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Fluoride Contamination in Groundwater in Northern India

Amartya Kumar Bhattacharya[1], Sumit Kumar[2]
[1]Chairman and Managing Director, MultiSpectra Amartya Consultants, Kolkata, West Bengal, India.
[2]Department of Civil Engineering, Indian Institute of Technology, Ropar, Punjab, India

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Corresponding author: Amartya Kumar Bhattacharya
Email: dramartyakumar@gmail.com

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Abstract

Fluoride's impact on human health varies based on its concentration in drinking water, being potentially beneficial or harmful. As specified by WHO, the suggesting maximum limitation of fluoride in potable water is approximately 1.2–1.5 mg/L. To better understand fluoride toxicity, this paper examines the adverse causes of excessive fluoride on various biological systems. Elevated fluoride levels in potable water can lead to several health issues, including dental fluorosis, skeletal fluorosis, and long-term effect to the kidneys, liver, and brain. This paper also reviews various techniques for eliminating fluoride from potable water. High concentrations fluoride are often associated with sodium bicarbonate-type water that is deficient in calcium.

Keywords: Fluoride contamination: Groundwater quality: Northern India: Dental fluorosis: Skeletal fluorosis: Health impacts:

Introduction

Potable water scarcity poses a major worldwide challenge and groundwater remains the main source for domestic, agricultural, and industrial use. Excessive groundwater extraction has altered its chemical composition, including fluoride (F^-) minerals derived from rocks and sediments, which accumulate in freshwater sources (Ahmad et al., 2022; Jha et al., 2013). While moderate fluoride (0.7–1.2 mg/L) helps prevent dental caries and is used in toothpaste, excess intake adversely affects health (Bhattacharya et al., 2019). The WHO sets a limit of 1 mg/L in hot climates and 1.5 mg/L in colder regions due to varying water consumption. Apart from water, fish and tea are significant fluoride sources. Fluoride occurs naturally in rocks like biotite, topaz, fluorapatite, and cryolite, and its concentration in groundwater depends on aquifer conditions, depth, weathering, soil porosity, and temperature. Higher levels are common in arid and semi-arid regions such as Africa and western India (Rajasthan, Punjab, Haryana), where alkaline conditions promote dissolution of fluoride minerals (Bhattacharya et al., 2018; Bhattacharya et al., 2019b). Since fluoride is tasteless and invisible, it often goes undetected without testing. Advanced geospatial and machine-learning models now predict fluoride hotspots by correlating environmental factors with observed concentrations. Such models indicate that over 120 million Indians are exposed to high-fluoride groundwater (Sarkar et al., 2023; Avni et al., 2021; Podgórski et al., 2018).

Fluoride Concentration in The Groundwater of India

Fluoride contamination in groundwater affects nearly 20 states in India, with semi-arid regions being the most vulnerable (Fig. 1). A systematic review highlighted high concentrations across northern states, with Madhya

Pradesh (5.98 mg/L), Punjab (4.67 mg/L), Chhattisgarh (3.80 mg/L), Rajasthan (3.30 mg/L), Karnataka (2.56 mg/L), Andhra Pradesh (2.03 mg/L), Maharashtra (1.70 mg/L), Haryana (1.65 mg/L), Telangana (1.64 mg/L), Uttar Pradesh (1.63 mg/L), and Bihar (1.54 mg/L) exceeding BIS and WHO limits (Chahal & Chahal, 2018). In Bihar's Jamui district, hazard indices surpassed 5, posing severe risks, especially to children (Singh and Neeti, 2023). Similarly, 49% of groundwater samples from Boudh and Nuapada districts in Odisha were found above WHO standards, threatening infant health (Barad et al., 2025). Endemic fluorosis has also been reported in Telangana's Siddipet district due to high-pH granitic aquifers (Siddipet Study, 2016).

