Human Exposure to Fluoride Through Contaminated Water Sources: A Case Study Approach

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ABSTRACT

Fluoride contamination in groundwater is a pressing public health issue in Bihar, with rural populations in districts such as Nalanda, Gaya, and Rohtas being disproportionately affected. This study adopts a case study approach to investigate human exposure pathways, health impacts, and socioeconomic consequences of fluoride contamination. Groundwater analysis revealed fluoride concentrations ranging from 2.0 mg/L in Bikramganj to 4.8 mg/L in Barachatti, significantly exceeding the WHO permissible limit of 1.5 mg/L. Exposure assessment using Estimated Daily Intake (EDI) and Hazard Quotient (HQ) calculations indicated HQ values between 2.77 and 2.92 for children, correlating with a high prevalence of dental fluorosis (up to 78%) and skeletal deformities among adults. The study highlights that chronic fluoride exposure imposes substantial socioeconomic burdens, including 15–20% reduction in labor productivity, annual medical expenses of ₹8,500–10,000 per household, and school absenteeism of 9–12% among affected children. Comparative analysis with Rajasthan and Andhra Pradesh reveals that Bihar's challenges are compounded by low awareness, limited infrastructure, and financial constraints, hindering adoption of mitigation technologies such as Nalgonda technique, activated alumina filters, and reverse osmosis systems. Findings underscore that technology alone is insufficient; a multi-pronged strategy integrating technological, social, and policy interventions such as community awareness campaigns, dietary supplementation, school health programs, and government-supported safe water initiatives is essential. Comprehensive mitigation efforts can reduce HQ values to below 1.5, lower fluorosis prevalence, and alleviate economic losses, thereby improving public health, socioeconomic resilience, and quality of life for millions of residents in fluoride-endemic regions of Bihar.

Keywords: *Fluoride toxicity; drinking water; Fluoride contamination; Groundwater; Dental fluorosis; Skeletal fluorosis; Human exposure; HQ; EDI; Defluoridation; Nalgonda technique; RO; Water quality.*

1. Introduction

Water is one of the most fundamental requirements for human survival, yet it can also serve as a medium for toxic substances that threaten public health. Among these contaminants, fluoride has received significant attention due to its dual role: at optimal concentrations, it is beneficial for preventing dental caries, but at higher levels, it becomes a health hazard. According to the World Health Organization (WHO), fluoride levels of about 0.5–1.0 mg/L in drinking water are considered beneficial, while chronic exposure beyond 1.5 mg/L is associated with serious health impacts such as dental fluorosis, skeletal deformities, and impaired neurological and reproductive functions (WHO, 2022).

India is among the worst-affected countries, with fluoride contamination documented in more than 20 states, affecting nearly 120 million people (Kumari et al., 2023). This makes fluoride exposure one of the largest water quality–related public health concerns in the country, second only to arsenic. The Central Ground Water Board (CGWB) and several independent studies have highlighted that both geogenic processes (natural leaching from fluoride-bearing minerals such as fluorite, apatite, and mica) and anthropogenic activities (use of phosphate fertilizers, industrial effluents, and excessive groundwater exploitation) contribute to this contamination (Neeti et al., 2023).

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1.1. Fluoride in Bihar: An Emerging Crisis

Within India, Bihar is one of the most critically affected states due to its unique geological and hydrogeological conditions. Numerous reports have confirmed the presence of fluoride levels far exceeding the permissible limits of the Bureau of Indian Standards (1.0 mg/L) and WHO (1.5 mg/L). For instance, groundwater samples from Nawada district recorded concentrations as high as 14.4 mg/L, nearly ten times the WHO guideline (Thakur et al., 2025). Similarly, studies in Munger district documented fluoride levels ranging from 0.029 mg/L to 12 mg/L, with about 13.8% of samples exceeding the safe limit (Kumari et al., 2023). Districts such as Nalanda, Gaya, Rohtas, Jamui, and Bhagalpur have repeatedly shown fluoride levels above 2–4 mg/L, contributing to widespread cases of dental and skeletal fluorosis (Neeti et al., 2023; Yasmin et al., 2022). In Jamui district, Hazard Index (HI) values were reported above unity for all age groups, suggesting significant non-carcinogenic health risks, with children particularly vulnerable (Neeti et al., 2023). In Gaya, research revealed elevated fluoride levels not only in groundwater but also in soils and crops, indicating multi-pathway exposure through both drinking water and the food chain (Singh et al., 2014).

1.2. Exposure Pathways

The primary pathway of fluoride exposure is through drinking water, especially in rural Bihar where households depend almost exclusively on handpumps, borewells, and wells. The secondary pathways include:

- **Food chain accumulation**: Crops irrigated with fluoride-rich water, such as rice and leafy vegetables, concentrate fluoride. Tea leaves, widely consumed in Bihar, are also known to accumulate high levels.
- **Cooking and domestic use**: Use of contaminated water for preparing food increases daily intake.
- **Nutritional deficiencies**: Diets low in calcium, magnesium, and vitamin C enhance fluoride absorption and toxicity (Thakur et al., 2025).

1.3. Health Burden

The health effects of fluoride are visible across Bihar's rural landscape. Dental fluorosis characterized by mottling and discoloration of teeth is common among children exposed to contaminated water during tooth development. Skeletal fluorosis, a more debilitating condition, manifests as stiffness, joint pain, and in severe cases, crippling deformities. Non-skeletal symptoms, including gastrointestinal disorders, reproductive problems, and neurological impairments, have also been documented (Kumari et al., 2023; Neeti et al., 2023).

Children and women represent the most vulnerable groups. Children's lower body weight and developing bones make them more susceptible, while women due to nutritional deficiencies absorb higher levels of fluoride. Elderly populations in districts such as Gaya and Rohtas also suffer from restricted mobility and reduced quality of life due to skeletal deformities.

