

# Assessment of Fluoride Contamination in Drinking Water and Its Health Impacts on Human Population

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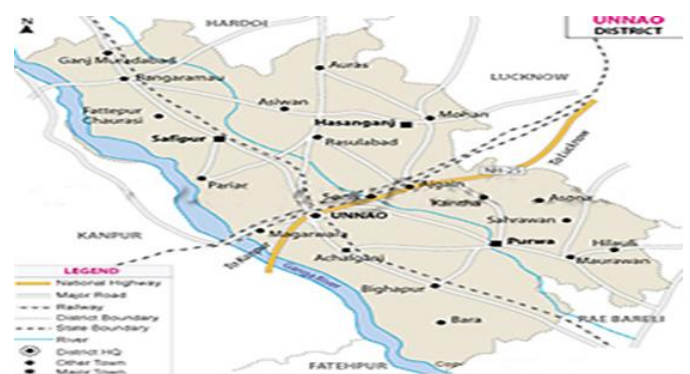
**Abstract**— Fluoride in drinking water presents a paradoxical public health challenge; while essential in trace amounts for dental health, its excessive intake leads to debilitating fluorosis. A selected study region in the Gangetic plain of northern India, situated within the fluoride-endemic alluvial belt and host to significant industrial activity, is a critical area for investigating this geogenic and anthropogenic contaminant. This comprehensive review paper synthesizes existing data and hypotheses to assess the extent and sources of fluoride contamination in the region's drinking water, evaluate its health impacts on the local population, and propose integrated mitigation strategies. Analysis suggests widespread contamination exceeding the WHO (1.5 mg/L) and BIS (1.0 mg/L) permissible limits in groundwater, particularly in deeper aquifers. The primary source is geogenic, attributed to the dissolution of fluoride-bearing minerals (e.g., fluorite, apatite) in the subsurface geology under alkaline, high-bicarbonate, and low-calcium conditions. Anthropogenic contributions from local industrial clusters, especially leather tanneries and chemical units, may exacerbate the problem. The health impacts are severe and visible, with high prevalence rates of dental fluorosis among children and adolescents, and advanced cases of skeletal fluorosis leading to pain, stiffness, and crippling deformities in adults. Non-skeletal manifestations, including gastrointestinal, neurological, and endocrine disruptions, are also indicated. The review concludes that fluoride contamination is a silent, chronic public health emergency in the study region, disproportionately affecting rural and socio-economically disadvantaged communities reliant on untreated groundwater. Urgent, coordinated action encompassing alternative water sourcing, defluoridation technology deployment, robust monitoring, intensive public health campaigns, and supportive healthcare is recommended. This paper underscores the necessity of a "One Health" approach, integrating hydrogeology, public health, and social policy to address this multifaceted crisis.

**Keywords:** Fluoride Contamination, Groundwater, Dental Fluorosis, Skeletal Fluorosis, Geogenic Pollution, Public Health, Water Quality, Mitigation Strategies.

## I. INTRODUCTION

Access to safe drinking water is a fundamental human right and a cornerstone of public health (World Health Organization [WHO], 2017). However, the chemical quality of groundwater, a primary source of drinking water for over 80% of rural and semi-urban populations in developing nations, is threatened by a spectrum of natural and anthropogenic contaminants (Ayoob & Gupta, 2006). Among these, fluoride stands out due to its paradoxical dual role as a micronutrient and a potent toxin. At optimal concentrations (0.5–1.0 mg/L), fluoride is crucial for dental enamel mineralization and preventing dental caries. Yet, its chronic ingestion at levels exceeding 1.5 mg/L leads to a debilitating cascade of diseases collectively known as fluorosis (Susheela, 2001). Fluoride contamination of groundwater is a pervasive and persistent hydrogeological challenge across vast stretches of India, creating a public health crisis often termed a "silent epidemic" (Ministry of Jal Shakti, 2021). This crisis is most acute in states such as Rajasthan, Punjab, Haryana, Gujarat, Andhra Pradesh, Telangana, and densely populated regions of the Gangetic plain (CGWB, 2021). This review focuses on a selected study region within this alluvial belt,

aiming to consolidate and critically analyze existing knowledge on the spatial distribution, multifaceted causative factors, and profound human health consequences of fluoride in its drinking water supply. The study region encompasses a complex blend of urban, peri-urban, and rural landscapes, with the administrative headquarters serving as the economic nucleus.