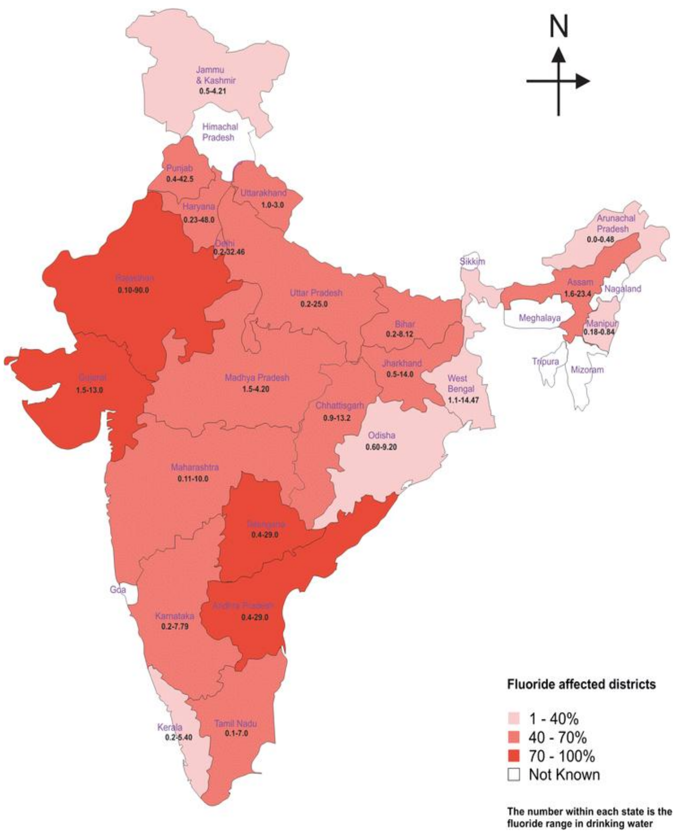

Fig 1. Map showing fluoride-affected states of India

Extent of Contamination in Rajasthan

Rajasthan, an arid state in northwestern India, faces severe fluoride pollution in groundwater—the primary supply of potable water in rural region. The problem is largely geogenic, stemming from fluoride-bearing minerals found in the rocks and soils, but is aggravated by over-extraction of groundwater, use of phosphate fertilizers, and scarce surface water. Contamination is widespread, affecting over 25,000 villages, making Rajasthan one of the world's most fluoride-affected regions. Despite awareness and limited interventions, the issue remains a major public health challenge. Effective mitigation demands integrated strategies involving safe water technologies, alternative water sources, community participation, and strong policy action.

In Rajasthan, more than 25 of the 33 districts report amount fluoride in groundwater above the permissible cap of 1.5 mg/L, with over 7,600 villages officially declared "fluoride-affected habitations" by the Ministry of Jal Shakti. Extreme concentrations have been observed in Nagaur (up to 8.5 mg/L) and Jaipur's Phulera block, where some villages report levels as high as 18 mg/L—over 12 times the safe limit (Agnihotri et al., 2007; Dauji et al., 2023). In Churu district, 37% of sampled sources were contaminated, while in Bhilwara, 57% of villages exceeded 1 mg/L (Fig. 2). Other affected districts include Sikar, Ajmer, Pali, Barmer, and Jodhpur, where concentrations range between 2.5 and 6 mg/L. Overall, rural habitations in northern Rajasthan face widespread fluoride contamination, frequently surpassing WHO limits (Agnihotri et al., 2007).