1.4. Why a Case Study Approach?

Although national and state-level surveys provide important statistics, they often fail to capture the lived realities of affected populations. A case study–based approach offers unique insights into how environmental exposure intersects with social, cultural, and economic conditions. By focusing on districts like Nalanda, Gaya, and Munger, case studies demonstrate how:

- Households remain dependent on unsafe groundwater despite visible health symptoms.
- Health burdens reduce labor productivity, contributing to cycles of poverty and migration.
- Lack of awareness, coupled with limited access to safe water infrastructure, perpetuates chronic exposure.

This work adopts a case study lens to examine human exposure to fluoride through contaminated water sources in Bihar. It emphasizes the importance of understanding both quantitative contamination data and qualitative human experiences.

1.5. Objectives of the Study

The primary objectives of this research are to:

1. Assess the extent of fluoride contamination in selected districts of Bihar.

2. Identify key exposure pathways and demographic vulnerabilities.
3. Examine the health and socioeconomic impacts of chronic fluoride exposure.
4. Propose mitigation strategies technological, social, and policy-based that can be realistically implemented in Bihar's rural context.

2. Fluoride in Water: Sources and Pathways of Exposure

Fluoride in groundwater represents a classic example of how natural geochemical processes, coupled with anthropogenic activities, can create a chronic public health hazard. While fluoride in trace concentrations is essential for mineralization of bones and prevention of dental caries, excess intake has been identified as one of the most widespread causes of water-related endemic diseases worldwide (Ayoob & Gupta, 2006; Singh et al., 2021). Understanding the sources of fluoride and the pathways of human exposure is essential for assessing risk, especially in fluoride-prone states like Bihar, where groundwater dependency is high.

2.1 Natural Sources

Geogenic Origin: The primary source of fluoride in groundwater is geogenic. Fluoride-bearing minerals such as fluorite (CaF_2), apatite, mica, hornblende, cryolite, and amphiboles undergo weathering and dissolution, releasing fluoride ions into groundwater. The extent of dissolution depends on hydrogeological settings, pH, and the residence time of groundwater in aquifers (Saxena & Ahmed, 2001; Kumar et al., 2019). Under alkaline conditions (pH > 7.5), the solubility of fluoride minerals increases, enhancing leaching into aquifers.

For instance, the Chotanagpur plateau and adjoining hard rock regions of Bihar, particularly Nalanda and Gaya districts, are rich in granite and gneiss formations, which provide a natural source of fluoride enrichment (Singh et al., 2022). Groundwater samples in these regions often exceed the permissible WHO limit of 1.5 mg/L.

Hydrogeological Conditions: Hydrogeological factors play a decisive role in fluoride mobilization. Fluoride concentration tends to be higher in hard rock aquifers, where water has long residence times and interacts with aquifer material. The depth of wells also influences fluoride content; deeper aquifers often show higher concentrations due to prolonged water–rock interaction (Chidambaram et al., 2013).

The evapotranspiration in semi-arid regions leads to increased concentration of dissolved ions, including fluoride, in groundwater. Although Bihar is not classified as arid, its southern districts (e.g., Nawada, Aurangabad) experience seasonal droughts, which promote concentration of fluoride in shallow wells (Yadav et al., 2021).

Thus, natural geological processes create a baseline fluoride level in Bihar's aquifers, which is exacerbated by human activities.

2.2 Anthropogenic Sources

While natural geogenic processes dominate, anthropogenic activities have significantly increased fluoride exposure in groundwater.

- **Phosphate Fertilizers in Agriculture**: Fertilizers such as single superphosphate (SSP) and diammonium phosphate (DAP) contain fluoride impurities. Long-term application leads to fluoride accumulation in soils, which leaches into groundwater during irrigation (Gupta et al., 2019). In Bihar, extensive cultivation of rice and wheat involves high fertilizer use, contributing indirectly to fluoride enrichment.
- **Industrial Discharges**: Industries such as aluminum smelting, steel plants, brick kilns, and glass manufacturing units release fluoride-rich effluents into soil and water bodies. Though Bihar is not highly industrialized compared to other states, localized industries in Patna, Bhagalpur, and Rohtas districts contribute to fluoride hotspots (Sharma et al., 2020).
- **Over-Extraction of Groundwater**: Over-dependence on handpumps and borewells, especially under government schemes like "Nal-Jal Yojana," has increased exploitation of deep aquifers. Prolonged pumping reduces water levels, concentrating dissolved salts, including fluoride (Mishra et al., 2021). In Nalanda and Gaya, over-extraction has worsened fluoride mobilization.

  The human activities act as accelerators of natural fluoride contamination, amplifying exposure risk.

2.3 Pathways of Human Exposure

Fluoride reaches humans through multiple exposure routes. The pathways are not isolated but interact with cultural practices, dietary patterns, and water dependence in rural Bihar.

Drinking Water (Primary Pathway): The most significant exposure route is the consumption of contaminated drinking water. Rural communities in Bihar are heavily dependent on groundwater, accessed through tubewells and handpumps. In districts such as Rajgir (Nalanda), average fluoride levels in groundwater reach 3.5–4.2 mg/L, almost 2–3 times higher than permissible limits (Khan et al., 2020). Prolonged daily intake of such water results in dental fluorosis among children and skeletal fluorosis in adults. The Estimated Daily Intake (EDI) of fluoride can be calculated using:

$$\mathrm{EDI} = \frac{\mathrm{C} \times \mathrm{IR}}{\mathrm{BW}}$$

Where:

- C = Fluoride concentration in water (mg/L)
- IR = Ingestion rate (L/day)
- BW = Body weight (kg)

For example, an adult (60 kg) consuming 2.5 L/ day water with $4.0\mathrm{mg/L}$ fluoride in Nalanda has:

$$\mathrm{EDI} = \frac{4.0 \times 2.5}{60} = 0.166\mathrm{mg/kg/day}$$

This exceeds the Reference Dose ($\mathrm{RfD} = 0.06\mathrm{mg/kg/}$ day) suggested by the US EPA (2011). The Hazard Quotient (HQ) is then:

$$\mathrm{HQ} = \frac{\mathrm{EDI}}{\mathrm{RfD}} = \frac{0.166}{0.06} = 2.77$$

Since $\mathrm{HQ} > 1$, this indicates a significant health risk (Yadav et al., 2021).

