Analyzing Fluoride-Induced Toxicity in Human Health: Case Studies and Applied Interventions for Safe Drinking Water

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ABSTRACT

In fluoride-endemic Bihar, India, drinking water contamination is a severe public health hazard. This research explores the health effects of fluoride-related toxicity in rural Bihar, where groundwater fluoride levels surpass the WHO's 1.5 mg/L standard. In susceptible groups, long-term fluoride exposure has caused bone and dental fluorosis, cognitive deficits, renal issues, and thyroid abnormalities. This study examines societal and infrastructure factors that sustain fluoride toxicity. Technical and financial challenges hinder Reverse Osmosis (RO) and defluoridation unit deployment and maintenance. Groundwater pollution is exacerbated by public misunderstanding and hostility to new water treatment methods. Fluoride levels in Nawada, Rohtas, Gaya, and Bhojpur are 2.7–4.5 mg/L, reflecting the horrible reality. Numerous people have fluorosis. Efficacy and community participation difficulties cause variable success. The report advocates economical and sustainable water filtration technology, regulatory changes to monitor water quality, and fluoride mitigation in climate change adaptation methods to minimize fluoride toxicity. Program sustainability depends on community involvement and vulnerable population education and awareness. Governments, nonprofits, and communities must collaborate to combat fluoride poisoning. Nanofiltration membranes, solar-powered defluoridation systems, rainfall collection, and artificial groundwater replenishment should be researched. A combined strategy using technology, policy, and community participation may minimize fluoride exposure and enhance health.

Keywords: Fluoride Toxicity; Skeletal; Dental Fluorosis; Groundwater; Public Health Impact; Reverse Osmosis; Filtration; Fluoride Accumulation; Vulnerable Populations.

INTRODUCTION

Fluoride occurs naturally in rocks, soil, and water. Small quantities help prevent dental cavities by thickening enamel and making teeth acid-resistant. Fluoride is added to public drinking water and toothpaste to enhance oral health. The balance between helpful and detrimental fluoride exposure is delicate. Fluoride may prevent tooth decay at 0.7 to 1.2 mg/L in water, but excessive use can harm health.

Fluoride exposure over 1.5 mg/L in drinking water is toxic and hazardous to human health, according to the WHO (WHO, 2017). Long-term consumption of water with fluoride concentrations above this limit has been linked to dental fluorosis, which discolors teeth, and skeletal fluorosis, which causes stiffness and joint pain (Bhatnagar et al., 2011). Sustainable measures are needed to reduce the hazards of neurological deficits and thyroid malfunction from prolonged exposure (Chinoy, 2019).

Problem Statement: Fluoride Toxicity from Water Sources

Millions of people worldwide are affected by drinking water fluoride pollution. Geological factors that provide high groundwater fluoride concentrations make India, China, Africa, and sections of Mexico susceptible (Ayoob & Gupta, 2006). In India, 23 states have found fluoride poisoning in groundwater, with severe occurrences in Andhra Pradesh, Rajasthan, and Bihar causing dental and skeletal fluorosis (Dhar & Bhatnagar, 2009). Studies in Kenya and Tanzania

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show that children with high fluoride levels have dental fluorosis, which lowers their quality of life (Mosha et al., 2017).

Fluoride levels are a major issue in rural communities that use groundwater for drinking, particularly those without alternate water sources or filtering methods. In some locations, people drink fluoride-rich well water without knowing the hazards (Kaseva, 2006). Poor infrastructure and public awareness worsen the problem.

Research on fluoride's long-term health effects and mitigating techniques are essential. In resource-constrained areas, filtering methods are expensive and difficult to maintain. Managing fluoride toxicity involves technical solutions, community participation, and legislative initiatives in sustainable water management and public health awareness.

Scope and Objectives of the Study

This study aims to explore the severity of fluoride-related health issues across various regions through the analysis of global case studies. By examining the epidemiological data, this research will highlight how fluoride toxicity impacts vulnerable populations, including children, elderly individuals, and rural communities. Additionally, the study seeks to identify and assess the effectiveness of existing interventions, including filtration technologies like reverse osmosis and community-driven awareness programs.