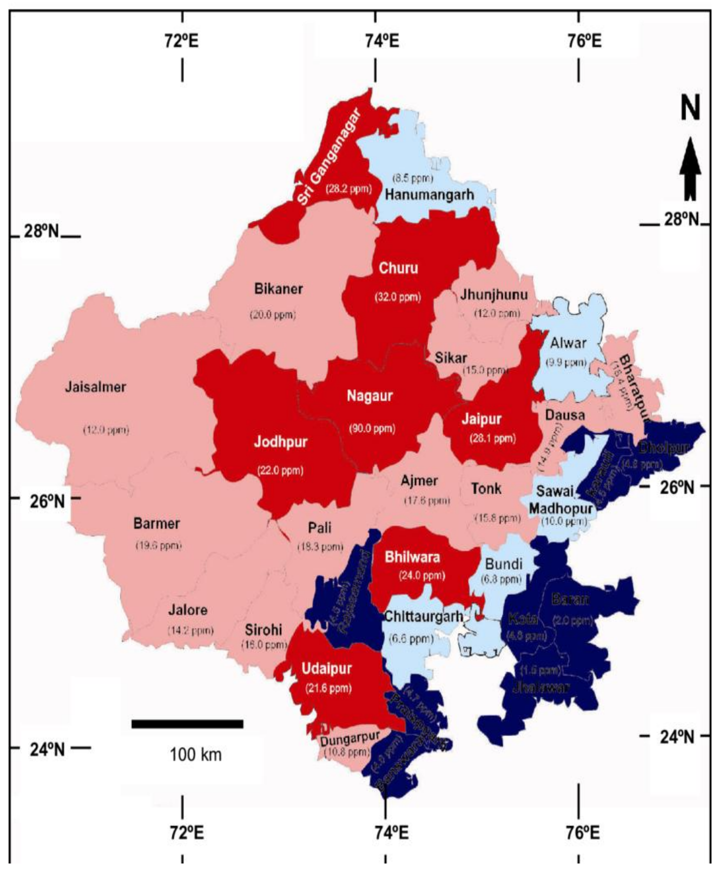

Fig 2. Fluoride-contaminated districts of Rajasthan (range is in ppm deep blue: 1.5-5.0; light blue: 5.1-10.0; light red:

10.1-20.0; and deep red: >20.0)

Extent of Contamination in Punjab

Fluoride contamination in Punjab is concentrated in districts such as Bathinda, Muktsar, Faridkot, Mansa, Fazilka, and Barnala, where calcareous soils with high alkalinity and salinity dominate. The Malwa region, which also contains dune formations covering 10–15% of its area, is particularly vulnerable. Groundwater contamination is driven by both industrial discharges and intensive agriculture (Chahal et al., 2021; Duggal and Sharma, 2022; Mittal et al., 2021). Punjab's phosphate fertilizer consumption is nearly ten times the national average, and the Malwa Belt hosts major industries including chemical and cement factories, oil refineries, National Fertilizer Limited, textiles, and thermal power plants. Collectively, these industrial and agricultural activities have led to elevated fluoride concentrations in groundwater, posing serious risks to public health.

Out of 23 districts in Punjab, around 17 are impacted by fluoride contamination in groundwater. The mean concentrations follow the order: Bathinda (3.2 mg/L), Muktsar (2.6 mg/L), Faridkot (2.4 mg/L), Mansa (2.3 mg/L), Fazilka (1.3 mg/L), Barnala (1.1 mg/L), and Moga (1.0 mg/L). Fluoride levels showed a significant correlation with total dissolved solids in every districts exception of Moga (Fig. 3). Hazard quotient (HQ) values were higher than 1 for all age category in Bathinda, Mansa, Faridkot, and Muktsar, with non-carcinogenic risk ranked as children > teenagers > adults > senior citizens > infants. Patiala is among the most severely affected regions, accounting for nearly 65% of Punjab's fluorosis cases from groundwater intake (Ahodvan and Sudhir, 2019). Fluoride concentrations in Patiala's aquifers increased sharply from 0.06–0.66 mg/L in 2003 to 1.5–9.8 mg/L in 2022. About 98% of the samples exceeded the WHO guideline of 1.5 mg/L, with approximately 23% above 4 mg/L.

Extent of Contamination in Haryana

Fluoride polution in underground water is a major public health situation in Haryana, arising from the geological composition of aquifers, industrial effluents, and intensive agricultural practices. The problem is most severe in the southern and western regions, where underground water is the primary source of potable water and irrigation water. As of December 2024, data from the Ministry of Jal Shakti showed that 23.7% of groundwater samples (208 out of 879) exceeded the allowable fluoride limit of 1.5 mg/L, affecting 17 of the state's 22 districts. A joint report for Punjab and Haryana confirmed that 34 districts—17 in each state—are impacted by unsafe fluoride levels. Furthermore, the Central Ground Water Board (CGWB) and state agencies identified 136 locations across 20 districts in Haryana with fluoride concentrations above safe limits.