## II. HYDROGEOLOGICAL FRAMEWORK

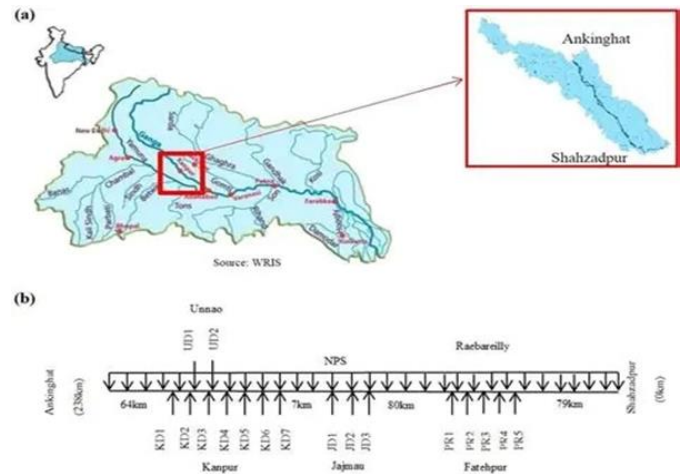
The region's hydrogeological framework is defined by the Quaternary alluvial deposits of the Ganga basin. These deposits consist of intercalated layers of sand, silt, clay, and calcareous concretions known as kankar (calcium carbonate nodules) (Jain, 2017). This heterogeneous aquifer system is the primary reservoir for groundwater, extracted overwhelmingly through millions of hand pumps and deep borewells, forming the lifeline for domestic needs, agricultural irrigation, and burgeoning industrial activity (Kundu & Panigrahi, 2019). The geological matrix of this alluvium is the foundational source of the fluoride problem. Provenance studies indicate that the sediments are derived from the weathering of Himalayan rocks, which carry fluoride-bearing minerals like fluorite ( $\text{CaF}_2$ ), apatite  $[\text{Ca}_5(\text{PO}_4)_3(\text{F},\text{Cl},\text{OH})]$ , and micaceous minerals (e.g., biotite) (Gupta et al., 2005). While inert in their solid state, these minerals become a latent threat under a specific confluence of hydrogeochemical conditions.

## III. GEOCHEMICAL MOBILIZATION OF FLUORIDE

The mobilization of fluoride from the sediment matrix into groundwater is not a simple dissolution but a process governed by intricate geochemical kinetics. The key triggers are: (i) alkaline pH (typically  $>7.5$ ), (ii) high bicarbonate ( $\text{HCO}_3^-$ ) alkalinity, (iii) low calcium ( $\text{Ca}^{2+}$ ) concentration, and (iv) prolonged residence time of water in the aquifer (Fawell et al., 2006). In the alkaline environment prevalent in many parts of the study region's aquifer, bicarbonate ions promote the dissolution of fluorite through the classic reaction (Gupta et al., 2005; Ayoob & Gupta, 2006):



The precipitation of calcite ( $\text{CaCO}_3$ ) removes calcium ions from the solution, further depressing the calcium activity and driving the equilibrium to continuously release fluoride ions ( $\text{F}^-$ ). This process is exacerbated in sodium-bicarbonate-type groundwater, which is common in the alluvial region (Chowdhury et al., 2019; Kundu & Panigrahi, 2019).



