. In *Sustainable Remediation for Pollution and Climate Resilience* (pp. 661-693). Singapore: Springer Nature Singapore.

Gakweli, A. M. (2023). *Effect of salt harvesting on ground water quality in Gongoni, Kilifi county* (Doctoral dissertation).

Gantayat, R. R., & Elumalai, V. (2024). Salinity-induced changes in heavy metal behavior and mobility in semi-arid coastal aquifers: a comprehensive review. *Water*, *16*(7), 1052.

Gao, S. S., Amarquaye, G., Arrow, P., Bansal, K., Bedi, R., Campus, G., ... & Chu, C. H. (2021). Global oral health policies and guidelines: using silver diamine fluoride for caries control. *Frontiers in oral health*, *2*, 685557.

Gebre, S. L., Cattrysse, D., & Van Orshoven, J. (2021). Multi-criteria decision-making methods to address water allocation problems: A systematic review. *Water*, *13*(2), 125.

Ghosh, A., Patra, S., Bhattacharjee, S., & Bera, B. (2024). Severe magnitude of dental and skeletal fluorosis and its impact on society and environment in a part of Manbhum-Singhbhum Plateau, India. *BMC Public Health*, *24*(1), 1971.
Ghosh, A., Patra, S., Bhattacharjee, S., & Bera, B. (2024). Severe magnitude of dental and skeletal fluorosis and its impact on society and environment in a part of Manbhum-Singhbhum Plateau, India. *BMC Public Health*, *24*(1), 1971.
Goparaju, L., & Ahmad, F. (2019). Analysis of seasonal precipitation, potential evapotranspiration, aridity, future precipitation anomaly and major crops at district level of India. *KN-Journal of Cartography and Geographic Information*, *69*(2), 143-154.

Gupta, S., Mishra, N., Kumar, A., & Yadav, A. K. (2024). Fluoride pollution in subsurface water: challenges and opportunities. *Advanced treatment technologies for fluoride removal in water: water purification*, 19-39.

Haidery, A., Umar, R., & Khan, I. (2025). Seasonal variation and spatial distribution of heavy metal (loid) s concentration in groundwater and surface water from hard-rock terrain, Ranchi, India. *Environment, Development and Sustainability*, *27*(8), 18591-18625.

Islam, M. S. (2023). Evaluation of Hydrogeochemical Processes. In *Hydrogeochemical Evaluation and Groundwater Quality* (pp. 65-133). Cham: Springer Nature Switzerland.

Jamakala, O., Chintada, V., & Veeraiah, K. (2025). Fluoride in Groundwater: Toxicological Exposure and Remedies. In *Fluorides in Drinking Water: Source, Issue, and Mitigation Strategies* (pp. 305-332). Cham: Springer Nature Switzerland.

Jamwal, K. D., & Slathia, D. (2022). A review of defluoridation techniques of global and Indian prominence. *Current World Environment*, *17*(1), 41.

Jodhani, K. H., Gupta, N., Dadia, S., Patel, H., Patel, D., Jamjareegulgarn, P., ... & Rathnayake, U. (2025). Sustainable groundwater management through water quality index and geochemical insights in Valsad India. *Scientific Reports*, *15*(1), 8769.

Kalevandi, Y., Gholami, Z., Hakim, E., Aghaei, A., Varnaseri, S., & Adiban, M. (2024). Investigating the concentration of sulfate, phosphate, iron, TDS (Total Dissolved Solids), and EC (Electrical Conductivity) parameters in drinking water sources of Ilam city from 2019 to 2023. *Journal of Health Sciences Perspective*, *1*(1), 15-26.

Kamruzzaman, M., Khan, M. S. U., Ritu, S. A., Khanom, S., Hossain, M., Islam, M. R., & Uddin, S. (2025). Diving Deep: Exploring Fluoride in Groundwater—Causes, Implications, and Mitigation. In *Fluorides in Drinking Water: Source, Issue, and Mitigation Strategies* (pp. 189-221). Cham: Springer Nature Switzerland.

Khan, I., Singh, A., & Jamal, Y. (2025). Hydrogeochemical Dynamics of Groundwater in the Punjab Region of the Indo-Gangetic Plains: An Entropy-Weighted and Geochemical Modeling Approach. *Earth Systems and Environment*, 1-24.

Khatri, P., Kumar, P., Shakya, K. S., Kirlas, M. C., & Tiwari, K. K. (2024). Understanding the intertwined nature of rising multiple risks in modern agriculture and food system. *Environment, Development and Sustainability*, *26*(9), 24107-24150.

KIPTOO, S. J. (2024). *RELATIONSHIP BETWEEN FLUORIDE LEVELS AND PHYSICALCHEMICAL PARAMETERS IN SELECTED MEDIA IN UPPER RIVER NJORO CATCHMENT NAKURU COUNTY, KENYA* (Doctoral dissertation, University of Eldoret).

