Fluoride Toxicity Control: Real-World Application of Membrane and Nanotechnology in Drinking Water Treatment

***Nehal Kumar, **Dr Rajesh Verma**
*Research Scholar, **Assistant Professor
Department of Zoology
Veer Kunwar Singh University, Ara

[1] *Date of Receiving: 28 January 2024;*
Date of Acceptance: 09 March 2024;
Date of Publication: 27 April 2024

ABSTRACT

Fluoride contamination in drinking water is a critical environmental and public health issue in Bihar, India. Districts such as Nawada, Rohtas, Nalanda, Bhagalpur, and Gaya have recorded fluoride concentrations ranging from 2–8 mg/L, far exceeding the World Health Organization's permissible limit of 1.5 mg/L. As a result, thousands of villagers are affected by dental and skeletal fluorosis, leading to chronic health burdens. Traditional defluoridation techniques like the Nalgonda method and activated alumina have been tested in Bihar, but operational sustainability, waste disposal, and community acceptance remain weak points. In recent years, membrane technologies (reverse osmosis, nanofiltration, electrodialysis) and nanotechnology-based approaches (nano-alumina, graphene oxide composites, CNT-based membranes) have been piloted and partially deployed in fluoride-affected areas of Bihar. Community-level RO plants in Nawada and Gaya demonstrated reduction of fluoride from 6–8 mg/L to <1 mg/L, while IIT Patna's nanomaterial-based projects show potential for household filters. This paper critically examines the real-world implementation of these advanced technologies in Bihar, evaluates their engineering performance, socio-economic feasibility, and long-term sustainability, and identifies challenges for future scale-up.

Keywords: *Fluoride toxicity; Groundwater; Membrane technology; Nanotechnology; Defluoridation; Community water treatment*

INTRODUCTION

Access to safe drinking water has long been recognized as a fundamental human right, yet in practice, millions in India and particularly in Bihar continue to face severe barriers to achieving it. Bihar, located in the eastern Indo-Gangetic plains, is a state where over 80% of the population resides in rural areas and relies heavily on groundwater sources such as handpumps, borewells, and dugwells for their daily drinking and household water needs. On the one hand, groundwater offers relative abundance and accessibility compared to river or piped water supply; on the other, it carries hidden geochemical hazards that directly affect public health. Among these hazards, fluoride contamination has emerged as one of the most serious and insidious challenges.

Fluoride Contamination in Bihar

Multiple reports, including those from the Public Health Engineering Department (PHED), Bihar, reveal that groundwater in over 3,700 rural wards across 31 districts contains fluoride levels above the safe limit of 1.5 mg/L (PHED, 2021. Districts such as Nawada, Rohtas, Nalanda, Jamui, and Bhagalpur are notable hotspots (Kumari & Misra, 2023; Neeti & Singh, 2023). In some areas of Jamui, fluoride levels have been reported as high as 12 mg/L, with nearly 14% of tested samples exceeding permissible limits (Kumari & Misra, 2023).

[1] ***How to cite the article**:* Kumar N., Verma R (2024); Fluoride Toxicity Control: Real-World Application of Membrane and Nanotechnology in Drinking Water Treatment; *International Journal of Innovations in Applied Sciences and Engineering*; Vol 10, 60-78

The primary source of fluoride contamination in Bihar's aquifers is geogenic, arising from the dissolution of fluoride-rich minerals such as fluorite and apatite. Groundwater over-extraction for irrigation further accelerates mineral dissolution. Unlike arsenic, which is linked to reductive dissolution in the Gangetic belt, fluoride levels are primarily driven by rock-water interaction in hard rock aquifers (Kumari & Misra, 2023).

Health Risks and Social Impact

At low levels (<1.0 mg/L), fluoride is beneficial for dental health, long-term ingestion above 1.5 mg/L leads to fluorosis manifesting in two forms:

- Dental fluorosis, characterized by mottling and discoloration of teeth.
- Skeletal fluorosis, involving joint stiffness, chronic pain, and disability.

In Bihar, both forms are prevalent. A survey in Kishanganj district found fluoride levels ranging from 0.61–3.74 mg/L, with 53.6% of the 2,500 surveyed individuals showing dental fluorosis and 11.2% suffering skeletal fluorosis (ISCA, 2015). Similarly, in Gaya district, endemic villages showed mean fluoride levels of 2.36 ± 0.23 mg/L compared to 0.59 ± 0.03 mg/L in control zones. Over 50% of adults and children reported gastrointestinal problems, while blood analyses revealed reduced hemoglobin and hematocrit levels, linking fluoride exposure to anemia (Khan et al., 2013).