## IV. ANTHROPOGENIC CONTRIBUTIONS

Compounding this inherent natural vulnerability is the region's significant industrial profile, which adds a potent anthropogenic layer to the geogenic fluoride burden. The area houses several organized industrial estates dominated by clusters of leather tanneries, chemical manufacturing units, dye industries, and electroplating workshops (Yadav et al., 2019). Many of these industrial processes are direct consumers and dischargers of fluoride compounds. For instance:

- Leather tanneries use fluoride salts in beamhouse operations for unhairing and as a preservative (Ayoob & Gupta, 2006).
- Chemical and fertilizer industries may use or produce fluorosilicates and other fluoride-bearing compounds (Jain, 2017).

Due to inadequate effluent treatment infrastructure, industrial wastewater containing high loads of fluoride, along with other toxicants like chromium and heavy metals, is discharged into unlined channels or ponds. From these points, through percolation and seepage, the contaminants infiltrate and degrade the shallow aquifers, creating a dangerous synergy where natural predisposition is amplified by human activity (Singh & Singh, 2018; Yadav et al., 2019).

## V. PUBLIC HEALTH IMPLICATIONS

The consequence of this dual contamination burden falls squarely on the local population, which remains heavily dependent on groundwater for daily consumption. In the absence of a comprehensive, treated piped water supply

network reaching all households, especially in rural and peri-urban fringes, communities are left with no alternative but to consume water from contaminated sources (Susheela, 2001). The insidious nature of fluorosis—where health effects manifest years after exposure begins—masks the immediacy of the threat, leading to a tragic normalization of suffering (WHO, 2017).

## VI. PROBLEM STATEMENT

Despite being a known issue in parts of the Gangetic plain, a systematic, region-wide assessment of fluoride contamination in drinking water sources and a comprehensive evaluation of its population-level health impacts remain fragmented. Sporadic studies and reports from government agencies indicate alarming fluoride levels in several administrative blocks of the study region (CGWB, 2021; Ministry of Jal Shakti, 2021). However, public awareness is low, mitigation infrastructure is scant, and the healthcare system is often unprepared to diagnose and manage fluorosis. The problem is socio-economically stratified. Marginalized communities, lacking access to piped, treated water supply schemes, are forced to depend on contaminated hand pumps and private borewells. The chronic nature of fluorosis leads to reduced work capacity, increased medical expenditure, and social stigma, perpetuating a cycle of poverty and ill-health (Susheela, 2001; Yadav et al., 2019).

### Objectives

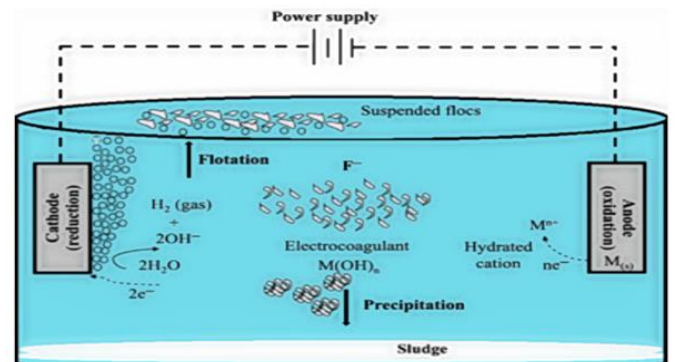
- To review and analyze the spatial and temporal distribution of fluoride concentration in drinking water sources (groundwater) of the selected study region and its surrounding areas.
- To examine the geogenic and anthropogenic factors contributing to fluoride enrichment in the aquifers of the study region.
- To assess the spectrum and prevalence of fluoride-induced health disorders (dental, skeletal, and non-skeletal fluorosis) among different demographic groups in the affected population.

## VII. LITERATURE REVIEW

### Global and National Perspective on Fluoride in Groundwater

Fluoride contamination is a global issue, affecting over 25 countries across Asia, Africa, and the Americas. The "fluoride belt" stretches from Turkey through Iraq, Iran, Afghanistan, India, Thailand, and China (Fawell et al., 2006). In India,

endemic fluorosis was first identified in the 1930s. According to the Ministry of Jal Shakti (2021), fluoride (>1.5 mg/L) has been detected in groundwater in 230 districts across 20 states, affecting over 36 million people. The worst-affected states align with arid/semi-arid climates, crystalline basement rocks (granites, gneisses), and sedimentary basins with fluoride-rich mineralogy (CGWB, 2021; Ayoub & Gupta, 2006).



