International Journal of Scientific Research and Engineering Development-– Volume 9 Issue 6, Nov – Dec 2026
Available at www.ijsred.com

RESEARCH ARTICLE OPEN ACCESS

Fluoride in Drinking Water: Geochemical Controls, Human Exposure, and Practical Strategies for Risk Reduction

Mrs. Sushma M. V., Bhuvan N., Hemanth S. Gowda, S. B. Sharath Gowda, Spoorthi G. K., and R. Deepika Patil
Department of Artificial Intelligence and Machine Learning, Malnad College of Engineering, Hassan, Karnataka, India
Corresponding author: bhuvanraj048@gmail.com

----------**********----------

Abstract
Fluoride in drinking water presents a water-quality challenge that depends strongly on local geology, groundwater chemistry and patterns of consumption. At appropriate concentrations, fluoride contributes to the prevention of dental caries; sustained intake above recommended levels, however, increases the risk of dental fluorosis and, at higher cumulative exposure, skeletal fluorosis. This review synthesizes three regional groundwater investigations from Markapur in India, Zhongning in China and Khushab in Pakistan, together with published evidence on health effects, drinking-water guidance and defluoridation. Across the three field studies, reported fluoride concentrations ranged from 0.06 to 7.9 mg/L. The findings associate elevated fluoride primarily with water–rock interaction and geochemical conditions that favour fluoride mobility, while nitrate contamination is more closely linked to land-use activities such as fertilizer application and wastewater inputs. Exposure assessments also indicate that children and infants may receive higher doses relative to body weight. The review compares source control, alternative water supplies, coagulation–precipitation, adsorption and membrane-based treatment. It argues that no single treatment process is suitable for every community: technology selection must account for raw-water chemistry, operating capacity, residual management and long-term monitoring. The paper provides a synthesis of existing studies and does not report new field measurements.

INDEX TERMS: Fluoride, groundwater, drinking-water quality, fluorosis, hydrogeochemistry, nitrate, health-risk assessment, defluoridation.

----------**********----------

I. INTRODUCTION
Safe drinking water is not defined by appearance alone. Groundwater may be clear and acceptable in taste while containing dissolved constituents that become harmful when consumed over long periods. Fluoride is one such constituent. It enters groundwater naturally when water interacts with fluoride-bearing minerals in rocks and sediments. Its final concentration depends not only on the mineral source but also on pH, residence time, calcium availability, alkalinity, evaporation and the movement of groundwater through an aquifer [1], [2].

Fluoride has a dose-dependent relationship with health. Exposure at suitable levels can help reduce dental caries, particularly through its topical action on tooth surfaces. Repeated intake above recommended levels can disturb enamel formation and cause dental fluorosis; sustained and higher exposure can contribute to skeletal fluorosis [3]. The World Health Organization (WHO) guideline value for fluoride in drinking water is 1.5 mg/L. WHO notes that the risk of dental fluorosis increases above this concentration and that progressively higher concentrations increase the risk of skeletal fluorosis [4]. India's National Programme for Prevention and Control of Fluorosis identifies 1.0 mg/L as the desirable limit under its programme guidance [5]. These values should be interpreted in their regulatory and public-health context rather than treated as interchangeable standards.

This paper revisits evidence from three regional groundwater studies and one critical review of fluoride exposure. Its objectives are to: (i) explain the geochemical conditions associated with elevated fluoride; (ii) compare reported concentrations and health-risk findings across the selected locations; (iii) distinguish geogenic fluoride sources from anthropogenic nitrate sources; and (iv) assess practical options for reducing exposure. The work is a narrative literature review based on published studies and does not claim to be a new sampling or epidemiological investigation.

II. REVIEW SCOPE AND EVIDENCE BASE
The evidence base comprises three field investigations and supporting public-health and treatment literature. Adimalla et al. examined 123 groundwater samples from a rural part of Markapur, Andhra Pradesh [1].

 ©IJSRED: All Rights are Reserved

Chen et al. assessed 50 shallow groundwater samples in Zhongning, north-west China, and estimated non-carcinogenic risks for different age groups [2]. Iqbal et al. investigated 161 drinking-well samples in South Punjab, Pakistan [6]. Peckham and Awofeso provide a broader, critical discussion of fluoride ingestion, dental benefits, potential adverse effects and the policy debate around community water fluoridation [3].

The studies were selected because they provide geographically distinct examples and report both fluoride measurements and relevant hydrochemical or health-risk observations. Their sample counts, sampling designs, analytical procedures and guideline comparisons are not identical. Consequently, the numerical results are compared descriptively; they are not pooled into a single statistical estimate. The review also uses WHO drinking-water guidance, Indian fluorosis programme information and recent reviews of fluoride-removal technologies to place the regional findings in a practical context [4], [5], [7], [8].