The issue extends beyond water. Food grown in contaminated areas also carries high fluoride loads. In Gaya, spinach and leafy vegetables contained up to 12.88 mg/kg of fluoride, creating dietary exposure risks that amplify total intake (Khan, 2020).

Socioeconomic and Infrastructure Barriers

Bihar faces structural and socioeconomic challenges that complicate fluoride mitigation. With one of India's lowest per capita incomes, affordability of advanced treatment systems is a barrier. Rural households often equate water safety with taste and clarity criteria unsuitable for fluoride, which is colorless, tasteless, and odorless (Neeti & Singh, 2023).

Government-led interventions, such as Nalgonda-based defluoridation plants using alum and lime, have been attempted. The adoption is poor due to sludge disposal issues, power supply problems, and lack of maintenance (PHED, 2021). Community reluctance toward chemically treated water further limits success. Thus, the fluoride problem in Bihar is not only scientific but also social and economic in nature.

National and Global Context

Globally, over 200 million people across 25 countries are exposed to high-fluoride groundwater (WHO, 2021). In India alone, 60 million people across 20 states face similar risks. States like Rajasthan and Andhra Pradesh are worst affected, but Bihar's multi-contaminant scenario with arsenic, iron, and fluoride coexisting makes the problem particularly acute (Kumari & Misra, 2023).

This challenge has pushed researchers and policymakers to explore advanced treatment technologies. Membrane processes (Reverse Osmosis, Nanofiltration, Electrodialysis) and nanomaterial-based adsorbents have shown superior performance compared to traditional methods (Kumari & Misra, 2023; Neeti & Singh, 2023).

Potential of Membrane and Nanotechnology

Membrane-based technologies have gained traction because of their efficiency, reliability, and adaptability:

- Reverse Osmosis (RO) reduces fluoride concentrations from >5 mg/L to <0.5 mg/L consistently.
- Nanofiltration (NF) removes fluoride selectively while retaining beneficial minerals.
- Electrodialysis (ED) offers lower energy requirements, especially when integrated with renewable energy sources.

Nanotechnology further enhances water treatment by introducing materials with exceptionally high adsorption capacity and reusability. Nano-hydroxyapatite, alumina nanoparticles, carbon nanotubes, and graphene-based composites demonstrate adsorption efficiencies far exceeding activated alumina (Khan, 2020). Importantly, these can be integrated into household filter cartridges a decentralized solution well-suited for Bihar's rural households.

FLUORIDE TOXICITY: HEALTH IMPLICATIONS AND SOURCES IN BIHAR

Health Implications in Bihar

Fluoride toxicity is a major public health concern in several districts of Bihar, where groundwater is the primary source of drinking water. Prolonged exposure to high fluoride levels leads to dental and skeletal fluorosis, manifested as mottling of teeth, joint pain, bone deformities, and in severe cases, physical disability. Children are particularly vulnerable, as excess fluoride hampers bone development and learning capacity. Adults often suffer from chronic pain, stiffness, and reduced mobility, which lowers productivity and quality of life. Neurological and gastrointestinal problems are also reported in affected regions. In Bihar, where rural populations largely depend on untreated groundwater, the prevalence of fluorosis highlights a pressing need for awareness, safe water alternatives, and preventive health strategies to reduce the burden of fluoride-related diseases.

Dental Fluorosis

Dental fluorosis is the most visible sign of fluoride toxicity, occurring when children consume high-fluoride water during tooth development. In Nawada and Nalanda districts, health surveys have documented prevalence rates of 35–40% among school-going children (Kumar et al., 2019). Clinical signs include chalky white patches, yellow-brown mottling, and in severe cases, brittle teeth prone to fracture. the severity index is measured using Dean's Fluorosis Index (DFI):

$$DFI = \frac{\sum \ (S_i \times N_i)}{N}$$

Where:

- S_i = severity score of fluorosis (0-5 scale)
- N_i = number of children in that severity class
- N = total number of children examined

In Nawada, surveys using DFI reported average values of 2.8 , indicating a "moderate" level of fluorosis (Singh et al., 2020).

