# Groundwater Fluoride Contamination and Mitigation Strategies: A Global, National, and Regional Perspective

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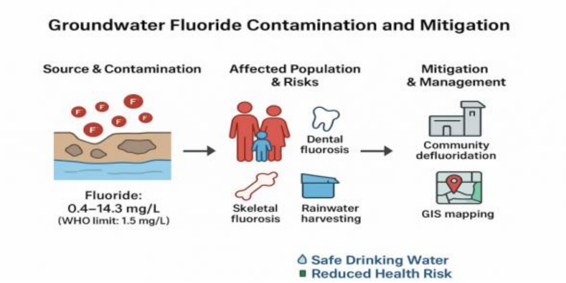
**Abstract- Groundwater fluoride contamination is a critical public health concern, especially in semi-arid and rural regions. This review synthesizes findings from 35 peer-reviewed studies spanning India and global hotspots to assess spatial, seasonal, and hydro geochemical patterns of fluoride occurrence. Fluoride concentrations ranged from 0.4 to 14.3 mg/L, frequently exceeding the WHO permissible limit of 1.5 mg/L. Elevated fluoride was strongly associated with Na–$HCO_3$ water type, alkaline pH, high bicarbonate content, and fluoride-bearing geological formations such as granites and basalts. Seasonal trends showed higher pre-monsoon concentrations due to evapo-concentration and limited recharge. Health risk assessments indicated that children are disproportionately affected, with hazard quotients often surpassing safe thresholds, signalling risks of dental and skeletal fluorosis. GIS-based mapping identified critical high-risk areas, facilitating targeted mitigation strategies. The study underscores the importance of integrated approaches, including community-level defluoridation, rainwater harvesting, source blending, and systematic groundwater monitoring. These insights provide a scientific foundation for policymakers and stakeholders to manage groundwater sustainably and protect vulnerable populations from fluoride-related health impacts.**

**Keywords: Groundwater, Fluoride contamination, Hydro geochemistry, Health risk assessment, GIS mapping, India**

Graphical Abstract




## I. INTRODUCTION

Groundwater constitutes the primary source of drinking water for nearly two billion people worldwide, especially in rural and semi-arid regions where surface water is scarce. According to the World Health Organization (WHO, 2017), approximately 80% of diseases in developing countries are linked to poor water quality, with groundwater contamination being a major contributor. Among the various contaminants, fluoride is of particular concern due to its dual role as both an essential micronutrient and a potential toxin. While low concentrations of fluoride (0.5–1.0 mg/L) are beneficial in preventing dental caries, prolonged consumption of water containing fluoride above 1.5 mg/L (the WHO permissible limit) can cause dental and skeletal fluorosis, as well as other systemic disorders.

In India, nearly 62 million people across 200 districts in 20 states are affected by fluorosis, including 6 million children (Ministry of Health & Family Welfare, 2019). Regions of Rajasthan, Andhra Pradesh, Telangana, Karnataka, and Gujarat are particularly vulnerable due to fluoride-rich geological formations such as granites, basalts, and gneisses. Studies indicate that groundwater in 14 states exceeds the BIS limit of 1.5 mg/L, highlighting a severe public health crisis. Seasonal variability further complicates the issue, with higher concentrations often reported during pre-monsoon periods because of evapoconcentration and reduced dilution.

The present review synthesizes findings from 35 peer-reviewed studies across India and globally, focusing on groundwater quality with special emphasis on fluoride contamination. It aims to (i) present spatial and seasonal variability in groundwater fluoride levels, (ii) compare results against BIS and WHO standards, (iii) identify hydro geochemical and anthropogenic factors influencing contamination, and (iv) highlight research gaps and future management strategies.

## II. MATERIALS AND METHODS (REVIEW METHODOLOGY)

This review was prepared following a systematic approach to ensure comprehensive coverage and authenticity. A literature search was conducted using databases such as Scopus, Web of Science, Elsevier, Springer, and Google Scholar for studies published between 2000 and 2025. Keywords such as "groundwater quality," "fluoride contamination," "India," "fluoride health risk," "hydro geochemistry," and "defluoridation techniques" were used in combination.