III. GEOCHEMICAL ORIGINS AND MOBILITY OF FLUORIDE

A. Mineral dissolution and water–rock interaction

Fluoride occurs in minerals such as fluorite and in some micas, amphiboles and apatite-bearing materials. As groundwater moves through weathered rock and sediment, mineral dissolution can release fluoride ions (F^-) into solution. The extent of release is controlled by the mineral assemblage, contact time and groundwater chemistry. In the Zhongning investigation, fluorite dissolution was identified as the principal source of fluoride [2]. In Markapur, the hydrochemical evidence pointed to rock weathering as the dominant control, with a tendency toward evaporation influence [1].

B. Role of pH and major ions

The Markapur study found higher fluoride in sodium–bicarbonate-type groundwater and lower fluoride in calcium–bicarbonate-type water [1]. This pattern is consistent with the importance of calcium in controlling dissolved fluoride. Where calcium activity is sufficiently high, fluoride may be constrained by mineral equilibria, including fluorite saturation. Conversely, groundwater with low calcium and alkaline conditions can favour higher dissolved fluoride, depending on the complete chemical system. Sodium, bicarbonate and pH should therefore be interpreted together rather than used as isolated predictors.

C. Evaporation and groundwater residence

In semi-arid settings, evaporation can concentrate dissolved constituents, particularly where recharge is limited and groundwater residence time is long. Mixing between water sources, mineral precipitation and ion exchange may further modify the concentration of fluoride. These processes are site-specific. A geochemical explanation developed for one aquifer should not be transferred automatically to another without local sampling and mineralogical evidence.

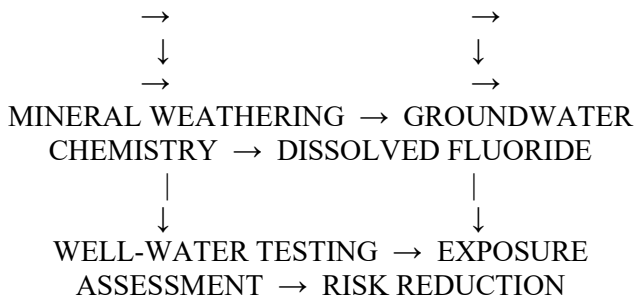


Fig. 1. Conceptual pathway linking geogenic fluoride release, groundwater monitoring and public-health response.

IV. COMPARATIVE FINDINGS FROM THE SELECTED REGIONS

Table I summarizes the principal fluoride results reported in the three field investigations. The ranges show that substantial variation can occur both between regions and among wells within the same region.

TABLE I. SUMMARY OF FLUORIDE RESULTS REPORTED IN THE SELECTED FIELD STUDIES

Study area	Samples	Fluoride range (mg/L)	Mean (mg/L)	Main interpretation
Markapur, India [1]	123	0.4–5.8	1.98	Rock weathering; Na-HCO3 water associated with higher F-
Zhongning, China [2]	50	0.11–6.33	0.85	Fluorite dissolution; nitrate linked to human activity
Khushab, Pakistan [6]	161	0.06–7.9	1.06	Geogenic fluoride; nitrate associated with sewage and agriculture

V. NITRATE: A DIFFERENT CONTAMINATION PATHWAY

Fluoride and nitrate may occur in the same groundwater source, but their dominant origins often differ. The studies from Zhongning and Khushab considered both constituents. In Zhongning, nitrate enrichment was associated mainly with human activities, including nitrogen-fertilizer use and wastewater inputs [2]. In Khushab, domestic sewage and agricultural fertilizers were identified as important potential contributors [6]. These findings point to a practical distinction: fluoride management must address aquifer geology and water chemistry, whereas nitrate prevention requires better sanitation, fertilizer

 ©IJSRED: All Rights are Reserved

management, drainage control and protection of wellheads.

The co-occurrence of the two contaminants also has operational implications. A treatment system selected only for fluoride should not be assumed to remove nitrate adequately. Water-quality surveillance should therefore test both contaminants where local evidence or land use indicates a risk.

VI. HEALTH EFFECTS AND EXPOSURE ASSESSMENT

A. Dental and skeletal effects

Dental fluorosis occurs when excessive fluoride is ingested while teeth are developing. Its appearance can range from faint white markings to more pronounced staining and enamel changes. Skeletal fluorosis is associated with prolonged, excessive exposure and can affect bone and joint function. The likelihood and severity of effects depend on total exposure, duration, age and other contextual factors. Fluoride exposure is not determined by drinking water alone; food, beverages and dental products can contribute to total intake. The critical review by Peckham and Awofeso discusses both the caries-prevention rationale for fluoride and concerns about excessive ingestion [3]. The evidence for different proposed systemic effects is not equally established, so this paper does not treat every association discussed in the literature as proven causation.