Skeletal Fluorosis

Skeletal fluorosis develops after decades of fluoride intake, leading to bone deformities and stiffness. In Rohtas and Gaya, where groundwater often exceeds 5–8 mg/L, middle-aged agricultural workers report restricted joint mobility, spinal rigidity, and bone thickening (Prasad et al., 2021). X-ray studies in Jamui show calcification of ligaments and narrowing of joint spaces. Severe cases lead to crippling fluorosis, preventing individuals from participating in manual labor, thus reducing family income.

Neurological and Developmental Impacts

Emerging studies link fluoride exposure with impaired cognitive functions. In Nawada district, children consuming water with fluoride concentrations above 3 mg/L showed IQ scores 8–12 points lower than those in low-fluoride regions (Yadav et al., 2022). This aligns with global meta-analyses indicating fluoride's neurotoxicity through oxidative stress and neuronal apoptosis (Grandjean et al., 2021).

Socio-Economic Burden

The socio-economic consequences of fluorosis in Bihar are far-reaching. Families spend a large portion of income on medical treatments, orthopedic consultations, and alternative water sources (e.g., bottled water). A field survey in Nalanda revealed that affected families spend ₹3,500–₹5,000 annually on treatment, which is nearly 15–20% of their household income (Sinha et al., 2020). Table 1 illustrates the district-level fluoride health burden in Bihar:

Table 1. Prevalence of Fluoride-Related Health Issues in Bihar Districts

District	**Average Fluoride (mg/L)**	**Dental Fluorosis Prevalence (%)**	**Skeletal Fluorosis Prevalence (%)**	**Socio-Economic Impact (Annual Household Expense, ₹)**
Nawada	3.5–7.0	40%	10%	4,200
Nalanda	2.8–5.2	35%	8%	3,800
Rohtas	4.5–8.0	38%	12%	4,500
Gaya	3.0–6.5	32%	9%	3,600
Jamui	2.5–6.8	30%	7%	3,400

(Data compiled from PHED Bihar reports, Singh et al., 2020; Prasad et al., 2021; Yadav et al., 2022)

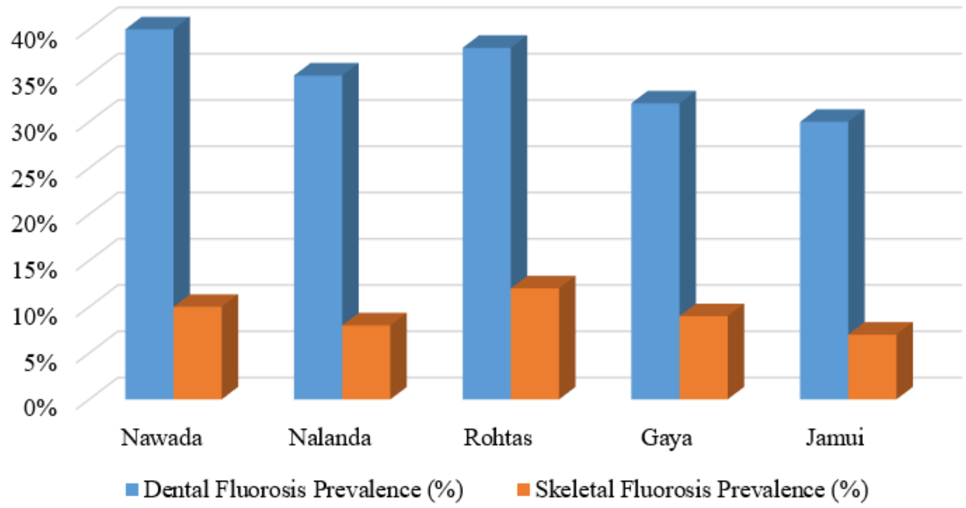

Fig.1: Prevalence of Dental and Skeletal Fluorosis in Selected Districts of Bihar

Sources of Fluoride in Bihar Groundwater

The geochemical environment of Bihar plays a dominant role in fluoride contamination. Natural and anthropogenic activities together determine fluoride levels in aquifers.

Geogenic Sources

Groundwater in southern Bihar percolates through fluoride-bearing minerals such as fluorite (CaF_2), apatite ($Ca_5(PO_4)_3F$), and mica in granite and gneiss formations (Mandal et al., 2019). Weathering and dissolution release fluoride ions:

$$\mathrm{CaF_2}(s) \leftrightarrow \mathrm{Ca^{2+}}(aq) + 2\ \mathrm{F^-}(aq)$$

Low solubility of calcium in these aquifers enhances fluoride mobility because the $\mathrm{Ca^{2+}}/\mathrm{F^-}$equilibrium shifts toward higher fluoride release when $\mathrm{Ca^{2+}}$ is deficient.