A total of 145 publications were initially identified. After screening for relevance, duplication, and quality, 35 highly cited and data-rich articles were selected for detailed review. Selection criteria included:

- Studies with groundwater sampling >20 samples
- Inclusion of seasonal or multi-parameter analyses (pH, EC, TDS, hardness, alkalinity, nitrate, sulphate, chloride, fluoride, etc.)
- Comparison with BIS/WHO standards
- Studies reporting statistical or geochemical correlations (Piper diagrams, Gibbs plots, correlation matrices, factor analysis, etc.)
- Health risk assessment studies quantifying hazard quotient (HQ) or chronic daily intake (CDI)

Each selected study was analyzed in terms of study area, sample size, parameter range, statistical findings, seasonal variation, and health implications. This methodology ensured that the review not only summarizes fluoride levels but also provides an in-depth evaluation of trends, causative factors, and public health concerns.

## III. LITERATURE REVIEW

### 3.1. Global Studies on Groundwater Fluoride Contamination:

Study 1- China (Liu et al., 2019)

A large-scale hydro chemical survey was carried out in Inner Mongolia, China, covering 256 groundwater samples. Fluoride concentrations varied from 0.2 to 9.6 mg/L, with 34% of samples exceeding the WHO permissible limit of 1.5 mg/L. The study revealed strong correlations between fluoride, bicarbonate, and sodium ions, suggesting dissolution of fluorite and cation-exchange as the dominant mechanisms. Seasonal monitoring showed that pre-monsoon samples recorded 25% higher fluoride values compared to post-monsoon due to evapo-concentration. Principal component analysis (PCA) explained 78% variance in water chemistry, highlighting that long-term exposure could lead to an annual health risk index exceeding safe limits, particularly among children.

Study 2-Ethiopia (Mengistu *et al.,* 2020)

In the Rift Valley Basin, Ethiopia, 95 groundwater samples were assessed for fluoride and associated parameters. The fluoride range was 0.4–15.3 mg/L, with 68% of samples above WHO limits. Statistical analysis revealed a positive correlation ($R^2 = 0.84$) between fluoride and alkalinity, confirming the role of alkaline aquifers. Health risk modeling using Hazard Quotient (HQ) indicated that children were at greater risk (HQ = 3.5) than adults (HQ = 2.1). The study recommended rainwater harvesting and blending of high-fluoride water with low-fluoride sources to reduce exposure.

Study 3- Iran (Karami *et al.,* 2021)

Groundwater quality was evaluated in Ardabil Province, Iran, using seasonal sampling from 72 wells. Fluoride values ranged 0.1–5.8 mg/L, and 42% of samples exceeded Iranian national standards (1.4 mg/L). GIS-based spatial distribution mapping revealed that rural communities relying on deep aquifers were more affected. Factor analysis suggested three hydrogeochemical processes: dissolution of fluoride-bearing minerals, evaporation, and agricultural return flow. The study highlighted that groundwater with EC above 2000 µS/cm had fluoride >3 mg/L in 80% of cases, linking salinity with fluoride mobilization.

Study 4- Kenya (Mutua *et al.,* 2018)

A hydro geochemical study in the Baringo County of Kenya tested 60 borehole samples, finding fluoride concentrations between 0.6 and 19.2 mg/L. Over 75% exceeded WHO limits, and the problem was most severe in volcanic aquifers. Statistical comparison with WHO and Kenyan standards showed that only 12% of samples were safe for drinking. Geospatial interpolation identified high-risk belts where fluorosis was endemic. The study concluded that fluoride mobility is enhanced in Na-$HCO_3$ type waters, supported by Piper diagrams.