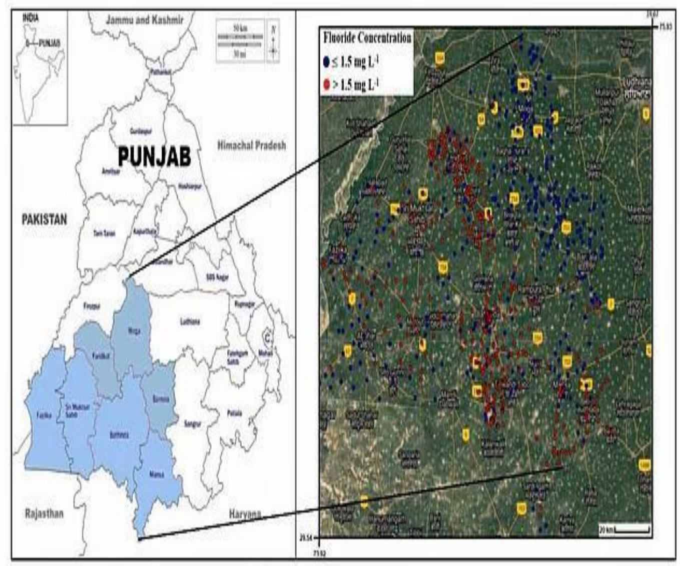

Fig 3. Geographical locations of seven districts in Punjab and sampling sites in each district.

The Mahendergarh district of Haryana has been classified as a Red Alert zone for high fluoride contamination by the Geological Survey of India (GSI). Groundwater, the primary source of drinking and irrigation in the district, was analyzed across all eight blocks. In the Mahendergarh block, fluoride levels in 63 villages ranged from 0.5–5.8 mg/L; 40 villages (62%) were within the WHO allow 1.5 mg/L, while 23 villages (38%) exceeded it. In the Sihma block, concentrations ranged from 0.9–6.0 mg/L across 29 villages, with 11 villages (38%) within safe limits and 18 (62%) above. Kanina block showed 0.4–2.5 mg/L, where 50 villages (89%) were safe and 6 (11%) exceeded the limit. Ateli block recorded 0.4–3.8 mg/L across 43 villages, with 36 villages (84%) safe and 7 (16%) unsafe. Narnaul block had the widest range (0.9–16.0 mg/L), with only 8 villages (12.5%) within limits, 35 moderately contaminated (1.6–2.5 mg/L), and 21 severely contaminated (>2.5 mg/L). In Nizampur, fluoride ranged from 0.6–2.6 mg/L across 29 villages, with 14 (52%) exceeding the permissible limit. Nangal Chaudhary block recorded 0.5 -- 8.0 mg/L, with 21 villages (44%) within the safe limit and 26 (56%) above it.

Extent of Contamination in Uttar Pradesh

Fluoride contamination in groundwater is a significant public health concern in Uttar Pradesh, with several studies reporting concentrations above the World Health Organization (WHO) permissible limit of 1.5 mg/L. The highest levels have been documented in the Raebareli district, while Agra and Kanpur Dehat also report elevated concentrations (Agnihotri et al., 2014). In Agra, groundwater samples collected from wells at depths of 60–90 m showed fluoride limitation ranging from 0.1 to 15 mg/L, exceeding the Indian standard of 0.6–1.2 mg/L. Approximately 80% of the samples contained fluoride levels above 1.5 mg/L, indicating widespread contamination. A study in the Bichpuri block of Agra further revealed that 90% of groundwater samples from 60 wells posed a risk of fluoride poisoning. In Kanpur Dehat, high fluoride levels were mainly attributed to geogenic conditions (Ahghari et al., 2021). These findings underscore the severity of fluoride limitation in Uttar Pradesh and highlight the urgent need for continuous monitoring and mitigation.

Fluoride polution in groundwater is a widespread issue across several districts of Uttar Pradesh. In Sonbhadra, villages in Kon, Bhabni, Myorpur, Duddhi blocks, and areas around the Govind Ballab Pant Reservoir consistently report levels 5–6 times higher than the prescribed standard, with concentrations ranging from 3–5 mg/L in Jhapar, Siswa, Bichhiari, Pindari, Pipri, Dhaurahwa, and Sonwani. In Agra, a study across 25 locations found fluoride levels above the desirable limit everywhere, with the highest limitation of 5 mg/L in the Bichpuri block. Fatehpur, located in the Central Ganga Alluvial Plain, also reported excessive fluoride, particularly in villages such as Chouhatta and Chitisapur. In Banda, groundwater concentrations varied between 0.32 and 3.5 mg/L, with Mavai village recording the highest value. In Rae Bareli, Dalmau and Amawa blocks are severely affected, with about 80% of villages exceeding the permissible limit, while Deeh and Unchahar blocks also show significant contamination. In Unnao, nearly 70% of the population suffers from dental decay and remains at risk of skeletal fluorosis due to fluoride exposure.