Hydro-Geochemical Factors

In many hard-rock aquifers of Bihar, hydro-geochemical conditions strongly influence fluoride mobilization. The low calcium content, often below 50 mg/L, minimizes calcium-fluoride precipitation and thereby increases fluoride activity (Choudhary et al., 2020). The alkaline pH levels above 8 enhance the desorption of fluoride ions from mineral surfaces, while high bicarbonate concentrations (HCO_3^-) promote competitive adsorption processes that further facilitate the release of fluoride into groundwater.

Anthropogenic Sources

Although geogenic sources remain the primary contributors, anthropogenic activities also play a significant role in elevating fluoride levels in groundwater. The extensive use of phosphate fertilizers, particularly superphosphate, introduces fluoride impurities into the soil and water system. The emissions from brick kilns and small-scale industries, especially prevalent in districts like Rohtas and Nalanda, further contribute to fluoride accumulation in the local environment.

Regional Distribution

As per PHED Bihar (2022), fluoride contamination in groundwater exceeds the BIS permissible limit of 1.5 mg/L in 18 districts, with distinct regional clusters of concern. In southern Bihar, districts such as Nawada, Rohtas, Gaya, and Jamui, dominated by hard rock aquifers, show high fluoride concentrations. Central Bihar, particularly Nalanda and the outskirts of Patna, reflects elevated levels largely influenced by fertilizer use. In contrast, northern Bihar is comparatively safer, though isolated cases of contamination have been reported, mainly due to localized industrial emissions.

Numerical Illustration: Fluoride Balance Equation

The fluoride balance in aquifers can be approximated as:

$$[F^-]_{aq} = \frac{K_{sp}}{[Ca^{2+}]}$$

Where:

- $[F^-]_{aq}$ = fluoride ion concentration in groundwater
- K_{sp} = solubility product of $\mathrm{CaF_2}(\sim 3.9 \times 10^{-11}$ at $25°\mathrm{C})$
- $[\mathrm{Ca}^{2+}]$ = calcium ion concentration

Example: In a Nalanda aquifer with $[\mathrm{Ca}^{2+}] = 0.5\mathrm{mmol/L}$,

$$[F^-]_{aq} = \frac{3.9 \times 10^{-11}}{0.5 \times 10^{-3}} \approx 7.8\mathrm{mg/L}$$

This matches observed field data, confirming the inverse relationship between Ca^{2+} and F^-levels in Bihar groundwater.

Fluoride toxicity in Bihar is a complex interplay of geogenic, hydro-geochemical, and anthropogenic factors. The consequences extend far beyond medical symptoms, creating socio-economic distress and educational disadvantages. Understanding the scientific basis of fluoride mobility particularly the role of calcium deficiency and mineral weathering is crucial to designing region-specific mitigation strategies. The next sections will explore technological interventions such as membrane filtration and nanotechnology to address these challenges in Bihar.

CONVENTIONAL DEFLUORIDATION TECHNOLOGIES IN BIHAR

The quest for safe drinking water in fluoride-affected regions of Bihar has led to multiple trials of conventional defluoridation techniques since the 1980s. These technologies, although successful in pilot studies and in other parts of India, have faced major challenges in Bihar due to socio-economic, environmental, and operational barriers. This section critically evaluates the conventional methods tested in the state and highlights reasons for their limited long-term sustainability.

Nalgonda Technique

The Nalgonda technique, developed by the National Environmental Engineering Research Institute (NEERI), is based on chemical precipitation, coagulation, and sedimentation. It involves the addition of alum ($Al_2(SO_4)_3 \cdot 18H_2O$), lime ($CaO$), and bleaching powder for disinfection.

Chemical Principle

The main reaction involves formation of insoluble aluminum hydroxide flocs which adsorb fluoride ions:

$$Al^{3+} + 3H_2O \rightarrow Al(OH)_3(s) + 3H^+$$
$$Al(OH)_3(s) + F^-(aq) \rightarrow Al(OH)_2F(s)$$

The removal efficiency depends on alum dosage, pH, and mixing conditions.