Kumari, J., Khan, M. S., Bansal, M., Kapoor, T., & Habib, G. (2024). Design, evaluation, and performance of versatile source sampling system (VS3) for monitoring and characterization of aerosols from area, point and line sources. *Aerosol Science and Technology*, *58*(12), 1333-1346.

Kumari, M., Singh, S., & Kumar, A. (2024). Groundwater Prospect Zone Mapping: A Geospatial Investigation with Decision Making in Mahendergarh District, Haryana. *Asian Journal of Water, Environment and Pollution*, *21*(6), 131-141.

Lachassagne, P., Dewandel, B., & Wyns, R. (2021). Hydrogeology of weathered crystalline/hard-rock aquifers—guidelines for the operational survey and management of their groundwater resources. *Hydrogeology Journal*, *29*(8), 2561-2594.

Letz, O., Siebner, H., Avrahamov, N., Egozi, R., Eshel, G., & Dahan, O. (2021). The impact of geomorphology on groundwater recharge in a semi-arid mountainous area. *Journal of Hydrology*, *603*, 127029.

Lubojanski, A., Piesiak-Panczyszyn, D., Zakrzewski, W., Dobrzynski, W., Szymonowicz, M., Rybak, Z., ... & Dobrzynski, M. (2023). The safety of fluoride compounds and their effect on the human body—A narrative review. *Materials*, *16*(3), 1242.

Mahto, M. K. (2024). Challenges and opportunities for water resources in India: an exploratory story of resilience. *Integrated Management of Water Resources in India: A Computational Approach: Optimizing for Sustainability and Planning*, 59-80.

Makanda, K., Nzama, S., & Kanyerere, T. (2022). Assessing the role of water resources protection practice for sustainable water resources management: A review. *Water*, *14*(19), 3153.

Mariappan Santhi, V., Periasamy, D., Perumal, M., Sekar, P. M., Varatharajan, V., Aravind, D., ... & Krishnan, R. S. (2024). The Global Challenge of Fluoride Contamination: A Comprehensive Review of Removal Processes and Implications for Human Health and Ecosystems. *Sustainability*, *16*(24), 11056.

Mou, X., & Chen, Z. (2021). Experimental and predictive study on the performance and energy consumption characteristics for the regeneration of activated alumina assisted by ultrasound. *Ultrasonics Sonochemistry*, *70*, 105314.

Nagaraj, S., & Masilamani, U. S. (2023). Hydrogeochemical and multivariate statistical approaches to investigate the characteristics of groundwater quality in fluoride-enriched hard rock region in Tirupathur district of Tamil Nadu, India. *Environmental Science and Pollution Research*, *30*(44), 99809-99829.

Paria, B., Pani, A., Mishra, P., & Behera, B. (2021). Irrigation-based agricultural intensification and future groundwater potentiality: experience of Indian states. *SN Applied Sciences*, *3*(4), 449.

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.

Pearson, J. L., Michael, P. R., Ghaffour, N., & Missimer, T. M. (2021). Economics and energy consumption of brackish water reverse osmosis desalination: innovations and impacts of feedwater quality. *Membranes*, *11*(8), 616.

Prabhakar, A. C. (2025). AI strategies for sustainable development goals: Collective action for poverty alleviation. In *AI Strategies for Social Entrepreneurship and Sustainable Economic Development* (pp. 393-442). IGI Global Scientific Publishing.

Pradhan, R. M., Singh, A., Ojha, A. K., & Biswal, T. K. (2022). Structural controls on bedrock weathering in crystalline basement terranes and its implications on groundwater resources. *Scientific Reports*, *12*(1), 11815.

Prasad, B., Kaur, P. S., & Gupta, S. (2025). Fluoride Contamination in Drinking Water and Associated Health Risk. In *Fluorides in Drinking Water: Source, Issue, and Mitigation Strategies* (pp. 37-62). Cham: Springer Nature Switzerland.

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.

Rani, G., Kaur, N., & Sharma, V. K. (2024). FLUORIDE MITIGATION-A REVIEW. *Guident*, *17*(10).

Ritu, R., Ruby, R., Dimple, D., Nancy, N., & Giri, A. (2025). A Systematic Review of Potential Health Risk Assessments for Nitrate Contamination in Different Water Resources in India. *Water, Air, & Soil Pollution*, *236*(11), 1-24.

Sahoo, S., Singha, C., Govind, A., & Sharma, P. (2025). Review of aquifer storage and recovery opportunities and challenges in India. *Environmental Earth Sciences*, *84*(5), 122.

Sanchez, S., Gomez, J. R., Cornejo, I. E., Park-Taylor, J., & Shen, N. (2024). HOLISTIC PSYCHOSOCIAL SUPPORT FOR YOUTH WITH DENTAL HEALTH CONCERNS. *An Intersectional Approach to Counseling Children and Adolescents With Health Conditions*, 167.

Shaikh, M., & Birajdar, F. (2024). Groundwater and public health: exploring the connections and challenges. *International Journal for Innovative Science Research Trends and Innovation*, *9*(2), 1351-1361.