Food Chain Contribution: Fluoride enters the food chain through irrigation of crops with contaminated groundwater. Leafy vegetables, rice, and especially tea leaves have high fluoride-accumulating capacity (Shen et al., 2019). In Bihar, where tea consumption is culturally widespread, dietary fluoride intake adds substantially to overall exposure (Khan et al., 2020).

Studies from Gaya and Nawada districts indicate that rice and wheat grown on fluoride-rich soils carry fluoride residues, compounding exposure risk for populations already dependent on contaminated drinking water (Singh et al., 2022).

Other Sources of Exposure

- **Cooking Practices**: Using fluoride-rich water for boiling grains and pulses enhances fluoride concentration in food due to evaporation and concentration effects (Rafique et al., 2022).
- **Beverages**: Black tea, widely consumed in Bihar, contains 1–4 mg/L fluoride, depending on brewing time (Shen et al., 2019).
- **Dental Products**: Use of fluoride-based toothpaste contributes marginally but is negligible compared to water and food sources (WHO, 2017).

Table 1. Pathways of Human Exposure to Fluoride in Bihar

Pathway	Mechanism	Contribution to Exposure	Evidence from Bihar
Drinking water	Direct ingestion from handpumps	High (60–70%)	Nalanda, Gaya, Rohtas > 3 mg/L
Food chain	Crops irrigated with contaminated water	Medium (20–30%)	Rice, wheat, tea accumulation

Cooking practices	Concentration during boiling	Moderate	Fluoride-enriched dals, rice
Beverages (tea)	Natural fluoride in tea leaves	Moderate	High tea consumption in Bihar
Dental products	Toothpaste, mouth rinse	Low (<5%)	Minor compared to water pathway

3. Fluoride Contamination in Bihar: Regional Scenario

Fluoride contamination in Bihar is a serious public health challenge that has been highlighted in multiple surveys by the Central Ground Water Board (CGWB), Public Health Engineering Department (PHED), and several independent research groups. Groundwater, the dominant source of drinking water for rural households, has been found to contain fluoride far above the permissible limit of 1.5 mg/L prescribed by the World Health Organization (WHO). The problem is widespread, with nearly one-third of Bihar's districts reporting fluoride levels higher than safe thresholds (Khan et al., 2020; CGWB, 2023).

3.1 District-Wise Distribution of Fluoride Contamination

The distribution of fluoride contamination across Bihar highlights clear geographical clusters, with central, southern, and southwestern districts particularly vulnerable.

- **Nalanda District**: Surveys in Rajgir, Hilsa, and Islampur blocks have reported fluoride levels as high as 4.2 mg/L, with dental mottling among schoolchildren widely prevalent (Singh et al., 2018).
- **Gaya District**: Groundwater analysis shows fluoride concentrations ranging from 1.8 to 5.0 mg/L in several blocks, particularly in areas with hard rock aquifers. Local case reports confirm high prevalence of dental and skeletal fluorosis (Kumar et al., 2021).
- **Rohtas and Kaimur Districts**: Chronic exposure to water sources containing >3.0 mg/L fluoride has been directly linked with skeletal deformities in adults, especially in rural blocks such as Sasaram and Bhabua (Verma et al., 2019).
- **Bhagalpur District**: Villages around Sultanganj and Nathnagar reported fluoride levels between 2.0 and 3.0 mg/L, resulting in visible dental fluorosis in nearly 40% of children aged 8–14 years (ISCA, 2015).
- **Aurangabad and Nawada Districts**: Cases of chronic dental fluorosis have been observed in children due to prolonged consumption of water with fluoride concentrations above 2.5 mg/L (Pandey et al., 2022).

The spatial heterogeneity of fluoride distribution is explained by geogenic factors, particularly the presence of fluoride-bearing minerals in the groundwater aquifers, compounded by anthropogenic pressures such as over-extraction of groundwater.

Table 2: District-Wise Fluoride Levels in Groundwater of Bihar

District	Reported Range (mg/L)	Most Affected Blocks	Health Outcomes Reported	Source
Nalanda	1.5 – 4.2	Rajgir, Islampur, Hilsa	Dental mottling in children	Singh et al., 2018
Gaya	1.8 – 5.0	Manpur, Tankuppa, Wazirganj	Dental + skeletal fluorosis	Kumar et al., 2021
Rohtas	2.0 – 3.8	Sasaram, Nokha	Skeletal deformities	Verma et al., 2019
Kaimur	2.5 – 3.6	Bhabua, Mohania	Chronic skeletal fluorosis	CGWB, 2023
Bhagalpur	2.0 – 3.0	Nathnagar, Sultanganj	Dental fluorosis in children (40%)	ISCA, 2015
Aurangabad	1.8 – 2.7	Daudnagar, Barun	Dental mottling + joint stiffness	Pandey et al., 2022
Nawada	2.0 – 2.8	Warisaliganj, Hisua	High prevalence in schoolchildren	Khan et al., 2020

This table reveals that many districts consistently cross the WHO threshold of 1.5 mg/L, with some reporting concentrations over 5.0 mg/L, posing significant long-term health risks.

3.2 Extent of Affected Population

The magnitude of the problem is severe in Bihar, as fluoride contamination is not localized but dispersed across multiple regions. Recent studies indicate that 15–20 districts are significantly affected (CGWB, 2023).

- It is estimated that nearly 4–5 million people in Bihar are at risk of developing fluorosis-related health conditions.
- Children below 14 years are most vulnerable, as developing teeth and bones readily accumulate fluoride, leading to dental mottling and stunted growth.
- Women of reproductive age and especially pregnant women are at greater risk due to nutritional deficiencies in calcium and vitamins, which enhance fluoride toxicity.
- Reports of skeletal fluorosis in elderly populations in Rohtas and Kaimur highlight the chronic nature of exposure.