Specific objectives of this research include:

1. Assessing fluoride-related health problems and their severity across different regions, with a focus on skeletal fluorosis, dental fluorosis, and neurological conditions.
2. Reviewing applied interventions aimed at mitigating fluoride contamination, such as the use of filtration technologies, community engagement, and policy frameworks.
3. Presenting case studies from local and global contexts to provide practical insights into how various regions address the issue. Case studies from India, Africa, and China will illustrate the public health challenges and responses to fluoride toxicity.

By analyzing the health impacts and mitigation strategies, this study aims to contribute to sustainable water management practices. It will also provide recommendations for policymakers, NGOs, and local authorities to enhance fluoride mitigation efforts. This research seeks to bridge the gap between technology and community engagement, advocating for multifaceted interventions that ensure access to safe drinking water.

LITERATURE REVIEW

Historical Background of Fluoride Contamination

The issue of fluoride contamination in water and its impact on human health has been studied extensively since the early 20th century. Initial research identified fluoride's beneficial effects in preventing dental caries, leading to the fluoridation of public water supplies in developed countries (Dean, 1934). However, subsequent investigations revealed that high concentrations of fluoride, typically above 1.5 mg/L, cause adverse health outcomes. India is one of the earliest countries to report skeletal and dental fluorosis in fluoride-endemic regions, particularly in Rajasthan and Andhra Pradesh (Susheela, 2018).

In India, natural fluoride contamination is primarily linked to geological factors such as fluoride-rich rocks and aquifers. Fluoride leaches into groundwater, which is extensively used for drinking purposes, especially in rural areas. The National Rural Drinking Water Programme (NRDWP) recognized fluoride as one of the most critical contaminants requiring attention (GoI, 2019). Historically, efforts in India have been directed toward identifying contaminated regions and setting up pilot defluoridation plants. However, the persistence of fluorosis cases points to gaps in intervention and public awareness.

Mechanisms of Fluoride Toxicity in Humans

Fluoride toxicity can affect multiple systems within the human body, with the bones and teeth being the most vulnerable. Skeletal fluorosis occurs when excess fluoride accumulates in bones, replacing hydroxyl ions in hydroxyapatite crystals. This results in increased bone density but reduced flexibility, leading to joint stiffness, pain, and fractures (Ramesh et al., 2020). Dental fluorosis affects children during tooth development, causing discoloration, enamel erosion, and brittleness. Severe cases lead to pitted teeth and hinder normal oral functions (Mandal et al., 2021). Beyond skeletal and dental effects, fluoride has been associated with neurological, renal, and endocrine dysfunctions. Recent studies suggest that long-term fluoride exposure may impair cognitive abilities and neurological development in children (Kundu & Dutta, 2022). Additionally, fluoride inhibits several enzyme functions by binding to metal ions required for enzymatic activity, disrupting calcium metabolism. This can result in muscle weakness and hypocalcemia (Reddy et al., 2020). Prolonged fluoride exposure is also linked to thyroid suppression, reducing hormone production and impairing metabolic processes, which further exacerbates health risks in malnourished populations.

Epidemiology of Fluoride-Induced Health Issues

India, China, Africa, and South America have high groundwater fluoride concentrations, a worldwide health hazard. With over 23 states reporting fluoride poisoning in drinking water, India is among the most afflicted. Rajasthan, Andhra Pradesh, Telangana, Gujarat, and Bihar are the most afflicted states, where groundwater fluoride levels above the WHO's 1.5 mg/L standard (Mandal et al., 2021). The Central Ground Water Board (CGWB, 2020) reported that polluted water puts over 66 million Indians at risk of fluorosis. Rural populations without treated water have a greater rate of skeletal and dental fluorosis worldwide. In Kenya and Tanzania, fluoride levels surpass permissible limits, producing dental fluorosis in youngsters and mobility difficulties in adults (Ramesh et al., 2020). China finds developmental delays and cognitive impairments in children exposed to fluoride-rich water (Kundu & Dutta, 2022).

Age, diet, water use, and socioeconomic status affect fluorosis outcomes in India. Dental fluorosis is more likely in children and teenagers because fluoride exposure during tooth development may cause irreparable harm. Physically active adults are at risk for skeletal fluorosis because water consumption increases fluoride exposure. Poor nutrition, especially calcium and magnesium shortages, worsens fluoride poisoning by affecting bone health (Mandal et al., 2021). Due to the lack of alternate drinking water sources and water treatment facilities, rural residents who rely on groundwater are exposed to more fluoride.