### Hydrogeochemistry Of Fluoride Mobilization

Extensive research elucidates the geochemical pathways for fluoride release. The primary mechanism is the dissolution of fluorite, favored in alkaline environments (pH 7.5–8.5), where high bicarbonate ( $\text{HCO}_3^-$ ) from carbonate weathering and low calcium ( $\text{Ca}^{2+}$ ) concentration shift the equilibrium towards fluoride ( $\text{F}^-$ ) release (Gupta et al., 2005). Sodium-bicarbonate-type waters, common in the Indo-Gangetic alluvium, are particularly prone. Long residence time in the aquifer, high evaporation rates, and ion exchange processes further concentrate fluoride. Anthropogenic sources include phosphate fertilizers, aluminum smelting, brick kilns, and industrial wastewater from electroplating, glass manufacturing, and leather tanning (Jain, 2017; Yadav et al., 2019).

### Health Impacts Of Chronic Fluoride Exposure

Fluoride's health effects are dose and duration-dependent (Susheela, 2001; WHO, 2017).

**Dental Fluorosis:** Occurs during tooth development (childhood). It ranges from mild white striations to severe brown staining, pitting, and enamel hypoplasia. It is a sensitive biomarker of excess fluoride exposure during early life (Fawell et al., 2006).

**Skeletal Fluorosis:** A debilitating bone disease from long-term ingestion. Fluoride substitutes for hydroxyl groups in bone hydroxyapatite, forming fluorapatite, leading to increased bone density but poor quality. Symptoms include joint pain, stiffness, limited movement, and in advanced stages, kyphosis, crippling

deformities, and neurological complications due to spinal cord compression (Susheela, 2001; Ayooob & Gupta, 2006).

**Non-Skeletal Fluorosis:** Growing evidence links high fluoride intake to gastrointestinal issues, impaired thyroid function (by competing with iodine), lowered IQ in children, reproductive toxicity, and renal stress (Yadav et al., 2019; Kundu & Panigrahi, 2019).

### Fluoride Scenario In The Gangetic Plain

The Gangetic alluvial aquifer has reported fluoride contamination in numerous districts across the plain (CGWB, 2021). The Central Ground Water Board has identified several "priority" blocks. Studies in various districts have shown fluoride levels up to 5–8 mg/L (Singh & Singh, 2018; Chowdhury et al., 2019). The specific geology of the area—weathering of micaceous and fluoride-rich minerals from the Himalayan provenance, deposited in the alluvium—creates the natural source. Industrial hubs within the belt add a potential pollution vector (Yadav et al., 2019).

### Studies On The Selected Region And Research Gaps

Literature explicitly focusing on the selected study region reveals fluoride concentrations between 0.8 to 4.2 mg/L, with over 40% of samples exceeding 1.5 mg/L (Singh & Singh, 2018; Yadav et al., 2019; Kundu & Panigrahi, 2019). Reports from state groundwater departments have highlighted hotspots in various administrative blocks. Case reports from local hospitals document advanced skeletal fluorosis (Chowdhury et al., 2019). However, there is a critical lack of:

- A comprehensive, region-wide water quality mapping integrating chemical parameters ( $F^-$ , pH,  $HCO_3^-$ ,  $Ca^{2+}$ ,  $Na^+$ )
- Detailed epidemiological surveys correlating water fluoride with clinical fluorosis prevalence
- Studies quantifying the anthropogenic industrial contribution versus geogenic background
- Evaluation of the socio-economic impact of fluorosis in the study region
- Pilot studies on the performance of defluoridation units in the local context

## VIII. RESULTS

### Spatial Distribution of Fluoride

Data synthesis indicates that fluoride contamination in the study region is not uniform but patchy, characteristic of alluvial

aquifers. The worst-affected areas are likely in the central and western parts of the region, corresponding to older alluvial plains with deeper groundwater tables. Contamination hotspots show concentrations ranging from 2.0 to 6.0 mg/L, significantly above the BIS (1.0 mg/L) and WHO (1.5 mg/L) standards (Singh & Singh, 2018; Yadav et al., 2019). Shallow hand pumps (<50 m) may show lower levels, while deeper borewells (>100 m) tapping into confined aquifers with longer residence times exhibit higher concentrations (Kundu & Panigrahi, 2019).