B. Screening-level health-risk calculations

Groundwater studies commonly estimate chronic daily intake (CDI) and a hazard quotient (HQ) to identify populations or locations that may warrant further investigation. A general drinking-water exposure expression is:

$$CDI = (Cw \times IR \times EF \times ED) / (BW \times AT) \quad (1)$$

where Cw is contaminant concentration in water (mg/L), IR is daily water ingestion rate (L/day), EF is exposure frequency (days/year), ED is exposure duration (years), BW is body weight (kg), and AT is the averaging time (days). For non-carcinogenic effects, AT is commonly expressed over the exposure period in days.

The hazard quotient is calculated as:

$$HQ = CDI / RfD \quad (2)$$

where RfD is the selected reference dose (mg/kg-day). A hazard quotient above 1 indicates that the estimated exposure exceeds the screening reference dose. It is not a prediction that an individual will develop a disease. The result depends on the exposure assumptions, water consumption rates, body weights and toxicity reference values used.

C. Differences between age groups

The Zhongning study reported a combined hazard index above 1 in 72% of samples for infants, 60% for children, 28% for adult women and 22% for adult men [2]. The authors attributed the greater estimated exposure among younger groups partly to higher water intake relative to body weight. These percentages describe the study's modelled results under its assumptions; they should not be generalized to all populations. The Khushab study also identified locations where the fluoride hazard quotient exceeded 1 and reported a greater contribution from fluoride than nitrate in its assessed risk [6]. Such screening results are useful for prioritizing monitoring, but they do not replace clinical diagnosis or population-based epidemiology.

VII. OPTIONS FOR REDUCING FLUORIDE EXPOSURE

A. Source protection and alternative supplies

The most direct way to reduce exposure is to prevent consumption of water that exceeds the applicable limit. Regular testing of drinking wells is essential because fluoride cannot be reliably identified by taste, smell or appearance. Where a source is unsuitable, communities may use a verified alternative supply, such as treated surface water, a tested piped supply or appropriately collected rainwater. Alternative sources also require routine quality checks; a source should not be considered safe merely because it is different from the original well.

B. Coagulation and precipitation (Nalgonda process)

The Nalgonda process uses alum and lime to promote coagulation, floc formation and removal of fluoride with settled solids. It has practical relevance in India because the chemicals and operating principles can be accessible at community scale. However, dosing and pH require control, and the process produces fluoride-bearing sludge that must be managed safely. Residual aluminium and final-water quality also need monitoring [7], [8]. The method is therefore not simply a matter of adding chemicals; it requires a controlled treatment sequence and trained operation.

C. Adsorption

Adsorption passes water through a solid medium that binds fluoride at its surface. Activated alumina is a commonly studied adsorbent; bone char and several locally available mineral or biomass-derived materials have also been investigated [7], [8]. Adsorption units can be suitable for household or community systems, but performance depends on pH, competing ions, contact time and media condition. Once the adsorbent approaches saturation, fluoride may break through into treated water. Media replacement or regeneration and spent-media disposal must be included in the operating plan.

D. Membrane separation

Reverse osmosis and nanofiltration can reduce fluoride by separating dissolved ions from water. These

 ©IJSRED: All Rights are Reserved

processes may provide high removal, but they need pressure, energy, periodic maintenance and replacement components. They also produce a concentrated reject stream that requires appropriate disposal. Reverse osmosis may remove other dissolved minerals as well, so post-treatment and remineralization may be needed depending on the final water quality and intended use [7], [8].

E. Selecting a technology for a real community

The most effective technology in a laboratory is not automatically the most sustainable option in a village. Selection should consider initial and recurring costs, local operator skills, availability of chemicals or replacement media, raw-water pH and competing ions, quantity of water required, waste handling and the ability to test treated water regularly. A treatment unit that is not maintained can create false confidence and allow exposure to continue. Pilot testing with the actual source water is recommended before a system is deployed at scale.

VIII. DISCUSSION

The three field investigations reinforce the importance of local hydrogeology. Markapur reported a mean fluoride concentration of 1.98 mg/L, Zhongning 0.85 mg/L and Khushab 1.06 mg/L [1], [2], [6]. These mean values should not obscure the high concentrations observed in individual wells: each study reported a maximum above 5 mg/L. This matters for public-health planning because an area-wide average can conceal households relying on highly contaminated sources.

A second common lesson is that water-quality management should be multi-parameter. Fluoride is primarily geogenic in the studies reviewed, while nitrate is more strongly associated with human activities. Monitoring only one contaminant may therefore miss a separate exposure pathway. The risk assessments also show why age-specific exposure assumptions matter. Infants and children can receive a larger dose per kilogram of body weight than adults under comparable water-quality conditions.