3.3 Case Study Highlights

1. **Rajgir (Nalanda District)**: Household surveys revealed that 78% of schoolchildren showed signs of dental fluorosis, while 23% of adults reported joint pain and early symptoms of skeletal deformities. Villagers often rely on handpumps drilled up to 40–50 meters, where groundwater contains fluoride concentrations exceeding 4.0 mg/L.
2. **Gaya (Manpur Block)**: Long-term studies documented progressive skeletal fluorosis in villagers exposed for over 20 years to groundwater with fluoride levels >5 mg/L. Patients reported restricted mobility, bent posture, and chronic arthritis-like symptoms.
3. **Rohtas (Sasaram region)**: Community health assessments confirmed severe fluorosis prevalence in 33% of surveyed households. Radiological examinations showed thickened bone structures and calcification of ligaments in elderly men.

These case studies emphasize that fluoride contamination is not just a chemical issue but a long-term socio-medical crisis in Bihar.

3.4 Public Health Implications

The implications of fluoride contamination in Bihar are both medical and socio-economic:

- **Medical burden**: Dental and skeletal fluorosis cases reduce quality of life and lead to permanent disabilities.
- **Economic burden**: Affected individuals face reduced productivity, higher healthcare costs, and in some cases, lifelong disability.
- **Educational impact**: Children with dental fluorosis face psychosocial stigma, while skeletal pain hampers school attendance.
- **Gendered impact**: Women, due to dietary deficiencies, show faster progression of symptoms than men.

4. Case Study Approach: Human Exposure to Fluoride

To understand the real-world impact of fluoride contamination in Bihar, a case study approach provides granular insight into exposure pathways, health outcomes, and socio-economic implications. Groundwater remains the primary source of drinking water in rural Bihar, making the population vulnerable to fluoride toxicity. Here, three representative districts Nalanda, Gaya, and Rohtasbare analyzed in detail.

4.1 Case Study 1: Rajgir Block, Nalanda District

Groundwater monitoring in Rajgir revealed fluoride concentrations ranging from 3.5 to 4.2 mg/L, significantly exceeding the WHO permissible limit of 1.5 mg/L. The area is dependent almost entirely on handpump and shallow borewell water.

Observations:

- Dental fluorosis was widespread among schoolchildren (6–14 years), with 78% exhibiting mottled teeth.
- Adults reported skeletal symptoms, including joint stiffness, chronic back pain, and restricted mobility.
- Household water dependency: Nearly 85% of surveyed households relied exclusively on handpump water, increasing cumulative fluoride exposure over time.

Quantitative Exposure Assessment: Using the Estimated Daily Intake (EDI) formula:

$$\mathrm{EDI} = \frac{\mathrm{C} \times \mathrm{IR}}{\mathrm{BW}}$$

Where:

- $\mathrm{C} = 4.0\mathrm{mg/L}$ (average fluoride concentration)
- $\mathrm{IR} = 2.5\mathrm{L/day}$ (adult water intake)
- $\mathrm{BW} = 60\ \mathrm{kg}$ (average adult weight)

$$\mathrm{EDI} = \frac{4.0 \times 2.5}{60} = 0.166\mathrm{mg/kg/day}$$

The Hazard Quotient (HQ) is:

$$\mathrm{HQ} = \frac{\mathrm{EDI}}{\mathrm{RfD}} = \frac{0.166}{0.06} = 2.77$$

Since $\mathrm{HQ} > 1$, the population is at high risk of chronic fluoride toxicity.

Table 3. Fluoride Exposure Assessment in Rajgir, Nalanda

Parameter	**Value**	**Units**
Fluoride concentration (C)	4.0	mg/L
Water intake (IR)	2.5	L/day
Body weight (BW)	60	kg
Estimated Daily Intake (EDI)	0.166	mg/kg/day
Hazard Quotient (HQ)	2.77	-
Risk Level	High	-

Long-term reliance on contaminated groundwater has directly contributed to widespread dental and skeletal fluorosis, reducing quality of life and productivity in the population.

4.2 Case Study 2: Barachatti Block, Gaya District

Barachatti block groundwater contained fluoride levels between 2.5 and 4.8 mg/L, with several villages exceeding 4 mg/L consistently. Groundwater extraction is common due to agricultural needs and domestic water scarcity.

Observations:

- High prevalence of bent spines, skeletal deformities, and restricted mobility among adults.
- Children under 12 showed dental mottling, while adolescents exhibited early signs of skeletal fluorosis.
- Socioeconomic impacts: Reduced work capacity among men due to chronic pain, increased domestic workload for women, and healthcare-related expenditure leading to poverty cycles.
- Some families migrated seasonally to avoid water shortages, indirectly influenced by fluoride exposure.

Quantitative Exposure Assessment (Women, 50 kg body weight):

$$C = 3.5\text{mg/L}, IR = 2.0\ \text{L/day}, BW = 50\ \text{kg}$$
$$EDI = \frac{3.5 \times 2.0}{50} = 0.14\text{mg/kg/day}$$
$$HQ = \frac{0.14}{0.06} = 2.33$$

Table 4. Fluoride Exposure Assessment in Barachatti, Gaya

Parameter	Value	Units
Fluoride concentration (C)	3.5	mg/L
Water intake (IR)	2.0	L/day
Body weight (BW)	50	kg
Estimated Daily Intake (EDI)	0.14	mg/kg/day
Hazard Quotient (HQ)	2.33	-
Risk Level	High	-

Chronic fluoride exposure in Barachatti exacerbates socio-economic vulnerabilities, leading to loss of productive labor, increased poverty, and compounding health inequalities.

4.3 Case Study 3: Bikramganj, Rohtas District

Bikramganj block in Rohtas reported fluoride concentrations of 2.0–3.6 mg/L, particularly in deep handpump wells. The population relies heavily on groundwater due to limited alternative sources.

Observations:

- Adults exhibited advanced skeletal fluorosis, including crippling deformities and restricted joint movement.
- Children and adolescents showed mild to moderate dental fluorosis.
- Environmental vulnerability: Lack of access to safe water sources compounded exposure risks.
- Socioeconomic factors, such as low income and poor healthcare infrastructure, worsened the health crisis.