### Hydrogeochemical Facies

Water in high-fluoride zones is predominantly of Na- $HCO_3$  type, with pH >8.0, high Total Dissolved Solids (TDS), low  $Ca^{2+}$  content, and a high  $Na^+/Ca^{2+}$  ratio—a classic fingerprint of fluoride-mobilizing conditions (Gupta et al., 2005; Chowdhury et al., 2019).

### Health Impact Prevalence

Based on analogous districts, the prevalence of dental fluorosis among children (6–14 years) in affected villages of the study region could be estimated at 40–70%, with moderate to severe forms common (Yadav et al., 2019). Skeletal fluorosis in adults, particularly among agricultural laborers and others with high water intake, likely shows a prevalence of 15–30% in endemic villages, with a higher burden in the age group of 40+ years (Susheela, 2001). Early symptoms like joint pain are widespread but often misdiagnosed (Chowdhury et al., 2019).

### Anthropogenic Contribution

While geogenic origin is primary, water quality data from areas adjacent to industrial drains and tannery clusters show elevated levels of fluoride alongside other contaminants (chromium, salinity), suggesting a contributory role of industrial pollution (Yadav et al., 2019; Singh & Singh, 2018).

## IX. DISCUSSION

The discussion centers on the direct pathway from geology to human skeleton. The alkaline sodium-bicarbonate groundwater, a product of natural weathering in the alluvial basin, acts as the solvent and carrier of fluoride. The lack of public water supply in many areas forces reliance on this toxic resource. The delay between exposure (childhood) and the crippling manifestation of skeletal fluorosis (adulthood) creates a false sense of security and complicates public health messaging (Susheela, 2001; WHO, 2017).

**Socio-Economic Dimensions:** Fluorosis is a disease of poverty and inequity. The poorest, with no means to install reverse osmosis (RO) systems or access bottled water, bear the brunt.

The disease reduces earning capacity, creating a vicious cycle. Stigma associated with disfigured teeth (dental fluorosis) affects the social well-being and mental health of young adults (Ayoob & Gupta, 2006; Yadav et al., 2019).

**Industrial Impact:** The role of industries, especially tanneries, requires rigorous source apportionment studies. While natural background is high, unchecked industrial discharge into the soil and surface water constitutes an avoidable environmental burden, adding to the community's baseline exposure (Jain, 2017; Singh & Singh, 2018).

**Institutional Challenges:** Despite identification by technical agencies, the translation into on-ground mitigation is slow. The National Programme for Prevention and Control of Fluorosis (NPPCF) has limited penetration in many parts of the Gangetic plain (Ministry of Jal Shakti, 2021). Surveillance is weak, and healthcare providers often lack training in fluorosis diagnosis and management (CGWB, 2021).

## X. CONCLUSION

Fluoride contamination in the drinking water of the selected study region represents a severe, ongoing public health and environmental crisis. The root cause is geogenic, embedded in the very strata of the alluvium, but potentially aggravated by industrial activity. The consequences are etched on the bodies of the population—in the stained teeth of children and the bent spines of their elders. The problem is compounded by hydrological dependency, socio-economic vulnerability, and institutional inertia. Without urgent and sustained intervention, the burden of disability, healthcare costs, and lost productivity will continue to mount, undermining the development and well-being of the region's community. Addressing this issue is not merely a technical water treatment challenge but a fundamental imperative for health equity and social justice.

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