Extent of Contamination in Himachal Pradesh

While Himachal Pradesh is generally not considered an endemic zone for severe fluorosis compared to states like Rajasthan or parts of Uttar Pradesh, fluoride contamination in groundwater is indeed a concern and has been reported in specific areas. The National Green Tribunal (NGT) has served notices to Himachal Pradesh, among other states, regarding escalating levels of arsenic and fluoride in their groundwater exceeding permissible limits. Fluoride polution in groundwater has been presented from several districts of Himachal Pradesh, though its severity varies across regions. In Sirmaur, particularly in the Paonta Valley, concentrations often exceed the permissible limit of 1.5 mg/L due to geological formations. In Una, localized contamination has been observed, with studies reporting dental fluorosis among schoolchildren; however, most groundwater samples in one study were within the permissible range (0.5–1.0 mg/L), suggesting limited but significant hotspots. In Shimla, one study recorded the highest prevalence of dental fluorosis (7%) among six districts surveyed, compared to the overall prevalence of 4.1%. In Kangra, groundwater quality studies highlight fluoride as a concern in specific valley-fill areas such as Nurpur–Jawali–Nagrota Surian, Pragpur–Dadasiba, and Palampur–Kangra, where groundwater dependence is high and continuous monitoring is essential. The Central Groundwater Board (CGWB) regularly monitors groundwater quality, while the Jal Jeevan Mission (JJM) is working to ensure a safe drinking water supply to rural households. In fluoride-affected habitations, mitigation strategies include the provision of alternative water sources and the installation of community-based water purification plants.

Extent of Contamination in Delhi

Fluoride polution in Delhi's groundwater is a significant concern, affecting several areas across the National Capital Territory. While not every part of Delhi is equally affected, studies and government reports have consistently identified pockets with fluoride concentrations exceeding the allowable limit of 1.5 mg/L (as per BIS standards) or 1.0 mg/L (as per WHO guidelines). In February 2024, the Delhi government informed the National Green Tribunal (NGT) that out of 1,256 tubewells sampled across the city, 58 had fluoride levels higher than the permitted standard of 1 mg/L (or 1.5 mg/L as per BIS). This indicates that a noticeable percentage of the city's groundwater sources are affected.

Fluoride polution in Delhi's groundwater occurs primarily in isolated pockets, with several areas consistently reporting concentrations above the permissible limits. In Northwest Delhi, high contamination has been documented in Bawana (33 out of 56 tubewells sampled in Narela and Bawana exceeded limits), Nangloi (11 out of 70 tubewells in the Najafgarh Zone and Nangloi above limits), Nizampur, and localities such as Rohini Sector 11 and Sainik Vihar. In Southwest Delhi, elevated levels are reported in Najafgarh, as well as in villages and neighborhoods including Dichaon Kalan, Paprawat, Jharoda, Kakrola, Khera Khurd, Dwarka Sector 23 DDA Park, and Jhuljhuli. In North Delhi, major hotspots include Narela (along with Bawana) and surrounding areas such as Alipur, Khera Kalan, Rohini Sector 28, and Haiderpur. While not uniformly distributed across the city, these findings indicate that several neighborhoods and villages are severely affected, highlighting the localized yet serious nature of fluoride contamination in Delhi's groundwater.