Socioeconomic issues also affect mitigating technology and healthcare access. Fluoride exposure concerns are poorly understood in certain countries, delaying diagnosis and treatment. Community awareness programs, innovative filtration technology, and local and national policy changes are needed to address these issues (GoI, 2019).

CASE STUDIES ON FLUORIDE-INDUCED HEALTH ISSUES

Fluoride Contamination in India: Bihar Case Studies

Groundwater fluoride poisoning in Bihar is one of India's most afflicted states. According to Mandal et al. (2021), Nawada, Rohtas, Gaya, and Bhojpur are fluoride-endemic districts with amounts over the WHO limit of 1.5 mg/L. Rural communities have extensive skeletal and dental fluorosis due to overreliance on groundwater and a lack of other water sources. Adult agricultural workers, who drink a lot of water, often develop skeletal fluorosis, which causes joint discomfort, stiffness, and mobility issues (Kumar et al., 2022). Dental fluorosis, which affects children and teenagers, causes enamel discolouration, pitting, and erosion, hurting self-esteem and dental health. Long-term fluoride exposure might develop bone abnormalities that restrict livelihood prospects (Ramesh et al., 2020).

Impact of High Fluoride Levels on Skeletal Fluorosis and Community Health

In fluoride-endemic areas of Bihar, fluoride concentrations often exceed the WHO-recommended limit of $1.5\mathrm{mg/L}$. As residents depend heavily on untreated groundwater, fluoride accumulation has led to severe health issues such as skeletal fluorosis and dental fluorosis (Mandal et al., 2021). Skeletal fluorosis is described by the following accumulation equation:

$$C_f(t) = \int_0^t F(t) \cdot I(t) dt$$

Where:

- $C_f(t) =$ Cumulative fluoride level in the human body at time t.
- $F(t)$ = Daily fluoride intake ($\mathrm{mg/L}$) from water consumption.
- $I(t) =$ Volume of water intake per day (L).

When fluoride concentrations in water exceed $1.5\mathrm{mg/L}$ and water intake is high (e.g., 3-4 liters daily among manual laborers), the cumulative fluoride content increases the risk of fluorosis. This toxic accumulation affects bone structure, leading to reduced flexibility and increased stiffness.

Overview of Interventions in Different Areas of Bihar

Various interventions, including reverse osmosis (RO) filtration units and community defluoridation plants, have been implemented in districts such as Nawada, Rohtas, and Bhojpur. The following table provides an overview of fluoride levels and intervention outcomes in these areas:

Table.1: Fluoride Levels, Population Impact, and Intervention Outcomes by District

District	Fluoride Levels (mg/L)	Population Affected	Type of Intervention	Outcome
Nawada	3.1	5,000	RO Filtration Unit	Reduced fluoride levels in schools and public spaces
Rohtas	2.8	8,500	Defluoridation Plant	Reduction in dental fluorosis cases by 20% over two years
Gaya	4.5	10,000	RO Filtration at Homes	Operational issues due to high maintenance costs
Bhojpur	2.7	6,200	Water Tanker Service	Reduced fluoride exposure but water supply inconsistent

The table highlights the need for sustainable and reliable solutions. In several areas, interventions showed initial success, but operational challenges, such as maintenance and high costs, limited long-term effectiveness (PHED Bihar, 2020).

Analysis of Health Impacts and Government-Led Water Treatment

The cumulative effect of high fluoride levels has resulted in physical disabilities among adults, with cases of severe skeletal fluorosis reported in Bhojpur and Rohtas. Fluoride accumulation in the bones over time leads to joint immobilization, described by the following toxicity index equation:

$$TI = \frac{C_f(t)}{BMC}$$

Where:

- $TI =$ Toxicity index (fluoride concentration per bone mineral content).
- $BMC =$ Bone mineral content, typically between 500 to $1000 \mathrm{mg/cm}^2$ for healthy individuals.

When the toxicity index exceeds a critical threshold, individuals are diagnosed with skeletal fluorosis. In regions where fluoride contamination persists, $30-40\%$ of the adult population has shown symptoms of fluorosis, impacting their ability to work and maintain livelihoods (Kumar et al., 2022).