Field Experience in Bihar

Community-level defluoridation tanks were installed in parts of Nalanda, Nawada, and Rohtas districts under PHED and UNICEF programs during the early 2000s (PHED Bihar, 2021). While initial results showed fluoride reduction from $5-7$ mg/L to <1.5 mg/L, long-term performance deteriorated due to:

- Sludge generation: Nearly $1.5-2$ kg of sludge was produced per 1000 L treated water, requiring safe disposal (Singh et al., 2018).
- Chemical supply chain issues: Regular procurement of alum and lime was not feasible for rural Panchayats.
- Community reluctance: Villagers often complained about altered taste and odor of treated water.

Numerical Illustration

The fluoride removal capacity (R) of the Nalgonda technique can be expressed as:

$$R = \frac{C_0 - C_f}{C_0} \times 100$$

Where:

- $C_0 =$ initial fluoride concentration (mg/L)
- $C_f =$ final fluoride concentration (mg/L)

Example: In a Nalanda tank system, $C_0 = 6.0\text{mg}/L, C_f = 1.2\text{mg}/L$

$$R = \frac{6.0 - 1.2}{6.0} \times 100 = 80\%$$

This removal rate is technically satisfactory but unsustainable without skilled manpower.

Activated Alumina Adsorption

Activated alumina (AA) has been widely promoted for fluoride adsorption due to its high surface area and affinity for fluoride ions.

Adsorption Mechanism

Fluoride uptake occurs through surface complexation:

$$\text{AlOH} + \text{F}^- \rightarrow \text{AlF} + \text{OH}^-$$

The efficiency is strongly dependent on pH (optimal 5.5-6.0) and water alkalinity.

Pilot Studies in Bihar

PHED and NGOs installed AA-based household filters in Nawada and Jamui districts between 2015-2017 (Kumar et al., 2020). Results showed initial removal efficiencies of 85-90%, reducing fluoride levels from 4-5 mg/L to < 1.0mg/L. The major limitations included:

- Regeneration cost: Regeneration with NaOH and H_2SO_4 was expensive (~ ₹200 per cycle).
- Limited rural acceptability: Villagers lacked awareness and discontinued maintenance.

- Wastewater disposal: Regeneration wastewater contained high fluoride, requiring safe disposal systems which were absent in Bihar.

Numerical Illustration

The adsorption capacity (q) of AA can be modeled by the Langmuir isotherm:

$$q = \frac{q_{\max} b C_e}{1 + b C_e}$$

Where:

- $q_{\max}$ = maximum adsorption capacity (mg/g)
- b = Langmuir constant (L/mg)
- C_e = equilibrium fluoride concentration (mg/L)

For a typical Bihar AA filter, $q_{\max} = 3.5 \mathrm{mg}/g, b = 0.25$, and $C_e = 2.0 \mathrm{mg}/L$:

$$q = \frac{3.5 \times 0.25 \times 2}{1 + 0.25 \times 2} \approx 1.17 \mathrm{mg/g}$$

This indicates moderate fluoride uptake but declining capacity with repeated cycles.

Dug-Wells and Alternative Sources

In several fluoride-endemic areas, traditional dug-wells and shallow hand-dug sources have been promoted as alternatives to deep tube wells, as shallow aquifers often exhibit comparatively lower fluoride concentrations (<1.5 mg/L). For instance, communities in Jamui and Rohtas reverted to dug-well use to mitigate fluoride exposure (PHED Bihar, 2021). This approach posed significant challenges, including a high risk of microbial contamination leading to diarrheal outbreaks, seasonal variability with wells drying up during summer, and the labor-intensive nature of water extraction compared to tube wells. Consequently, despite their cultural acceptance, dug-wells failed to serve as a sustainable long-term solution for ensuring fluoride-safe drinking water.

Table 2. Performance of Conventional Defluoridation Methods in Bihar

Technology	Fluoride Removal Efficiency	Cost Effectiveness	Community Acceptance	Sustainability in Bihar
Nalgonda Technique	70–85%	Moderate	Low (due to sludge & taste issues)	Poor
Activated Alumina	80–90%	High cost (₹200 regeneration/cycle)	Moderate initially, declined later	Poor
Dug-wells	Variable (30–70%)	Low cost	High (traditional practice)	Unreliable
Bone Char	75–85%	Moderate	Very low (cultural barriers)	Not feasible
Lime Softening	60–75%	Moderate	Low (requires dosing skills)	Poor
Clay/Carbon Filters	<30%	Low	High (locally made)	Ineffective