Extent of Contamination in Jammu and Kashmir

Fluoride contamination in the groundwater of Jammu & Kashmir is a significant concern, although its extent and severity can vary across the Union Territory. While some regions, particularly in the Jammu Province, show higher levels, the Kashmir Valley generally reports lower concentrations. Fluoride contamination in groundwater is a growing concern in Jammu and Kashmir, particularly in Doda district, where concentrations have reached up to 7.0 mg/L in Doda and Bhagwah blocks—far exceeding the WHO limit of 1.5 mg/L. Research from the University of Jammu has further confirmed the presence of contamination in other districts of the Jammu province, including Jammu, Kathua, Rajouri, Reasi, Samba, and Udhampur, highlighting the need for geospatial mapping and remediation strategies. Studies across the arid zone of Jammu province reported fluoride levels ranging from 0.2 to 4.2 mg/L, with a mean concentration of 1.63 mg/L; notably, 46% of 53 community tubewell samples exceeded WHO guidelines, posing health risks to both children and adults. Evidence also suggests that contamination increases with depth, as aquifers below 40 m bgl often surpass the BIS permissible limit of 1.0 mg/L. These findings underscore the widespread and multi-dimensional nature of fluoride contamination in the Jammu region.

Extent of Contamination in Madhya Pradesh

Madhya Pradesh is one of the states in India significantly affected by fluoride contamination in its groundwater, posing a substantial public health challenge, particularly in rural areas that heavily rely on groundwater for drinking. The contamination is primarily geogenic, stemming from the natural presence and leaching of fluoride-bearing minerals in the underlying rocks. Fluoride contamination in groundwater is a major public health issue in Madhya Pradesh, particularly in the southern and western tribal belts. Dhar district is among the most severely affected, with concentrations as high as 17.2 mg/L in Umarban block and 11.8 mg/L in Tirla block, far exceeding the permissible limits of 1.5 mg/L (BIS) and 1.0 mg/L (WHO). Nearly 70% of habitations in the district face serious groundwater quality problems, and dental fluorosis is widely prevalent. Similarly, extremely high fluoride levels have been reported in Seoni (14.20 mg/L) and Jhabua (13.86 mg/L), with the adjoining Alirajpur district hosting "fluoride warriors" to combat endemic fluorosis. Other districts show varying but concerning levels of contamination. In Chhindwara, groundwater fluoride ranged from 0.11–7.9 mg/L in the pre-monsoon season and 0.27–17 mg/L post-monsoon, with 25–43% of samples from blocks such as Parasia, Chhindwara, Chourai, and Amarwara exceeding safe limits. Shivpuri has reported levels up to 3.60 mg/L, particularly in the Pichhore block, alongside increasing signs of fluorosis. Elevated concentrations are also reported from Gwalior (6.20 mg/L), Jabalpur (5.00 mg/L), Vidisha (4.43 mg/L), and parts of Dhar (4.07 mg/L). In Mandla, reports are highly inconsistent, with one study citing an anomalously high value of 3030 mg/L, though other findings (e.g., 18.2 mg/L in Mandia) suggest extreme localized contamination. Collectively, these findings indicate widespread fluoride endemicity across Madhya Pradesh, posing serious risks to public health.

Harmful Effects of Fluoride

Fluoride plays a dual role in human health: at moderate concentrations, it strengthens bones and reduces dental caries, but chronic ingestion can lead to severe health issues (Aw et al., 2003; Aoba, 1997). Interest in fluoride risk assessment dates back to the 1980s in India (Brouwer et al., 1988), though its connection to dental caries prevention was first observed in the 1930s by F.S. McKay in the United States. Since then, controlled fluoride levels have been adopted in many developed countries to reduce tooth decay, particularly in children. In India, however, high fluoride in drinking water remains a widespread concern, particularly in states such as Andhra Pradesh, Tamil Nadu, Karnataka, Bihar, Gujarat, Rajasthan, and Punjab. Excess fluoride is linked to dental, skeletal, and crippling fluorosis, as well as systemic effects on intelligence, reproduction, and the pineal gland. Other complications, including gastrointestinal disorders, muscular weakness, and cardiovascular abnormalities, have been reported globally, with industrial exposure also linked to bladder cancer (Alexander & Olsen, 2007). Dental fluorosis—marked by tooth discoloration and structural damage—is endemic in 14 Indian states, affecting nearly 150,000 villages, especially in Bihar, Gujarat, Madhya Pradesh, Rajasthan, and Uttar Pradesh.