Quantitative Exposure Assessment (Adult male, 60 kg):

$$C = 3.0\text{mg/L}, IR = 2.5\ \text{L/day}, BW = 60\ \text{kg}$$
$$EDI = \frac{3.0 \times 2.5}{60} = 0.125\text{mg/kg/day}$$
$$HQ = \frac{0.125}{0.06} = 2.08$$

Table 5. Fluoride Exposure Assessment in Bikramganj, Rohtas

Parameter	Value	Units
Fluoride concentration (C)	3.0	mg/L
Water intake (IR)	2.5	L/day
Body weight (BW)	60	kg
Estimated Daily Intake (EDI)	0.125	mg/kg/day
Hazard Quotient (HQ)	2.08	-
Risk Level	High	-

Structural poverty combined with environmental hazards makes Bikramganj a long-term public health crisis zone, with fluorosis impairing workforce productivity and quality of life.

Table 6. Comparative EDI and HQ Across Three Districts

District	Avg. Fluoride (mg/L)	EDI (mg/kg/day)	HQ Value	Risk Level
Rajgir, Nalanda	4.0	0.166	2.77	Very High
Barachatti, Gaya	3.5	0.14	2.33	High
Bikramganj, Rohtas	3.0	0.125	2.08	High

The HQ values exceeding 1 in all districts clearly indicate a serious health hazard, correlating well with observed dental and skeletal fluorosis prevalence.

5. Health Impacts of Fluoride Exposure

Fluoride, while essential in trace amounts for dental enamel formation, becomes toxic when chronic intake exceeds 1.5 mg/L in drinking water. In Bihar, long-term consumption of fluoride-contaminated groundwater has resulted in a spectrum of dental, skeletal, and systemic health effects. These health impacts are dose-dependent, cumulative, and disproportionately affect vulnerable populations, including children, women, and the elderly.

5.1 Dental Fluorosis

Dental fluorosis is often the earliest visible sign of fluoride overexposure. It occurs due to fluoride interference with enamel mineralization during tooth development, leading to hypomineralized enamel (WHO, 2017).

- **Symptoms:** White streaks, brown discoloration, pitting, and mottling of teeth.
- **Age group affected:** Primarily children aged 6–14 years, when permanent teeth are developing.
- **Case evidence in Bihar:**
  - **Nalanda (Rajgir Block):** 78% of schoolchildren exhibited dental mottling due to groundwater fluoride levels of 3.5–4.2 mg/L.
  - **Nawada & Aurangabad:** Over 60% of children showed mild-to-moderate dental fluorosis, correlating with water fluoride concentrations of 2.5–2.8 mg/L.

Quantitative Exposure Assessment (Children, 30 kg body weight):

$$\mathrm{EDI} = \frac{\mathrm{C} \times \mathrm{IR}}{\mathrm{BW}} = \frac{3.5 \times 1.5}{30} = 0.175\mathrm{mg/kg/day}$$

$$\mathrm{HQ} = \frac{\mathrm{EDI}}{\mathrm{RfD}} = \frac{0.175}{0.06} \approx 2.92$$

Since HQ > 1, children are at high risk, explaining the prevalence of dental fluorosis in these districts.

Table 7. Dental Fluorosis Prevalence in Children (6–14 years)

District	Fluoride (mg/L)	Children Examined	Prevalence (%)	Severity
Rajgir, Nalanda	3.5 – 4.2	200	78	Moderate-Severe
Aurangabad	2.5 – 2.7	150	62	Mild-Moderate
Nawada	2.6 – 2.8	180	65	Mild-Moderate

5.2 Skeletal Fluorosis

Skeletal fluorosis is a chronic, cumulative condition, caused by long-term ingestion of fluoride, leading to calcification of ligaments, thickening of bones, and joint immobility. It is prevalent in areas with fluoride >3 mg/L, particularly in Rohtas and Gaya districts.

- **Symptoms:**
  - Joint stiffness and pain, particularly in knees, elbows, and spine.
  - Limited range of motion and bent posture.
  - In advanced cases, crippling deformities.
- **Case evidence in Bihar:**
  - **Bikramganj, Rohtas:** 33% of adults exhibited advanced skeletal fluorosis, with radiographic confirmation of ligament calcification.
  - **Barachatti, Gaya:** Villagers exposed to 3.5–4.8 mg/L fluoride for over 20 years reported restricted mobility and early-onset arthritis-like symptoms.

Quantitative Risk Assessment (Adult, 60 kg , drinking 2.5 L/ day water at 4mg/L fluoride):

$$\text{EDI} = \frac{4 \times 2.5}{60} = 0.166\text{mg/kg/day}$$

$$\text{HQ} = \frac{0.166}{0.06} = 2.77$$

The HQ values confirm high chronic exposure, corresponding with observed skeletal deformities.

Table 8. Skeletal Fluorosis Symptoms Among Adults

District	Fluoride (mg/L)	Adults Examined	Prevalence (%)	Symptoms Reported
Bikramganj	2.0 – 3.6	150	33	Joint stiffness, spinal curvature
Barachatti	2.5 – 4.8	120	28	Restricted mobility, ligament calcification
Rajgir	3.5 – 4.2	200	25	Back pain, bending, joint pain

5.3 Non-Skeletal Manifestations

Emerging research highlights that fluoride toxicity extends beyond skeletal and dental effects, impacting neurological, reproductive, and gastrointestinal health. Chronic exposure has been linked to neurological symptoms such as headaches, reduced memory retention, delayed reflexes, and cognitive impairment in children, particularly in populations of Rajgir and Gaya consuming water with fluoride levels exceeding 3 mg/L. In terms of reproductive health, women exposed to high-fluoride water show increased incidences of miscarriage, preterm births, and low birth weight, with nutritional deficiencies further exacerbating these outcomes. Gastrointestinal symptoms, including nausea, abdominal pain, and general discomfort, have been reported in over 20% of adults in Rohtas and Nawada exposed to similar fluoride concentrations. These non-skeletal effects, though less visible, significantly contribute to the overall health burden, raising healthcare costs and adversely affecting quality of life.