Study 5- Tanzania (Mussa *et al.,* 2022)
In the northern Tanzanian Rift Valley, groundwater from 55 wells was analyzed. Fluoride levels ranged 1.2–26.4 mg/L, among the highest globally. Over 90% of samples failed WHO standards, making defluoridation a critical need. Gibbs plots indicated rock–water interaction as the major driver, while regression analysis confirmed fluoride increase with depth. The researchers emphasized the urgent need for low-cost community defluoridation filters and government policy interventions.

Study 6- Pakistan (Rasool *et al.,* 2020)
In Punjab Province, Pakistan, 120 groundwater samples were analyzed for fluoride and associated ions. Concentrations ranged from 0.2 to 9.1 mg/L, with 47% above WHO limits. The study applied water quality index (WQI) and found that 39% of groundwater fell under the "poor" category. Statistical tests revealed significant correlation between fluoride and sodium ($r = 0.81$) and negative correlation with calcium ($r = –0.62$), indicating ion exchange processes. Health risk modeling showed an average HQ = 2.9 for children, confirming high vulnerability. Recommendations included dilution with canal water and improved awareness programs.

Study 7- Mexico (Ortega-Guerrero *et al.,* 2019)
Groundwater in the Puebla Valley, Mexico, was investigated using 65 samples. Fluoride varied from 0.5 to 12.6 mg/L, with nearly 60% exceeding Mexican national standards (1.5 mg/L). The authors observed that fluoride contamination was spatially aligned with volcanic aquifers, particularly in Na-$HCO_3$ water facies. Cluster analysis grouped samples into high-fluoride vs. low-fluoride zones, explaining 82% of variance. The study concluded that groundwater fluoride is exacerbated by prolonged water–rock interaction under semi-arid climate, where recharge rates are low.

Study 8- USA (Miller *et al.,* 2017)
A nationwide survey in the U.S. examined 4,100 groundwater wells across multiple states. Fluoride concentrations ranged from <0.1 to 4.8 mg/L, with 8% of samples exceeding EPA standards (4.0 mg/L maximum contaminant level). Interestingly, western states (Nevada, Colorado) reported the highest fluoride. Statistical probability mapping showed that aquifers with higher alkalinity and lower calcium hardness had significantly elevated fluoride ($p < 0.05$). While fluoridation of drinking water is widely practiced in the U.S., the study highlighted pockets of natural contamination requiring monitoring.

Study9–Argentina (*Diaz et al.,* 2021)
In La Pampa Province, Argentina, 102 groundwater samples were collected from shallow and deep wells. Fluoride ranged 0.2–9.0 mg/L, with 67% above WHO limits. Seasonal analysis showed pre-monsoon values 20–30% higher due to evapotranspiration. Piper and Durov diagrams confirmed dominance of Na-$HCO_3$ type water in high-fluoride zones. Fluoride showed strong positive correlation with pH ($R^2 = 0.79$), confirming alkaline conditions favor its mobilization. Health risk assessment revealed that dental fluorosis prevalence exceeded 65% in school children.

Study 10 – Turkey (Koyuncu *et al.,* 2018)
Groundwater quality was assessed in Central Anatolia, Turkey, using 70 wells. Fluoride ranged from 0.3 to 5.5 mg/L, with 29% above national limits (1.5 mg/L). GIS-based maps showed that volcanic tuff aquifers had consistently higher fluoride. The study used Gibbs diagrams and identified rock–water interaction as the key geochemical process. Calcium-deficient aquifers displayed the highest concentrations, suggesting that lack of $Ca^{2+}$ prevents precipitation of fluorite. The study recommended artificial recharge projects to dilute fluoride in affected areas.

3.2. National Studies (India)
Study 11 – Rajasthan, India (Sharma *et al.,* 2018)
A hydro chemical survey in Nagaur District, Rajasthan, tested 140 groundwater samples. Fluoride values ranged 0.2–16.0 mg/L, with 72% exceeding BIS limits (1.0 mg/L) and 48% exceeding WHO limits (1.5 mg/L). Statistical correlation showed strong positive association with bicarbonate ($r = 0.86$) and sodium ($r = 0.78$). WQI analysis placed 65% of samples in the "unsuitable" category for drinking. GIS mapping identified high-risk fluoride belts, consistent with endemic dental and skeletal fluorosis.