Excessive fluoride intake through drinking water is strongly associated with skeletal fluorosis, particularly when concentrations exceed 4–8 mg/L. Early symptoms include increased bone density, stiffness, joint pain, and spinal deformities, while advanced stages can lead to neurological complications and paralysis. Crippling skeletal fluorosis typically occurs above 10 mg/L, and concentrations above 8 mg/L may also cause osteosclerosis. Based on severity, skeletal fluorosis is categorized into mild, moderate, and severe forms. Beyond musculoskeletal effects, fluoride exposure has been linked to alterations in reproductive health, including reduced fertility in females, impaired testosterone levels, and decreased sperm motility in males. Research further highlights fluoride's systemic effects. The U.S. National Toxicology Program (1990) reported carcinogenic potential of fluoridated water due to fluoride accumulation in bones.

A 2024 pan-India study revealed that 8.65% of pre-monsoon groundwater samples exceeded WHO limits, disproportionately affecting children (Pan-India Study, 2024). Chronic exposure is also linked to gastrointestinal problems, thyroid dysfunction through disruption of T3, T4, and TSH, and reduced IQ in children (Aravind et al., 2016). Globally, wildlife in geothermally active regions such as Yellowstone National Park has also been affected by naturally elevated fluoride. These findings underscore fluoride's wide-ranging impacts, making it a critical global public health challenge.

Treatment Processes of Fluoride Removal

A wide range of techniques has been developed to remove high fluoride concentrations from drinking water, including coagulation-precipitation, adsorption, ion exchange, electrocoagulation, and membrane-based processes such as nanofiltration and reverse osmosis. Among these, adsorption has been considered the most cost-effective and technically simple, using materials such as activated alumina, natural adsorbents, and metal mixtures. Activated alumina and its derivatives are widely applied at both household and community levels. The Nalgonda technique, which utilizes alum and lime to form aluminum hydroxide flocs that trap fluoride ions, is particularly prevalent in rural India (Bhattacharya et al., 2015), although it generates substantial volumes of sludge that require safe disposal. Electrocoagulation offers a variation, producing coagulants in situ through electric current.

Membrane technologies such as reverse osmosis and nanofiltration can remove up to 90–99% of fluoride (Ndiaye et al., 2015) but are energy-intensive, costly, and generate brine waste, with periodic membrane replacement adding to expenses (Kumar and Gopal, 2000). Ion exchange using synthetic resins provides high-quality treated water but requires regeneration with salt solutions, producing concentrated brine. Distillation, while highly effective, is slow and energy-intensive, limiting its use to small-scale applications. Overall, each technique has limitations, and the choice depends on cost, efficiency, and local resource availability.

Extent of Contamination in Haryana

Fluoride polution in underground water is a major public health situation in Haryana, arising from the geological composition of aquifers, industrial effluents, and intensive agricultural practices. The problem is most severe in the southern and western regions, where underground water is the primary source of potable water and irrigation water. As of December 2024, data from the Ministry of Jal Shakti showed that 23.7% of groundwater samples (208 out of 879) exceeded the allowable fluoride limit of 1.5 mg/L, affecting 17 of the state's 22 districts. A joint report for Punjab and Haryana confirmed that 34 districts—17 in each state—are impacted by unsafe fluoride levels. Furthermore, the Central Ground Water Board (CGWB) and state agencies identified 136 locations across 20 districts in Haryana with fluoride concentrations above safe limits.

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Fluoride polution in Delhi's groundwater is a significant concern, affecting several areas across the National Capital Territory. While not every part of Delhi is equally affected, studies and government reports have consistently identified pockets with fluoride concentrations exceeding the allowable limit of 1.5 mg/L (as per BIS standards) or 1.0 mg/L (as per WHO guidelines). In February 2024, the Delhi government informed the National Green Tribunal (NGT) that out of 1,256 tubewells sampled across the city, 58 had fluoride levels higher than the permitted standard of 1 mg/L (or 1.5 mg/L as per BIS). This indicates that a noticeable percentage of the city's groundwater sources are affected.