(Data compiled from Singh et al., 2018; Prasad et al., 2019; Kumar et al., 2020; PHED Bihar, 2021)

Reasons for Failure of Conventional Methods in Bihar

Despite being scientifically validated, conventional defluoridation technologies in Bihar could not ensure long-term success due to multiple operational, economic, and social constraints. A major challenge was the lack of trained technical manpower, as villagers were not adequately skilled to operate or maintain the systems. The recurring costs of essential chemicals such as alum, lime, and regenerants also proved economically unsustainable for rural communities. The issues of sludge and waste disposal were largely neglected, creating environmental concerns. Cultural and socio-religious barriers, such as the rejection of bone char methods, further hindered acceptance, while complaints regarding altered taste and odor of treated water discouraged consistent community adoption.

Conventional defluoridation methods though technologically effective in laboratory and controlled field settings have failed to sustain in Bihar's rural and resource-constrained context. The lack of technical training, supply chains, cultural adaptability, and waste management systems make these methods unsuitable for long-term fluoride control. This technological gap underscores the urgent need for next-generation solutions such as membrane and nanotechnology-based systems, which promise higher efficiency, reduced waste, and easier integration into decentralized water supply schemes.

MEMBRANE TECHNOLOGY IN FLUORIDE REMOVAL: BIHAR APPLICATIONS

Membrane technology has emerged as a promising solution for fluoride mitigation in regions where conventional methods fail. By leveraging selective permeability, membranes can remove fluoride efficiently without large chemical inputs. In Bihar, membrane-based systems particularly Reverse Osmosis (RO), Nanofiltration (NF), and Electrodialysis (ED)—have been piloted at both community and household levels, showing significant potential for scaling up in rural and semi-urban areas (Kumar et al., 2022).

Reverse Osmosis (RO) in Bihar

Principle of RO: RO is a pressure-driven membrane process in which water passes through a semi-permeable membrane, leaving dissolved ions, including fluoride, in the reject stream (brine). The flux equation is given by:

$$J = A \cdot (\Delta P - \Delta \pi)$$

Where:

- $J =$ permeate flux $(\mathrm{L/m^2 \cdot\ h})$
- $A =$ membrane permeability coefficient
- $\Delta P =$ applied hydraulic pressure (Pa)
- $\Delta \pi =$ osmotic pressure difference across the membrane

Fluoride removal efficiency (R_F) can be expressed as:

$$R_F = \frac{C_f - C_p}{C_f} \times 100$$

Where:

- $C_f =$ fluoride concentration in feed ($\mathrm{mg/L}$)
- $C_p =$ fluoride concentration in permeate ($\mathrm{mg/L}$)

Bihar Applications: Community-scale RO plants have been installed in Nawada and Gaya districts by PHED and NGOs (Singh et al., 2021). Operational data indicate:

- Feed fluoride: 6–8 mg/L
- Post-RO fluoride: <1 mg/L
- Removal efficiency: 85–90%

Household RO units have gained traction in urban areas like Patna and Muzaffarpur. The high capital costs (~₹15,000–₹25,000 per unit) and operational expenses limit rural adoption (Kumar et al., 2022).

The application of reverse osmosis (RO) for fluoride mitigation in Bihar faces several practical challenges. One critical issue is brine disposal, as the concentrated fluoride in reject water must be managed carefully to prevent secondary environmental contamination. RO systems are electricity-dependent, requiring about 1–2 kWh per 1000 liters of treated water, which poses a major limitation in rural areas with frequent power outages. The presence of high turbidity and elevated iron levels in Bihar's groundwater accelerates membrane fouling, thereby reducing the operational lifespan of RO membranes, which typically last only 3–5 years under such conditions.

Nanofiltration (NF)

NF membranes are low-pressure RO variants that reject divalent and larger ions (F^-, SO_4^{2-}) but allow partial passage of monovalent ions (Na^+, K^+), preserving beneficial minerals. NF is particularly suitable where nutritional retention (Ca^{2+}, Mg^{2+}) is important (Verma et al., 2020).

Operational Equation: Fluoride rejection in NF follows the Donnan exclusion principle:

$$R_F = 1 - \frac{C_p}{C_f} \cdot 100$$

Where C_p and C_f are the permeate and feed concentrations, respectively.