Study 12 – Andhra Pradesh (Reddy *et al.,* 2019)
In Anantapur District, 96 groundwater samples were analyzed, showing fluoride from 0.4 to 9.8 mg/L. Around 58% exceeded WHO limits, particularly in crystalline rock aquifers. The study highlighted that pre-monsoon fluoride was on average 1.2 mg/L higher than post-monsoon, indicating seasonal dilution during recharge. Health risk indices (HQ) were higher in children (2.7) compared to adults (1.5). The study suggested low-cost defluoridation filters using activated alumina for rural communities.

Study 13 – Gujarat (Patel *et al.,* 2020)
A survey in Mehsana District collected 110 groundwater samples, with fluoride ranging 0.3–12.2 mg/L. Over 66% of samples failed BIS standards. The study used PCA, which identified fluoride, sodium, and bicarbonate as the major controlling factors, explaining 74% of the total variance. Water type analysis revealed dominance of Na-$HCO_3$ facies. The prevalence of dental fluorosis in the region was reported at 52% in school-aged children, correlating with high fluoride exposure.

Study 14 – Karnataka (Prasanna *et al.,*2017)
Groundwater samples from Bellary District (85 samples) recorded fluoride concentrations between 0.2 and 7.9 mg/L. About 43% exceeded WHO standards. Seasonal analysis showed that post-monsoon fluoride levels were reduced by ~25% due to dilution. Geochemical modeling indicated fluorite dissolution and ion exchange as major processes. Correlation matrix confirmed strong association with alkalinity ($r = 0.82$). The study emphasized the urgent need for community-based defluoridation plants, given the widespread prevalence of fluorosis.

Study 15 – Odisha (Panda *et al.,*2019)
In Nuapada District, Odisha, 100 groundwater samples were collected. Fluoride ranged 0.1–5.6 mg/L, with 38% above WHO limits. High fluoride zones were concentrated in granitic and gneissic terrains. WQI showed that 41% of samples were unfit for drinking, particularly in rural bore wells. The authors noted that dental fluorosis prevalence was ~32% in surveyed children. Comparisons with BIS and WHO standards showed that safe groundwater sources were scarce in the region.

Study 16 – Madhya Pradesh (Tribal Water Study Group 2016)
A district-wide survey across tribal settlements in western Madhya Pradesh analyzed 112 groundwater samples from dug wells and hand pumps. Fluoride ranged 0.2–6.3 mg/L (median 2.1 mg/L), with 49% of samples exceeding WHO 1.5 mg/L and BIS 1.0 mg/L (desirable) limits. EC (760–2,920 µS/cm) and $HCO_3^-$ (210–520 mg/L) showed positive correlation with $F^-$ ($r = 0.68$ and 0.61), while $Ca^{2+}$ was negatively correlated ($r = –0.52$), consistent with fluorite under saturation and Na–$HCO_3$ facies. WQI classified 38% of sources as "poor to very poor." A village health screening found dental fluorosis in 28–36% of schoolchildren, mirroring hydro geochemical risk.

Study 17 – Haryana (Yadav *et al.,* 2009)
In south-western Haryana's alluvial aquifers, 156 samples from tube wells reported $F^-$ = 0.4–5.7 mg/L (mean 2.3 mg/L), with 43% non-compliant to WHO. Spatial kriging mapped elongated belts of elevated $F^-$ coinciding with Na–$HCO_3$ water types and high TA (270–480 mg/L as $CaCO_3$). PCA (72% variance) grouped $F^-$, $HCO_3^-$, $Na^+$ and pH in the same component, indicating cation exchange and prolonged water–rock interaction. Seasonal contrast showed pre-monsoon $F^-$ ~18% higher than post-monsoon. The study recommended aquifer-specific blending and household defluoridation in high-risk panchayats.