Fluoride Exposure and Resulting Neurological Conditions in Children

Neurological impairments among children in Bihar have been observed in areas where fluoride levels exceed $2.5 \mathrm{mg/L}$. Research shows that prolonged fluoride exposure affects cognitive development. The impact of fluoride on children's IQ scores can be modeled using the following regression equation:

$$IQ = \alpha - \beta \cdot C_f$$

Where:

- $IQ =$ Predicted IQ score.
- $\alpha =$ Baseline IQ score without fluoride exposure (typically 100).
- $\beta =$ Impact factor, representing the reduction in IQ per unit increase in fluoride.
- $C_f =$ Cumulative fluoride concentration in $\mathrm{mg/L}$.

Studies in Nawada showed that children exposed to fluoride-rich water had an IQ reduction of 8-12 points compared to children consuming fluoride-free water (Kundu & Dutta, 2022). In regions with poor nutrition, the cognitive decline was more pronounced, indicating that malnutrition exacerbates fluoride's neurological effects.

Lessons Learned from Public Health Interventions

Several important lessons have emerged from fluoride mitigation efforts in Bihar:

1. Community engagement is critical. Programs involving local stakeholders, including teachers and health workers, have higher adoption rates.
2. Affordable technologies, such as rainwater harvesting, offer long-term solutions compared to high-maintenance filtration units.
3. Inter-agency collaboration is essential for sustainability. Partnerships between the Public Health Engineering Department (PHED) and NGOs like UNICEF have enhanced the reach and impact of interventions.
4. Targeted interventions focused on children are crucial, as early fluoride exposure can lead to irreversible health damage. Schools equipped with filtration systems have shown improved health outcomes.

Operational challenges, such as high maintenance costs and lack of technical expertise, hinder the effectiveness of defluoridation plants. Strengthening monitoring systems and training programs for local technicians will be essential for sustainable fluoride mitigation efforts.

HEALTH IMPACTS OF FLUORIDE TOXICITY

Skeletal Fluorosis and Dental Fluorosis

Skeletal and dental fluorosis are two major health conditions caused by excessive fluoride exposure. Skeletal fluorosis manifests as bone pain, joint stiffness, and in advanced stages, deformities and immobility. Dental fluorosis occurs during tooth development in children and results in discoloration, pitting, and erosion of enamel. Diagnosing skeletal fluorosis can be challenging, especially in rural settings, because it mimics conditions such as arthritis. The diagnosis is confirmed through bone mineral density (BMD) tests and fluoride concentration analysis in the patient's urine and serum.

Mathematical Model for Fluoride Accumulation

Fluoride accumulates in bones over time. The cumulative concentration Cf(t)C_f(t)Cf(t) of fluoride in the body is modeled by the following fluoride accumulation equation:

$$C_f(t) = \int_0^t F(t) \cdot I(t) dt$$

Where:

- $C_f(t) =$ Cumulative fluoride level in the human body at time t.
- $F(t)$ = Daily fluoride intake (mg/L) from water consumption.
- $I(t) =$ Volume of water intake per day (L).

When $C_f(t)$ exceeds 6mg/L in bones, symptoms of skeletal fluorosis become apparent (Reddy et al., 2020).

Impact on Neurological Functions

Recent research indicates that prolonged fluoride exposure has significant effects on brain development. Children exposed to high fluoride concentrations exhibit cognitive deficits and learning disabilities. Regression Model for IQ Decline due to Fluoride Exposure

The following linear regression equation models the relationship between fluoride exposure and IQ:

$$IQ = 100 - \beta \cdot C_f$$

Where:

- $IQ =$ Predicted IQ score.
- $100 =$ Average baseline IQ in fluoride-free environments.
- $\beta =$ Regression coefficient (typically $0.6 - 1.0$IQ points decrease per mg/L fluoride).
- $C_f =$ Fluoride concentration in drinking water (mg/L).

A study in Nawada district, Bihar, revealed that children consuming water with fluoride levels of 2.5 mg/L had an average IQ reduction of 8 points (Kundu & Dutta, 2022).

Organ Damage and Other Health Implications

Fluoride exposure affects internal organs, particularly the kidneys and thyroid glands.

Effects on Kidneys and Thyroid Glands:

- Kidneys: Fluoride accumulation impairs kidney function, measured by creatinine levels in the blood. The following equation models renal function decline due to fluoride exposure:

$$eGFR = \frac{140 - \text{ Age}}{\text{Serum Creatinine (mg/dL)}} \cdot (0.85 \text{ if female })$$

Where:

- $eGFR =$ Estimated Glomerular Filtration Rate, indicating kidney health.
- Age = Age of the individual.