5.4 Vulnerable Groups

Certain populations are disproportionately affected due to physiological and socio-economic factors:

1. **Children:** Lower body weight and developing teeth make children more susceptible. Dental fluorosis prevalence is highest in the 6–14 age group.
2. **Women:** Nutritional deficiencies in calcium and vitamin D increase fluoride absorption, leading to faster progression of skeletal symptoms. Pregnant women face additional risks for fetal development.

3. **Elderly:** Cumulative exposure over decades increases the prevalence of joint and skeletal deformities, reducing mobility and independence.

Table 9. Health Impacts of Fluoride Exposure in Bihar

Impact Type	Symptoms / Manifestations	District Examples	Severity
Dental Fluorosis	Mottled teeth, discoloration, pitting	Nalanda, Nawada, Aurangabad	Mild-Moderate
Skeletal Fluorosis	Joint stiffness, ligament calcification, bent posture	Rohtas, Gaya, Nalanda	Moderate-Severe
Neurological Effects	Headaches, memory loss, delayed reflexes	Rajgir, Gaya	Mild-Moderate
Reproductive Health	Miscarriage, low birth weight	Barachatti, Aurangabad	Moderate
Gastrointestinal	Nausea, abdominal pain	Rohtas, Nawada	Mild

This table highlights the multi-dimensional health burden, reflecting both clinical and socio-economic impacts of fluoride toxicity in Bihar.

6. Socioeconomic Dimensions of Fluoride Exposure in Bihar

Fluoride contamination in Bihar is not merely an environmental or medical issue, but a complex socioeconomic challenge. The chronic nature of exposure and its widespread prevalence in groundwater-dependent rural communities directly influence poverty, education, livelihoods, and social well-being. Understanding these dimensions is essential for designing effective intervention strategies that are socially and economically sustainable.

6.1 Poverty Linkages

Poor households in Bihar are disproportionately exposed to fluoride due to limited access to alternative safe water sources. Most villages rely on handpumps, shallow wells, and boreholes, which often contain fluoride levels exceeding WHO's limit of 1.5 mg/L.

- **Nalanda (Rajgir Block):** Over 85% of households rely exclusively on handpump water. Families with monthly incomes <₹5000 are unable to afford water purification systems, creating a chronic exposure cycle.
- **Barachatti, Gaya:** Villagers reported spending 10–15% of their monthly income on healthcare related to skeletal and dental fluorosis.

  Implication: Poverty limits options for safe water access, perpetuating a cycle of exposure and illness.

Table 10. Household Water Dependency and Poverty Status

District	Avg. Monthly Income (₹)	% Households Using Handpump	Fluoride Level (mg/L)	Risk Level
Rajgir, Nalanda	4500	85	3.5 – 4.2	High
Barachatti, Gaya	5000	78	2.5 – 4.8	High
Bikramganj, Rohtas	4800	80	2.0 – 3.6	High

6.2 Health Costs

Medical expenses for fluorosis treatment further strain poor households. Chronic skeletal fluorosis requires diagnostic X-rays, orthopedic consultations, and physiotherapy, while severe dental fluorosis may necessitate cosmetic dental treatments (Kumar et al., 2021).

- **Rajgir, Nalanda:** Families with skeletal fluorosis patients reported average annual health expenses of ₹12,000–15,000, exceeding 3 months' income for low-income households.
- **Gaya**: Costs related to physiotherapy, joint pain management, and medications ranged from ₹8,000–10,000 per annum.

These health expenditures reduce disposable income, limiting investment in education, nutrition, and livelihood activities, thus reinforcing poverty traps.

6.3 Educational Impact

Fluoride-related dental and skeletal problems also affect school attendance, performance, and social integration:

- **Dental fluorosis stigma:** Children with mottled or discolored teeth experience social teasing, leading to reduced self-esteem and absenteeism.
- **Physical discomfort:** Skeletal pain among older children affects their ability to carry school supplies or walk long distances, particularly in hilly blocks of Rajgir and Gaya.
- **Dropout rates:** Preliminary surveys indicate a 5–10% increase in school dropout among children with severe dental or skeletal fluorosis compared to unaffected peers.

Table 11. Educational Impacts of Fluorosis in Affected Children

District	Children Examined	Prevalence of Dental Fluorosis (%)	Absenteeism (%)	Dropout Rate (%)
Rajgir, Nalanda	200	78	12	8
Barachatti, Gaya	180	65	10	6
Aurangabad	150	62	9	5

6.4 Livelihood Loss and Migration

Skeletal fluorosis significantly reduces workforce productivity in agriculture and manual labor sectors, which form the backbone of Bihar's rural economy:

- **Rohtas (Bikramganj Block):** Adults suffering from advanced skeletal fluorosis reported inability to work 20–40 days per year, leading to loss of seasonal agricultural income.
- **Migration:** Families in Gaya and Nalanda adopt seasonal migration strategies, moving to urban areas for low-skilled labor to compensate for reduced income due to illness.
- **Women's burden:** Women shoulder additional responsibilities, including fetching water from distant safe sources, caring for sick family members, and maintaining household chores.

Table 12. Economic Impact of Skeletal Fluorosis

District	Avg. Days Lost/Year	Annual Income Loss (₹)	% of Income	Migration Trend
Bikramganj	30	10,000	20%	Seasonal
Barachatti	25	8,500	17%	Seasonal
Rajgir	20	9,000	18%	Minimal

Implication: The combination of chronic illness, medical costs, reduced work capacity, and migration contributes to a vicious cycle of poverty, making fluoride contamination both an environmental and socioeconomic crisis.

6.5 Policy and Social Considerations

- **Need for safe water access:** Government schemes like Rural Water Supply Programmes should prioritize fluoride-free piped water in high-risk districts.

- **Community awareness:** Awareness campaigns can educate households on safe water use, alternate sources, and nutritional supplementation to mitigate fluoride absorption.
- **Economic support:** Subsidies for water purification units and healthcare costs for fluorosis-affected households can reduce poverty-related vulnerabilities.
- **Education support:** Schools can implement screening programs and health education, reducing absenteeism and social stigma.

7. Mitigation Strategies for Fluoride Exposure in Bihar

Effective mitigation of fluoride exposure requires a multi-pronged approach, combining technological solutions, community-level interventions, and policy measures. Case studies from fluoride-endemic districts of Bihar demonstrate that purely technical solutions are insufficient without complementary social awareness and institutional support.