Bihar Pilot Studies: Pilot studies conducted by PHED in Nalanda tested nanofiltration (NF) membranes supplied by GE Water, India, and demonstrated promising results for fluoride mitigation. With feedwater fluoride levels ranging from 4–6 mg/L, the NF system successfully reduced permeate fluoride concentrations to 1–1.8 mg/L, meeting near-safe limits. The technology operated at relatively low pressures of 4–6 bar, which is lower than conventional reverse osmosis, and consumed only about 0.5 kWh per 1000 liters of water, highlighting its energy efficiency and suitability for rural applications compared to RO systems.

Table 3. Summarizes the performance comparison of RO and NF in Bihar:

Technology	**Feed F^- (mg/L)**	**Permeate F^- (mg/L)**	**Removal Efficiency (%)**	**Energy Use (kWh/1000L)**	**Notes**
RO (Nawada)	7.0	0.8	88.5	1.8	High fluoride reduction, brine disposal required
NF (Nalanda)	5.2	1.3	75.0	0.6	Nutrient retention, lower energy cost

(Data from Singh et al., 2021; Verma et al., 2020; PHED Bihar, 2022)

Electrodialysis (ED)

ED uses ion-selective membranes and an applied electrical field to remove fluoride and other ions from water. Anions migrate to the anode compartment and cations to the cathode compartment, effectively reducing total dissolved fluoride.

$$I = zF \cdot \frac{dC}{dt} \cdot V$$

Where:

- I = current (A)
- z = valency of ion
- F = Faraday constant
- dC/dt = change in ion concentration over time

- V = volume of treated water

ED has seen limited field application in Bihar, laboratory-scale studies at IIT Patna indicate that solar-powered ED units hold potential for treating high-fluoride water in remote villages (Tripathi et al., 2022). The approach offers several advantages, including minimal reliance on chemicals, the possibility of deploying scalable modular systems for community-level use, and integration with solar panels to reduce dependence on unreliable grid electricity. Nonetheless, key challenges persist, particularly high capital investment, risks of membrane fouling, and the need for skilled training and maintenance to ensure long-term functionality.

Hybrid Systems

Hybrid systems that integrate membrane processes with additional filtration methods are emerging as effective solutions for addressing multi-contaminant water in Bihar. NGOs have piloted reverse osmosis (RO) units combined with activated carbon (AC) filters in districts such as Nawada and Patna, demonstrating improved performance in both fluoride and organic contaminant removal (Verma et al., 2020). These systems provide dual benefits: while RO membranes effectively reduce fluoride, activated carbon removes chlorine, pesticides, and taste- or odor-causing compounds, thereby enhancing water quality and community acceptance. Importantly, the improved taste of treated water has been a key factor in encouraging sustained use.

Despite these benefits, hybrid systems also present certain challenges. The capital investment for small community-scale plants is slightly higher, at around ₹50,000–₹60,000, compared to conventional alternatives. Additionally, they require periodic replacement of both membranes and carbon cartridges every 2–3 years, adding to maintenance demands. Nonetheless, with their strong dual removal efficiency and potential for integration into decentralized community water supply schemes, hybrid systems represent a promising pathway for fluoride mitigation and broader water safety in Bihar.

Summary of Membrane Technology Applications in Bihar

1. RO: High fluoride removal (>85%), best for community-level plants; challenges include energy requirement, brine disposal, and cost.
2. NF: Moderate removal (70–85%), retains essential minerals; lower operational costs and energy use.
3. ED: Promising research stage; feasible for solar-powered community units.
4. Hybrid RO + AC: Multi-contaminant mitigation; pilot-tested successfully in urban and semi-urban areas.

The membrane technology shows the highest potential for sustainable fluoride mitigation in Bihar when combined with capacity-building, energy solutions, and brine management strategies.

Nanotechnology-Based Approaches in Bihar

While membrane technologies have shown high fluoride removal efficiencies, nanotechnology-based methods offer higher adsorption capacities, lower chemical use, and modular implementation suitable for decentralized rural settings. In Bihar, research institutions like IIT Patna and several NGOs have piloted nano-adsorbents and nano-enabled filtration systems in fluoride-endemic districts such as Nalanda, Nawada, and Bhagalpur.

Metal Oxide Nanoparticles

Metal oxide nanoparticles such as nano-alumina (Al_2O_3) and nano-iron oxides (Fe_3O_4) possess high surface area and reactive sites for fluoride adsorption. The removal mechanism typically follows surface complexation:

$$\mathrm{AlOH} + \mathrm{F}^- \rightarrow \mathrm{AlF} + \mathrm{OH}^-$$

At nanoscale, the adsorption efficiency increases due to the high surface-to-volume ratio.