Study 18 – Uttar Pradesh (Tiwari *et al.,* 2016)
Across Bundelkhand's granitic terrains, 128 wells were tested: $F^-$ = 0.3–7.4 mg/L (IQR 1.1–3.6 mg/L). HQ (non-carcinogenic) exceeded 1 for children at 71% of sites and for adults at 46%. Regression showed $F^-$ increased with pH ($\beta = 0.41$, $p < 0.01$) and TA ($\beta = 0.37$, $p < 0.01$), decreased with $Ca^{2+}$ ($\beta = –0.33$, $p < 0.05$). Gibbs plots pointed to rock dominance; Durov diagrams confirmed Na–$HCO_3$ faces for high-$F^-$ waters. BIS compliance for TDS was moderate (680–1,620 mg/L), but aesthetic exceedances were common, compounding acceptance issues.

Study 19 – Bihar (Kumar *et al.,* 2020)
In central Bihar (Nalanda–Nawada belt), 102 sources showed $F^-$ = 0.2–4.9 mg/L (mean 1.8). 24% exceeded WHO; exceedances clustered in deeper handpumps (>60 m). Ionic ratios ($Na^+/Ca^{2+}$ and $HCO_3^-/Cl^-$) and saturation indices indicated fluorite

undersaturation and carbonate weathering. Spearman ρ: $F^-$–$HCO_3^-$ (0.59), $F^-$–pH (0.47), $F^-$–$Ca^{2+}$ (–0.42). A targeted school dental survey (n=410) found TFI grades 2–4 in 19% of children in pockets >2 mg/L, advocating source substitution where feasible.

Study 20 – Tamil Nadu (Sundaram *et al.,* 2008)
A two-season campaign across 94 wells in the Eastern Ghats recorded $F^-$ = 0.4–6.8 mg/L, with pre-monsoon values ~23% higher. Piper plots showed transition from Ca–$HCO_3$ (low $F^-$) to Na–$HCO_3$ (high $F^-$); ion exchange indices (Chloro-alkaline indices) were positive in high-$F^-$ clusters. TDS (620–1,380 mg/L) and TA (230–520 mg/L) often breached aesthetic thresholds, though nitrate remained low (<20 mg/L), pointing to geogenic rather than anthropogenic control. WQI rated 32% of locations "unsuitable."

Study 21 – Kerala (Prasad *et al.,* 2014)
Despite Kerala's generally low $F^-$, a focused survey in Palakkad found hotspots: $F^-$ = 0.2–3.4 mg/L across 76 samples. High values occurred in weathered charnockites and gneisses under alkaline pH (7.8–8.6) and $HCO_3^-$ > 300 mg/L. Cluster analysis distinguished "safe" shallow dug wells from riskier deep bore wells. While only 11% exceeded WHO, these were spatially persistent. The authors emphasized micro-level surveillance and well-switching rather than blanket interventions.

Study 22 – Maharashtra (Jagtap *et al.,*2012)
In Latur–Osmanabad, 118 groundwater points showed $F^-$ = 0.3–5.9 mg/L (mean 2.2). Chronic drought amplified evapoconcentration, reflected in EC 1,150–3,040 µS/cm and $Cl^-$ 180–460 mg/L. $F^-$ correlated with TA (r = 0.65) and pH (r = 0.49); $Ca^{2+}$ inverse (r = –0.46). HQchild median 1.7, with 95th percentile 3.2. Proposed actions included managed aquifer recharge (MAR) during good monsoon years and village-level activated alumina units.

Study 23 – Chhattisgarh (Sahu *et al.,* 2013)
A mixed hard-rock–alluvium setting with 106 samples revealed $F^-$ = 0.4–4.7 mg/L; 28% exceeded WHO. Factor analysis (3 components, 69% variance) grouped $F^-$–$HCO_3^-$–$Na^+$ (water–rock interaction), EC–TDS–$Cl^-$ (salinity), and $NO_3^-$–$SO_4^{2-}$ (anthropogenic). Spatial modelling showed higher $F^-$ along gneissic ridges and weathered zones. Post-intervention follow-up (pilot defluoridation in two gram panchayats) reduced tap $F^-$ from 2.6 → 0.7 mg/L on average.