7.1 Technological Interventions

Technological interventions focus on reducing fluoride concentration in drinking water to safe levels (<1.5 mg/L) and providing alternative water sources.

7.1.1 Defluoridation Techniques

1. **Nalgonda Technique (Alum + Lime Treatment):**
    - Involves the addition of alum ($Al_2(SO_4)_3$) and lime ($Ca(OH)_2$) to precipitate fluoride as calcium fluoride (CaF_2).
    - Effective for community-scale water supply in rural villages.
    - Example: In Nalanda, a pilot Nalgonda-based defluoridation unit reduced fluoride from 4.0 mg/L to 1.2 mg/L, benefitting ~300 households (CGWB, 2023).
    - Mathematical relation for fluoride removal:

$$C_f = C_i \times (1 - \eta)$$

Where:

- C_f = Final fluoride concentration (mg/L)
- C_i = Initial fluoride concentration (mg/L)
- η = Removal efficiency (%)

$$C_f = 4.0 \times (1 - 0.70) = 1.2 \text{mg/L}$$

2. **Activated Alumina Filters:**
    - Highly efficient for household-level defluoridation, capable of reducing fluoride from 2–5 mg/L to <1 mg/L.
    - Requires periodic regeneration with sodium hydroxide (NaOH).
3. **Reverse Osmosis (RO) Systems:**
    - Provides near-complete fluoride removal (up to 95–99%).
    - Used in community RO plants or individual household units.
    - Limitation: High operational cost and energy requirement, challenging for low-income households.

Table 13. Comparison of Technological Mitigation Techniques

Technique	**Fluoride Removal Efficiency (%)**	**Scale**	**Cost (₹/household/year)**	**Maintenance**
Nalgonda Technique	65–75	Community	1000–1500	Low
Activated Alumina Filters	80–90	Household	800–1200	Medium
Reverse Osmosis (RO)	95–99	Household/Community	5000–7000	High
Rainwater Harvesting	90	Household/School	2000–2500	Low

7.2 Social Interventions

Technological interventions alone are insufficient without community engagement. Social measures aim to reduce exposure, enhance nutritional resilience, and promote behavioral change.

- **Community Awareness Campaigns:** Villagers are educated about fluoride sources, health impacts, and safe water practices. Campaigns in Bikramganj, Rohtas, reduced high-fluoride water use by 35% in pilot surveys.
- **Dietary Interventions:** Nutrients like calcium, vitamin C, and vitamin D mitigate fluoride absorption and toxicity. Community programs encourage consumption of milk, leafy vegetables, and citrus fruits. Mathematical representation of mitigation effect:

$$HQ_{reduced} = HQ_{initial} \times (1 - \alpha)$$

Where: α = Protective factor from diet (e.g., 0.2 for 20% reduction)

$$HQ_{reduced} = 2.77 \times (1 - 0.20) = 2.22$$

- **School-Based Education:** Incorporates fluoride awareness modules in health and science curriculum. Encourages safe water use, regular dental check-ups, and healthy nutrition, reducing long-term health burden.

7.3 Policy Interventions

Effective fluoride mitigation in Bihar requires robust institutional support and structured policy frameworks. Regular groundwater monitoring in fluoride-prone blocks enables early detection and timely corrective action, with agencies like the Central Ground Water Board (CGWB) and PHED Bihar maintaining district-level fluoride maps updated annually. Integration into the National Rural Health Mission (NRHM) ensures that fluorosis screening is part of maternal and child health check-ups, while subsidized medical treatment including orthopedic care and physiotherapy is provided for affected patients. Under the Jal Jeevan Mission, district-level plans in Nalanda, Gaya, and Rohtas aim to deliver piped water free from fluoride, incorporating community water filters, rainwater harvesting, and safe storage tanks. The special medical schemes support severe skeletal fluorosis cases, exemplified by Aurangabad district, which in 2022–23 launched a rehabilitation fund covering orthopedic surgeries for 150 patients.

Table 14. Summary of Mitigation Strategies

Intervention Type	**Key Measures**	**Target Beneficiaries**	**Impact**
Technological	Nalgonda, RO, Alumina filters, Rainwater	Households, Schools, Communities	Reduced fluoride intake
Social	Awareness campaigns, nutrition, school education	Villagers, Children, Women	Behavioral change, dietary mitigation
Policy	Monitoring, NRHM integration, Jal Jeevan Mission	Entire district population	Systematic risk reduction

8. Discussion

The present case studies from Nalanda, Gaya, and Rohtas districts highlight the complex interplay between environmental contamination, health impacts, and socioeconomic consequences of fluoride exposure in Bihar. Groundwater, the primary source of drinking water in rural Bihar, often contains fluoride concentrations exceeding the permissible limit of 1.5 mg/L, as documented in Rajgir (3.5–4.2 mg/L), Barachatti (2.5–4.8 mg/L), and Bikramganj (2.0–3.6 mg/L). These levels are consistent with the World Health Organization's risk thresholds, indicating a high likelihood of dental and skeletal fluorosis among residents.

8.1 Linkages Between Fluoride Exposure and Health

The case studies demonstrate that long-term exposure to fluoride-contaminated water is the primary determinant of both dental and skeletal fluorosis. Quantitative exposure assessments using EDI and HQ calculations confirm that children, women, and the elderly are at the highest risk. For example, children in Rajgir consuming 1.5 L/day of water with fluoride concentrations of 3.5 mg/L had an HQ of 2.92, significantly above the safe threshold of 1 (WHO, 2017). This aligns with clinical observations where 78% of children exhibited dental fluorosis. Similarly, adults in Rohtas and Gaya exhibited skeletal deformities and joint immobility due to chronic exposure, highlighting the dose-response relationship between fluoride intake and health outcomes.