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Fluoride contamination in the groundwater of Jammu & Kashmir is a significant concern, although its extent and severity can vary across the Union Territory. While some regions, particularly in the Jammu Province, show higher levels, the Kashmir Valley generally reports lower concentrations. Fluoride contamination in groundwater is a growing concern in Jammu and Kashmir, particularly in Doda district, where concentrations have reached up to 7.0 mg/L in Doda and Bhagwah blocks—far exceeding the WHO limit of 1.5 mg/L. Research from the University of Jammu has further confirmed the presence of contamination in other districts of the Jammu province, including Jammu, Kathua, Rajouri, Reasi, Samba, and Udhampur, highlighting the need for geospatial mapping and remediation strategies. Studies across the arid zone of Jammu province reported fluoride levels ranging from 0.2 to 4.2 mg/L, with a mean concentration of 1.63 mg/L; notably, 46% of 53 community tubewell samples exceeded WHO guidelines, posing health risks to both children and adults. Evidence also suggests that contamination increases with depth, as aquifers below 40 m bgl often surpass the BIS permissible limit of 1.0 mg/L. These findings underscore the widespread and multi-dimensional nature of fluoride contamination in the Jammu region.

Extent of Contamination in Madhya Pradesh

Madhya Pradesh is one of the states in India significantly affected by fluoride contamination in its groundwater, posing a substantial public health challenge, particularly in rural areas that heavily rely on groundwater for drinking. The contamination is primarily geogenic, stemming from the natural presence and leaching of fluoride-bearing minerals in the underlying rocks. Fluoride contamination in groundwater is a major public health issue in Madhya Pradesh, particularly in the southern and western tribal belts. Dhar district is among the most severely affected, with concentrations as high as 17.2 mg/L in Umarban block and 11.8 mg/L in Tirla block, far exceeding the permissible limits of 1.5 mg/L (BIS) and 1.0 mg/L (WHO). Nearly 70% of habitations in the district face serious groundwater quality problems, and dental fluorosis is widely prevalent. Similarly, extremely high fluoride levels have been reported in Seoni (14.20 mg/L) and Jhabua (13.86 mg/L), with the adjoining Alirajpur district hosting "fluoride warriors" to combat endemic fluorosis. Other districts show varying but concerning levels of contamination. In Chhindwara, groundwater fluoride ranged from 0.11–7.9 mg/L in the pre-monsoon season and 0.27–17 mg/L post-monsoon, with 25–43% of samples from blocks such as Parasia, Chhindwara, Chourai, and Amarwara exceeding safe limits. Shivpuri has reported levels up to 3.60 mg/L, particularly in the Pichhore block, alongside increasing signs of fluorosis. Elevated concentrations are also reported from Gwalior (6.20 mg/L), Jabalpur (5.00 mg/L), Vidisha (4.43 mg/L), and parts of Dhar (4.07 mg/L). In Mandla, reports are highly inconsistent, with one study citing an anomalously high value of 3030 mg/L, though other findings (e.g., 18.2 mg/L in Mandia) suggest extreme localized contamination. Collectively, these findings indicate widespread fluoride endemicity across Madhya Pradesh, posing serious risks to public health.

Conclusions

This paper highlights major fluoride-affected states in

India, including Madhya Pradesh, Punjab, Rajasthan, and Haryana, where average concentrations have been reported as high as 5.98 mg/L, 4.67 mg/L, 3.30 mg/L, and 1.65 mg/L, respectively—well above BIS and WHO limits. Himachal Pradesh and Jammu & Kashmir also face localized issues, while Punjab and Rajasthan consistently report widespread contamination (Bhattacharya and Dutta, 2013; Duggal and Sharma, 2022). Globally, fluoride in small amounts supports dental health, but excessive exposure through groundwater leads to dental and skeletal fluorosis, thyroid imbalances, neurological disorders, and other chronic conditions. While primarily geogenic in origin due to leaching from fluoride-bearing minerals, contamination is further aggravated by agricultural intensification, phosphate fertilizer use, industrial effluents, and groundwater over-extraction. Despite awareness and interventions, fluoride contamination remains persistent, requiring affordable and sustainable solutions. Techniques such as reverse osmosis, activated alumina adsorption, and the Nalgonda method show promise but must be made accessible in rural and low-income regions. Equally vital are continuous groundwater monitoring, predictive geospatial mapping, and public education to mitigate health risks. Recent advances in spatial interpolation and machine learning have improved high-fluoride zone identification, supporting more effective, targeted remediation (Avni et al., 2021).

Data Availability Statement

The datasets generated during the current study are available from the corresponding author on reasonable request.

Conflict of 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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