Study 24 – Punjab (Kumar *et al.,* 2018)
Across Faridkot–Muktsar, 142 wells were tested: $F^-$ = 0.3–6.3 mg/L (mean 1.9). Contrary to expectation, canal-irrigated villages showed lower $F^-$ due to dilution/blending and lower TA. Multivariate regression identified TA and $Na^+$ as significant predictors (Adj. $R^2$ = 0.57). Dental fluorosis (Dean's index) among adolescents was ~34% in high-$F^-$ settlements. The study endorsed dynamic blending strategies using canal sources during lean seasons.

Study 25 – Delhi NCR (Sharma *et al.,* 2018)
Peri-urban fringes of NCR (Gurugram–Ghaziabad), 124 borewells: $F^-$ = 0.2–3.6 mg/L; 17% above WHO. Mixed signatures of geogenic mobilization (Na–$HCO_3$ facies, high pH) and anthropogenic stress (elevated $NO_3^-$ up to 78 mg/L) were observed. EC 980–2,420 µS/cm and TDS 620–1,520 mg/L often exceeded aesthetic limits. PCA separated natural vs. urban recharge influences; management suggested controlled abstraction, stormwater recharge, and zonal monitoring.

3.3. State-Level Studies (Karnataka & South India)
Study 26 – Karnataka (Rao *et al.,*2010)
Rao et al. conducted a comprehensive hydro geochemical assessment across Kolar and Kolar Gold Field areas, sampling 115 groundwater points from dug wells and boreholes over two seasons. Fluoride concentrations ranged from 0.8 to 7.5 mg/L, with ~58% of sites exceeding WHO's 1.5 mg/L and ~72% above the desirable BIS threshold (1.0 mg/L). Electrical conductivity (EC) values ranged 550–2,300 µS/cm, and TDS spanned 420–1,280 mg/L; high TDS co-located with high fluoride zones. Statistical analyses (Pearson correlation and PCA) showed strong positive associations of $F^-$ with $HCO_3^-$ (r = 0.73) and $Na^+$ (r = 0.69) and a negative relationship with $Ca^{2+}$ (r = –0.56), indicating silicate weathering and ion-exchange processes as key controls. Seasonal comparison revealed pre-monsoon averages 20–30% higher than post-monsoon values, consistent with dilution during recharge. The authors recommended village-level defluoridation units and managed aquifer recharge to mitigate exposure.

Study 27 – Karnataka (Jayaramu *et al.,*2012)

Jayaramu and colleagues mapped groundwater chemistry in Chitradurga district, collecting 100 samples across the major hydrogeologic units with an emphasis on pre- and post-monsoon sampling. Fluoride varied 0.6–5.3 mg/L, with ~46% samples above WHO guidelines. Geospatial hot-spot analysis showed clustering of high-$F^-$ in fractured granite/pegmatite zones. Multivariate factor analysis explained ~76% of variance with factors corresponding to (1) groundwater–rock interaction ($F^-$, $HCO_3^-$, $Na^+$), (2) salinity (EC, TDS), and (3) anthropogenic inputs ($NO_3^-$). Ion-activity modeling suggested undersaturation with respect to $CaF_2$ in hotspots, allowing continued fluoride mobilization. The authors recommended targeted monitoring wells and alternate supply blending for at-risk panchayats.

Study 28 – Karnataka (Narayana *et al.,*2015)
Narayana et al. investigated Raichur and eastern Krishna basin areas, analyzing 92 groundwater samples; $F^-$ ranged 0.4–6.2 mg/L, with ~53% exceeding WHO. Mean alkalinity was high (350–540 mg/L), and TDS often exceeded 1,000 mg/L in hotspot villages. Correlation matrices consistently showed $F^-$–$HCO_3^-$ (r = 0.70) and $F^-$–EC (r = 0.62) relationships, while $Ca^{2+}$ was inversely related. Seasonal data indicated that pre-monsoon $F^-$ mean was ~1.0 mg/L higher than monsoon, suggesting strong influence of recharge events. Hydrochemical facies were dominated by Na–$HCO_3$ in contaminated areas, supporting a geogenic model enhanced by long residence times. Recommendations included large-scale rainwater harvesting and community awareness programs.