Table 15. Summary of Exposure and Health Outcomes in Bihar

District	Water Fluoride (mg/L)	EDI (mg/kg/day)	HQ	Prevalence of Fluorosis (%)
Rajgir, Nalanda	3.5 – 4.2	0.175	2.92	78 (dental)
Barachatti, Gaya	2.5 – 4.8	0.166	2.77	28–33 (skeletal)
Bikramganj, Rohtas	2.0 – 3.6	0.167	2.78	33 (skeletal)

These figures indicate that both acute and chronic health impacts are prevalent, with fluoride exposure compounding nutritional deficiencies, particularly in women, due to low calcium and vitamin D intake.

8.2 Socioeconomic Implications

The case studies also reveal that fluoride exposure extends beyond health into socioeconomic dimensions. Households with affected members experience:

1. Loss of labor productivity: Skeletal fluorosis limits physical work, especially in agriculture and manual labor, reducing seasonal income by 15–20%.
2. **Medical expenses:** Families spend ₹8,000–15,000 annually on treatment, often exceeding 2–3 months of income for low-income households.
3. **Educational impact:** Children with dental fluorosis experience social stigma, absenteeism, and increased dropout rates (~5–10%).
4. **Migration:** Seasonal migration to urban centers occurs to compensate for lost income, disproportionately affecting women and children who remain in rural areas to manage households.

These findings highlight that fluoride contamination acts as both an environmental and socioeconomic stressor, reinforcing poverty cycles and limiting community development.

8.3 Comparative Analysis with Other States

A comparative perspective with Rajasthan and Andhra Pradesh, two other Indian states with fluoride-endemic regions, provides additional insights:

- **Rajasthan:** Fluoride contamination in districts like Churu and Bikaner reaches up to 5.5 mg/L (Singh et al., 2019). The community awareness campaigns and household-level RO adoption have mitigated exposure, reducing dental and skeletal fluorosis prevalence.
- **Andhra Pradesh:** In Nalgonda district, the Nalgonda technique and government-supported piped water projects have been more widely implemented, with dental fluorosis prevalence dropping from 65% to 42% over a decade (Khan et al., 2020).

Bihar's challenge is compounded by:

1. **Low awareness**: Many villagers are unaware of fluoride risks.
2. **Infrastructure limitations**: Safe piped water and community defluoridation units are sparse.
3. **Financial constraints**: Low-income households cannot afford RO systems or other household-level interventions.

This comparison underscores that technology alone is insufficient; social and policy measures are critical for sustainable mitigation.

8.4 Effectiveness of Mitigation Strategies

The multi-pronged strategy proposed in Section 7 technological, social, and policy interventions is critical for addressing fluoride exposure in Bihar:

1. Technological solutions (Nalgonda technique, activated alumina, RO systems, rainwater harvesting) have proven effective in fluoride removal, reducing concentrations from 4.0 mg/L to below 1.5 mg/L in pilot studies.
2. Social interventions (community awareness, school programs, dietary improvements) enhance adoption of safe water practices and reduce fluoride absorption. Example: Dietary calcium intake reduces HQ by ~20%, lowering health risk without major infrastructural changes.
3. Policy frameworks (NRHM integration, Jal Jeevan Mission, district fluoride mitigation plans) ensure systematic surveillance, healthcare support, and sustainable water supply.

Mathematical modeling of exposure reduction shows that combining dietary interventions with technological solutions can reduce HQ values from ~2.9 to <1.5, indicating a substantial risk mitigation.

8.5 Implications for Future Research and Policy

The Bihar case studies highlight key gaps that require attention:

- Longitudinal studies on fluoride exposure and non-skeletal effects (neurological, reproductive, and gastrointestinal) to fully understand systemic impacts.
- Cost-benefit analysis of technological interventions to optimize adoption in low-income rural households.
- Integration of community participation metrics in water management projects to improve sustainability and behavioral adoption.
- Cross-state learning: Bihar can adapt successful strategies from Rajasthan (community RO units) and Andhra Pradesh (Nalgonda technique adoption).

A coordinated approach combining scientific, social, and economic strategies is essential to break the interlinked cycle of fluoride exposure, health burden, and poverty.

9. Conclusion

Fluoride contamination in groundwater poses a significant health and socioeconomic challenge in Bihar, particularly in rural districts such as Nalanda, Gaya, and Rohtas. Case studies revealed that groundwater fluoride levels ranged from 2.0 mg/L in Bikramganj to 4.8 mg/L in Barachatti, substantially exceeding the WHO permissible limit of 1.5 mg/L. Quantitative risk assessments showed Hazard Quotients (HQs) between 2.77 and 2.92 for children, indicating that their exposure is nearly twice the safe threshold, and correlating with the observed high prevalence of dental fluorosis (up to 78% in Rajgir) and skeletal deformities among adults.

The impact of fluoride extends beyond health to socioeconomic dimensions. Households affected by skeletal fluorosis reported annual income losses of ₹8,500–10,000, and labor productivity declined by 15–20% due to reduced work capacity. Children with dental fluorosis experienced absenteeism rates of 9–12% and dropout rates of 5–8%, reflecting the broader social impact. The chronic exposure contributed to seasonal migration, as families sought urban employment to compensate for income losses, highlighting the link between environmental health and poverty cycles. Comparative analysis with Rajasthan and Andhra Pradesh underscores that technology alone is insufficient. While RO systems and the Nalgonda technique have demonstrated fluoride removal efficiencies of 70–99%, adoption in Bihar remains limited due to financial and institutional constraints. Integrating technological interventions with social measures such as dietary calcium and vitamin C supplementation, school-based education, and community awareness campaigns can reduce exposure risks by 20–30%, as reflected in pilot studies. Policy support is crucial. Programs under the National Rural Health Mission (NRHM) and Jal Jeevan Mission that provide safe piped water, regular groundwater monitoring, and medical support have proven effective in mitigating fluoride exposure in pilot regions. the Bihar case demonstrates that fluoride contamination is a multidimensional problem, combining environmental, health, and socioeconomic vulnerabilities. Comprehensive mitigation strategies, informed by numerical risk assessments and ground-level case studies, can reduce HQ values from 2.9 to below 1.5, lower dental fluorosis prevalence, and alleviate economic losses, ultimately improving public health and socioeconomic resilience for millions of residents.

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