The available evidence has limitations. The studies cover specific locations and sampling periods; their results cannot establish the present-day condition of every well in those districts. The health-risk estimates are model-based screening tools and depend on assumed ingestion rates, body weights and reference values. In addition, this review is narrative rather than systematic: it does not claim exhaustive database coverage, formal risk-of-bias assessment or meta-analysis. Future work should combine seasonal groundwater sampling, geochemical modelling, well-level spatial mapping, treatment pilot studies and community-level exposure information.

IX. RECOMMENDATIONS

1) Establish routine fluoride and nitrate testing for public and private drinking-water sources, with results recorded against well location and sampling date.
2) Prioritize repeat sampling of wells with previously elevated fluoride, particularly where children depend on those sources.
3) Communicate results in plain language and provide a verified alternative supply while an affected source is assessed or treated.
4) Select defluoridation systems only after testing the raw-water chemistry and conducting a pilot trial.
5) Monitor treated water for fluoride and relevant process indicators, including pH and residual aluminium where alum-based treatment is used.
6) Provide safe management of sludge, spent adsorbent and membrane reject streams to avoid transferring contamination to soil or surface water.
7) Address nitrate at source through sanitation improvements, careful fertilizer application and protection of wellheads.
8) Link water-quality surveillance with local public-health programmes so that environmental measurements and fluorosis prevention activities inform one another.

X. CONCLUSION

Excess fluoride in drinking water is best understood as a combined geochemical and public-health problem. The reviewed field studies show that mineral dissolution and groundwater chemistry can produce substantial well-to-well variation, even within a single region. Alkaline, sodium–bicarbonate-rich groundwater and relatively low calcium can be associated with elevated fluoride, although the controlling reactions must be evaluated for each aquifer. Nitrate, by comparison, is more closely linked to fertilizer use and wastewater in the studies considered.

The health-risk calculations identify groups and locations that merit closer attention, but they should be interpreted as screening estimates rather than forecasts of disease. Effective prevention depends on routine testing, safe alternative supplies, fit-for-purpose treatment and reliable operation after installation. Coagulation–precipitation, adsorption and membrane processes each have advantages and constraints; no single option is universally appropriate. A sustainable response therefore combines local hydrogeochemical assessment, community participation, trained operation, residual management and continued verification of treated-water quality.

REFERENCES

[1] N. Adimalla, S. Venkatayogi, and S. V. G. Das, “Assessment of fluoride contamination and

 ©IJSRED: All Rights are Reserved

distribution: A case study from a rural part of Andhra Pradesh, India," Applied Water Science, vol. 9, art. no. 94, 2019, doi: 10.1007/s13201-019-0968-y.
[2] J. Chen, H. Wu, H. Qian, and Y. Gao, "Assessing nitrate and fluoride contaminants in drinking water and their health risk of rural residents living in a semiarid region of Northwest China," Exposure and Health, vol. 9, no. 3, pp. 183–195, 2017, doi: 10.1007/s12403-016-0231-9.
[3] S. Peckham and N. Awofeso, "Water fluoridation: A critical review of the physiological effects of ingested fluoride as a public health intervention," The Scientific World Journal, vol. 2014, Art. ID 293019, 2014, doi: 10.1155/2014/293019.
[4] World Health Organization, Guidelines for Drinking-water Quality: Fourth Edition Incorporating the First and Second Addenda. Geneva, Switzerland: WHO, 2022, "Chemical fact sheets: Fluoride."
[5] Directorate General of Health Services, Ministry of Health and Family Welfare, Government of India, "National Programme for Prevention and Control of Fluorosis (NPPCF)," programme information, updated Apr. 17, 2025.
[6] J. Iqbal, C. Su, M. Wang, H. Abbas, M. Y. Jat Baloch, J. Ghani, Z. Ullah, and M. E. Huq, "Groundwater fluoride and nitrate contamination and associated human health risk assessment in South Punjab, Pakistan," Environmental Science and Pollution Research, vol. 30, no. 22, pp. 61606–61625, 2023, doi: 10.1007/s11356-023-25958-x.
[7] P. Pillai, S. Dharaskar, S. Pandian, and H. Panchal, "Overview of fluoride removal from water using separation techniques," Environmental Technology & Innovation, vol. 21, Art. no. 101246, 2021, doi: 10.1016/j.eti.2020.101246.
[8] S. Tagar, M. Rizwan, and N. A. Qambrani, "Defluoridation of drinking water by using low cost point of use treatment technologies: A review," European Journal of Environment and Public Health, vol. 8, no. 2, Art. no. em0158, 2024, doi: 10.29333/ejeph/14739.

 ©IJSRED: All Rights are Reserved