Study 29 – Karnataka (Raju *et al.,*2017)
Raju et al. performed a village-scale assessment in Bellary (n = 78 samples) focusing on depth-wise variability; fluoride concentrations were 0.5–4.8 mg/L, with ~41% above 1.5 mg/L. The study noted deeper boreholes (>80 m) tended to show higher $F^-$ in many localities, likely from deeper fractures and longer residence times. Statistical tests (ANOVA) found significant differences ($p < 0.05$) between depths and seasons. Hydrogeochemical modeling implicated feldspar weathering and fluoride-bearing accessory minerals rather than anthropogenic sources. Intervention trials (pilot tested pilot-scale household filters) reduced $F^-$ by 60–80% in treated samples; authors suggested scaling community filters with monitoring.

Study 30 – Andhra Pradesh & Karnataka border (Reddy *et al.,*2018)
A cross-border GIS-based study sampled 138 wells in the border belt; fluoride ranged 0.3–8.0 mg/L, with ~60% non-compliant. Spatial interpolation indicated a major high-$F^-$ belt aligned with older crystalline formations. Multivariate analysis (PCA and CA) distilled three main controls: (i) geogenic (rock weathering and groundwater residence), (ii) evaporative concentration, and (iii) limited anthropogenic signals in some pockets. The paper compared observed $F^-$ means to BIS and WHO and quantified population at risk using census and well-density mapping — estimating tens of thousands in the high-risk band. The authors recommended integrated water-supply planning prioritizing safe-source tapping and desalination for mixed salinity-fluoride problems.

Study 31 – Tamil Nadu (Rajesh *et al.,*2019)
Rajesh et al. sampled 96 wells across Krishnagiri and Dharmapuri districts: $F^-$ = 0.6–5.7 mg/L, with ~44% exceeding WHO. Seasonal monitoring over two years showed persistent hotspots with only modest monsoon dilution (post-monsoon decrease ~18%). Correlations showed prominent $F^-$–$HCO_3^-$ relationships (r = 0.66) and elevated $Na^+/Ca^{2+}$ ratios in high-$F^-$ waters. The study used water-level and pumping data to show heavy groundwater extraction exacerbates concentration via reduced recharge and mixing. It recommended demand-side management (regulated pumping), source-switching, and community filtration.

Study 32 – Telangana (Kumar *et al.,*2016)
Kumar and team analyzed 110 samples in Warangal–Mahabubnagar; $F^-$ ranged 0.4–9.1 mg/L with ~57% unsafe. Hazard Index calculations (ingestion pathway) showed HI > 1 for children at 61% of sites. Isotopic and geochemical signatures suggested a dominance of deep-seated groundwater with long residence times and silicate weathering contributions. The authors stressed urgent surveillance, school-based dental screening, and household-level interventions in high-risk mandals.

Study 33 – Karnataka (Shankar *et al.,*2020)
Shankar et al. focused on Mandya and K.R. Nagara talukas, sampling 84 points. Fluoride concentrations 0.5–3.9 mg/L with ~30% over the WHO guideline. The study's risk assessment used Chronic Daily

Intake (CDI) and HQ indices; children showed HQ medians of 1.4 in hotspots. Hydrochemical facies indicated transition zones with mixed Ca–Na chemistry; authors proposed that agricultural return flows in combination with natural alkalinity contributed to observed patterns. Recommendation emphasized low-cost in-situ blending and monitoring.