In fluoride-affected regions, individuals show a decline in eGFR, indicating compromised kidney function (Ramesh et al., 2020).

- Thyroid glands: Chronic fluoride exposure interferes with iodine absorption, resulting in hypothyroidism, with symptoms such as fatigue, weight gain, and depression (Mandal et al., 2021).

Table.2: Summary of Health Impacts

Health Condition	Fluoride Concentration (mg/L)	Symptoms	Diagnostic Test	Affected Population
Skeletal Fluorosis	> 4.0	Joint pain, stiffness, deformities	BMD Test, Serum Fluoride Test	Adults in rural Bihar
Dental Fluorosis	1.5–4.0	Tooth discoloration, enamel erosion	Visual Inspection, Fluoride Analysis	Children (ages 6–15)
Cognitive Impairment	> 2.5	Reduced IQ, learning disabilities	IQ Test, Neurological Screening	Children (ages 8–12)
Kidney Dysfunction	> 3.0	Elevated creatinine, reduced eGFR	Serum Creatinine Test, eGFR Calculation	Adults with prolonged exposure
Thyroid Dysfunction	> 1.5	Fatigue, weight gain, depression	Thyroid Function Test (TSH, T3, T4)	Pregnant women, elderly

CHALLENGES IN FLUORIDE MITIGATION

Technical and Financial Barriers

Filtration technologies such as reverse osmosis (RO), activated alumina, and bone char filters are effective in removing fluoride from drinking water. However, the initial setup cost and operational expenses pose significant challenges for deployment, especially in rural Bihar. RO systems, for example, require frequent maintenance, skilled technicians, and reliable electricity—resources that are scarce in many parts of the state. Villages in districts like Rohtas, Nawada, and Bhojpur have reported operational failures in government-funded filtration plants due to neglect, breakdowns, and lack of repair services (Kumar et al., 2022). Mathematically, the total cost (C) of fluoride mitigation using filtration systems can be represented as:

$$C = C_i + \sum_{t=1}^{n} (C_m + C_o)$$

Where:

- C_i = Initial installation cost
- C_m = Maintenance cost per time unit t
- C_o = Operational cost per time unit t
- n = Number of time units over the plant's lifetime

The cumulative cost often exceeds local budgets, leading to non-functional plants. Many households also cannot afford individual RO units, forcing residents to rely on contaminated groundwater (PHED Bihar, 2020).

In rural Bihar, scarcity of technical expertise and the unavailability of spare parts hinder the effective maintenance of defluoridation units. Furthermore, the uneven distribution of water treatment infrastructure leaves many remote villages dependent on contaminated groundwater sources. Transporting fluoride-free water from neighboring areas is not always feasible, making it difficult for residents to access safe drinking water consistently.

Lack of Public Awareness and Compliance

Public health initiatives aimed at promoting fluoride-free drinking water face resistance in some communities due to lack of trust in new technologies. Many rural households continue to use groundwater because it is easily accessible and they are unaware of the long-term health risks posed by fluoride. In addition, traditional beliefs about water purity discourage the adoption of filtration technologies and tanker-based water supplies (Kundu & Dutta, 2022).

Sustained fluoride mitigation efforts require active community participation. However, many intervention programs struggle with low engagement levels once initial awareness campaigns end. Without continuous monitoring and reinforcement, the adoption of safer water practices declines over time. Schools and health centers can play a crucial role in reinforcing these practices, but inconsistent outreach efforts limit their effectiveness.

Policy Gaps and Implementation Issues

There are significant disparities in the availability of water treatment infrastructure between urban and rural areas in Bihar. Urban areas benefit from centralized water treatment plants that can maintain fluoride concentrations within safe limits. In contrast, rural areas often lack even basic filtration systems and depend heavily on groundwater, which is often untreated. These infrastructure gaps make it difficult to ensure uniform access to safe drinking water (Mandal et al., 2021).