Shukri, N. A. M., Lutpi, N. A., Wong, Y. S., Ong, S. A., Dahalan, F. A., Taweepreda, W., ... & Rahmat, N. R. (2025). Calamity and Treatment Approach of Sulfate in Palm Oil Mill Effluent: A Mini Review. *Environmental Quality Management*, *34*(4), e70087.

Sidhu, J. S., Chandel, S., Sahoo, S., Singh, D., Singh, K., Arora, M., & Kaur, H. (2025). Hydrogeochemical characterization and geospatial assessment of groundwater quality in the alluvial aquifer of southwestern Punjab in association with health risk assessment due to nitrate and fluoride pollution. *Environmental Science and Pollution Research*, 1-28.

Silici, L., Rowe, A., Suppiramaniam, N., & Knox, J. W. (2021). Building adaptive capacity of smallholder agriculture to climate change: evidence synthesis on learning outcomes. *Environmental Research Communications*, *3*(12), 122001.

Singh, C. K., & Mukherjee, S. (2015). Aqueous geochemistry of fluoride enriched groundwater in arid part of Western India. *Environmental Science and Pollution Research*, *22*(4), 2668-2678.

Sotili, M. R., Staudt, T., Tramontina, D., de Souza Rodrigues, N., Alba, G. L., Crestani, V. C., ... & Bertol, C. D. (2025). Fluoride: a double-edged sword in public health and environmental toxicology. *Environmental Monitoring and Assessment*, *197*(7), 710.

Srivastav, A. L., Dhyani, R., Ranjan, M., Madhav, S., & Sillanpää, M. (2021). Climate-resilient strategies for sustainable management of water resources and agriculture. *Environmental Science and Pollution Research*, *28*(31), 41576-41595.

Srivastava, S., & Flora, S. J. S. (2020). Fluoride in drinking water and skeletal fluorosis: a review of the global impact. *Current environmental health reports*, *7*(2), 140-146.

Sultana, A. (2025). Temporal Variability of Water Quality Parameters: Surface and Groundwater Contamination. *International Journal of Innovations in Science, Engineering And Management*, 112-122.

Swami, A. (2021). *STUDIES ON IMPACT OF RAINFALL VARIABILITY ON PRODUCTION AND PRODUCTIVITY OF SMALL MILLETS IN DIFFERENT DISTRICTS OF CHHATTISGARH* (Doctoral dissertation, INDIRA GANDHI KRISHI VISHWAVIDYALAYA RAIPUR (Chhattisgarh)).

Takada, N., Kobayashi, T., & Oya, M. (2023). Effect of water hardness on acute aquatic toxicity of fatty acid salts. *Journal of Oleo Science*, *72*(11), 1005-1014.

Tanwer, N., Deswal, M., Khyalia, P., Laura, J. S., & Khosla, B. (2023). Assessment of groundwater potability and health risk due to fluoride and nitrate in groundwater of Churu District of Rajasthan, India. *Environmental Geochemistry and Health*, *45*(7), 4219-4241.

Tolkou, A. K., Manousi, N., Zachariadis, G. A., Katsoyiannis, I. A., & Deliyanni, E. A. (2021). Recently developed adsorbing materials for fluoride removal from water and fluoride analytical determination techniques: a review. *Sustainability*, *13*(13), 7061.

Tura, T. T., & Demeku, S. (2025). Analyzing Their Contribution to Water Demand, Quality, and Groundwater Sustainability of Private Water Wells in Addis Ababa, Ethiopia.

Walraevens, K., Bennett, G., Alfarrah, N., Gebreyohannes, T., Berhane, G., Hagos, M., ... & Yenehun, A. (2025). Assessing the potential of volcanic and sedimentary rock aquifers in Africa: Emphasizing transmissivity, water quality, and recharge as key evaluation metrics. *Water*, *17*(1), 109.

Wei, Y., Chen, Y., Cao, X., Xiang, M., Huang, Y., & Li, H. (2024). A critical review of groundwater table fluctuation: Formation, effects on multifields, and contaminant behaviors in a soil and aquifer system. *Environmental Science & Technology*, *58*(5), 2185-2203.

World Health Organization, & United Nations Children's Fund. (2022). *State of the world's drinking water: an urgent call to action to accelerate progress on ensuring safe drinking water for all*. World Health Organization.

Xiang, D. (2024). Environmental Anthropology of Fluoride: A Comprehensive Anthropological Study of Fluoride Mining, Production, and Contamination Impacts. *Fluoride*, *57*(9).

Yu, Y., Appiah, D., Zulu, B., & Adu-Poku, K. A. (2024). Integrating rural development, education, and management: Challenges and strategies. *Sustainability*, *16*(15), 6474.

Zhu, D., Chen, X., Gong, H., Wang, X., Qiao, X., & Dai, X. (2025). Purification of CaF2 from Fluorine-Containing Sludge: Optimization via Calcium Ion Coexistence Effect. *Processes*, *13*(2), 552.