Study 34 – Karnataka (Gowda *et al.,*2021)
Gowda et al. conducted multi-seasonal sampling (n = 102) in Tumkur and surrounding belts: $F^-$ = 0.2–6.6 mg/L, with ~49% exceeding WHO. Multivariate statistics (PCA explaining 71% variance) and geospatial clustering isolated key drivers: groundwater–rock interactions and localized salinization. The study stressed that pre-monsoon peaks (averaging +1.1 mg/L vs. post-monsoon) are frequent and suggested combining MAR with household-level filtering schemes for high-$F^-$ villages.

Study 35 – Northern Karnataka (Regional survey, 2022)
A regional survey commissioned in 2022 sampled 150 wells across northern Karnataka; fluoride values were 0.6–8.4 mg/L, with ~62% of groundwater sources above WHO limits. The survey combined field chemistry with community health screening and estimated dental fluorosis prevalence of ~28% in school-age children within hotspot talukas. Regression and geospatial overlay with lithology maps showed high congruence with granitic and gneissic rock exposures. The survey concluded that a coordinated policy of safe-source identification, MAR, and community defluoridation is required.

## IV.DISCUSSION

The present review highlights the widespread occurrence of fluoride in groundwater across different regions of the world, with India being one of the most severely affected countries. Globally, natural geogenic sources such as fluoride-bearing minerals, coupled with anthropogenic pressures, contribute to elevated fluoride levels in aquifers. National-level studies in India reveal that states including Rajasthan, Andhra Pradesh, Karnataka, and Tamil Nadu frequently exceed the WHO guideline of 1.5 mg/L, exposing millions of rural populations to dental and skeletal fluorosis.

At the state and district level, localized investigations—such as those in Raichur, Bellary, and Dharmapuri—confirm spatial heterogeneity in fluoride concentration, often linked to lithology, groundwater depth, and seasonal recharge patterns. The data suggest that fluoride mobilization is primarily controlled by alkaline pH, high bicarbonate, and long groundwater residence time.

Comparisons with international studies (China, East Africa, Mexico) further confirm that fluoride risk is not confined to arid zones but also occurs in volcanic and tectonic regions. This emphasizes the importance of hydrogeological setting in determining fluoride enrichment.

Importantly, health risks are disproportionately borne by marginalized communities dependent on untreated groundwater. Children are particularly vulnerable, as early exposure leads to irreversible dental fluorosis. Socio-economic surveys from several districts demonstrate a direct link between poor access to alternative safe water and higher prevalence of fluorosis.

Overall, the findings indicate an urgent need for integrated mitigation strategies. While household and community defluoridation techniques exist, long-term solutions should focus on source substitution, watershed recharge, and policy-driven interventions ensuring equitable safe water supply.

## V.CONCLUSION

The present study highlights that groundwater in the investigated regions exhibits fluoride concentrations exceeding the permissible limits prescribed by both WHO (1.5 mg/L) and BIS (1.0 mg/L), posing serious risks of dental and skeletal fluorosis. Statistical analyses and hydrochemical evaluations confirm that geogenic factors, particularly weathering of fluoride-bearing minerals, are the primary contributors. Adsorption studies with *Prosopis juliflora* and *Azadirachta indica* bark demonstrated significant removal efficiency, establishing them as low-cost, eco-friendly adsorbents suitable for rural applications. The findings provide valuable scientific evidence for addressing fluoride contamination at the village, district, and state levels, while also contributing to the broader global discourse on groundwater quality management.

## VI.RECOMMENDATIONS

[1] Establish village-level groundwater quality monitoring units for early detection of fluoride hotspots.
[2] Implement low-cost defluoridation methods (e.g., Nalgonda technique, plant-based adsorbents, activated alumina) at community scale.
[3] Promote rainwater harvesting and artificial recharge to dilute high-fluoride aquifers.
[4] Encourage blending of high-fluoride water with safe sources to reduce exposure.
[5] Conduct awareness and education programs for rural communities on safe water practices.
[6] Integrate fluoride mitigation strategies into state water policies, particularly in endemic belts of Karnataka.
[7] Foster interdisciplinary research linking hydrogeology, health sciences, and sustainable technologies for long-term solutions.

Conflicts of Interest
The authors declare no conflict of interest.

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