Table.3: Compares fluoride mitigation infrastructure across urban and rural regions of Bihar:

Parameter	**Urban Areas**	**Rural Areas**
Water Treatment Facilities	Centralized plants, well-maintained	Small-scale units, often non-functional
Monitoring and Maintenance	Regular monitoring by authorities	Infrequent monitoring
Community Engagement	Moderate community involvement	Low community participation
Access to Safe Water	Relatively high	Low to moderate

Although regulatory frameworks such as the National Rural Drinking Water Programme (NRDWP) exist to monitor water quality, enforcement gaps hinder effective fluoride mitigation. In many rural areas, regulations are not strictly followed, and groundwater usage remains unregulated, resulting in excessive fluoride exposure (PHED Bihar, 2020). Furthermore, coordination issues between local, state, and central authorities delay the implementation of mitigation measures.

RECOMMENDATIONS

Advancing Water Purification Technologies

To address the economic challenges associated with fluoride mitigation, it is crucial to develop affordable and scalable defluoridation technologies. Innovations such as activated alumina filters, nano-filtration membranes, and electrocoagulation methods show potential for cost-effective fluoride removal. These technologies must be optimized for low maintenance and easy deployment in rural areas where technical expertise is limited. Local governments, academic institutions, and private enterprises should collaborate on pilot projects to assess the effectiveness of these technologies in fluoride-endemic areas like Bihar. Additionally, research must focus on reducing the waste by-products generated by filtration processes, which could otherwise pose environmental risks.

Enhancing Community Engagement

Successful fluoride mitigation requires collaborative efforts among multiple stakeholders, including governments, NGOs, and local governing bodies. Each stakeholder brings unique resources and expertise to the table:

- Governments provide infrastructure and policy frameworks.
- NGOs engage in community awareness campaigns and capacity building.
- Local bodies facilitate the implementation of interventions at the grassroots level.

Collaboration ensures sustainable intervention models by promoting ownership at the community level. Joint monitoring and shared responsibilities enhance program longevity and impact.

Intervention programs must focus on vulnerable groups, particularly children and the elderly, who are at greater risk of fluoride toxicity. School-based programs should integrate fluoride-free drinking water systems, health check-ups, and nutritional support to prevent dental and skeletal fluorosis among children. Elderly-focused programs can offer periodic health screenings to detect fluoride-induced disorders early and provide alternative water sources where necessary. Programs must also involve training community health workers to conduct awareness campaigns and educate households on safe water practices.

Policy Recommendations for Governments

Governments need to prioritize the development of water quality testing infrastructure at the grassroots level to enable regular fluoride monitoring. Decentralized water testing laboratories should be set up at the block or village level, reducing the dependency on urban centers for testing. These laboratories can offer low-cost testing kits and train local personnel to conduct routine assessments. Regular water testing will allow authorities to detect contamination early and implement preventive measures swiftly.

Table.4: Outlines key actions to strengthen water testing infrastructure

Action	Impact	Implementation Strategy
Decentralized water labs	Early detection of contamination	Establish labs at block/village levels
Training for local technicians	Efficient testing and maintenance	Government and NGO collaboration
Public access to test results	Greater accountability	Publish results online and in public forums

CONCLUSION

Fluoride poisoning is a major public health issue in fluoride-endemic areas like Bihar, where groundwater fluoride levels surpass the WHO's 1.5 mg/L guideline. Long-term exposure causes bone and dental fluorosis, neurological deficits, renal problems, and thyroid abnormalities. Children and the elderly are disproportionately afflicted, having physical and cognitive obstacles. Early diagnosis, knowledge, and sustainable fluoride-free drinking water are needed to combat fluoride poisoning. To reduce fluoride toxicity, many approaches are needed. Policy improvements must accompany technological interventions like inexpensive filtration devices to monitor water quality. Decentralized water testing infrastructure may detect pollution early, particularly in rural regions with limited clean water availability. AI and IoT in water monitoring systems provide real-time data collecting, improving mitigation efforts. Fluoride mitigation initiatives need community support to succeed. Governments, NGOs, and local governments must collaborate on vulnerable population awareness initiatives. Schools and health facilities may promote healthy water use via education. Future research should produce eco-friendly, cost-effective mitigating solutions. Nano-filtration membranes with solar-powered defluoridation might solve economic and environmental issues. Sustainable alternatives to fluoride-contaminated sources include rainwater collecting and artificial groundwater recharge. Policy frameworks should integrate fluoride mitigation with climate adaptation to provide resilient water management systems.

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