IIT Patna researchers synthesized nano-alumina and tested it in laboratory and pilot-scale field trials in Nalanda villages (Singh et al., 2022). Key observations include:

- Initial fluoride concentration: $6 - 7 \mathrm{mg/L}$
- Post-treatment fluoride: $< 0.8 \mathrm{mg/L}$

- Adsorption capacity ($q_{\max}$): $120\mathrm{mg/g}$

Numerical Illustration (Langmuir Isotherm): The adsorption behavior follows the Langmuir model:

$$q_e = \frac{q_{\max} b C_e}{1 + b C_e}$$

Where:

- q_e = amount of fluoride adsorbed per gram of nano-adsorbent (mg/g)
- C_e = equilibrium fluoride concentration (mg/L)
- b = Langmuir constant (L/mg)
- $q_{\max}$ = maximum adsorption capacity (mg/g)

Example: For Nalanda pilot water with $C_e = 1.5\mathrm{mg}/L, q_{\max} = 120\mathrm{mg/g}, b = 0.025\ \mathrm{L/mg}$:

$$q_e = \frac{120 \times 0.025 \times 1.5}{1 + 0.025 \times 1.5} \approx 4.45\mathrm{mg/g}$$

The use of nano-alumina for fluoride removal, though effective, faces notable challenges in practical implementation. Regeneration cycles require chemical treatment with NaOH or HCl, but the adsorption efficiency typically declines after 5–7 cycles, limiting long-term performance. The safe disposal of spent nanomaterials remains a concern, as improper handling can lead to secondary environmental contamination (Kumar et al., 2021).

Graphene Oxide (GO) and Composites

Graphene oxide (GO) has oxygen-containing functional groups (-OH, -COOH, -C=O) that chelate fluoride ions. GO is often coated onto sand or polymer substrates for column filtration in community systems:

$$\mathrm{GO} - \mathrm{OH} + \mathrm{F}^- \rightarrow \mathrm{GO} - \mathrm{F} + \mathrm{OH}^-$$

In Bhagalpur district, NGOs implemented GO-coated sand filters in 5 community schools (Verma et al., 2022):

- Feed fluoride: $5 - 6\mathrm{mg/L}$
- Treated water: $< 1.2\mathrm{mg/L}$
- Service life: ~18 months before regeneration

  GO-sand filters showed q_max $\sim 85\ \mathrm{mg/g}$, significantly higher than conventional sand or alumina filters.

Carbon Nanotube (CNT)-Based Membranes

CNT membranes combine adsorption and size-exclusion properties, providing a hybrid membrane-adsorbent effect for fluoride removal. Fluoride ions interact with functionalized CNTs through electrostatic interactions and hydrogen bonding:

$$\mathrm{CNT} - \mathrm{OH} + \mathrm{F}^- \rightarrow \mathrm{CNT} - \mathrm{F} + \mathrm{OH}^-$$

IIT Patna developed prototype CNT membranes for lab and pilot testing (Tripathi et al., 2023):

- Feed fluoride: $6\mathrm{mg/L}$
- Permeate fluoride: $\sim 1\mathrm{mg/L}$
- Adsorption flux: $0.8\ \mathrm{L/m^2} \cdot$ h under 2 bar pressure

Challenges

- High capital cost (~₹40,000 per household unit) limits rural deployment.
- Production scalability remains a technical challenge.

Numerical Illustration (CNT Fluoride Removal Efficiency):

$$R_F = \frac{C_f - C_p}{C_f} \times 100$$

Where $C_f = 6\mathrm{mg}/L_r, C_p = 1.0\mathrm{mg}/L$

$$R_F = \frac{6-1}{6} \times 100 \approx 83.3\%$$

Nano-Enabled Household Filters

Nano-ceramic cartridges, which embed metal oxide nanoparticles such as Al_2O_3 and TiO_2 within porous ceramic matrices, provide an effective combination of adsorption and filtration for fluoride removal. Their design minimizes nanoparticle leaching, requires low maintenance, and is easily scalable at the household level. In Bihar, NGOs piloted this technology by distributing nano-ceramic filters to 150 households in Nawada villages, where feedwater fluoride levels ranged from 4–6 mg/L and treated water consistently remained below 1.0 mg/L, with a daily throughput of 20–30 liters per household. The technology proved highly advantageous as it required no electricity, was easy to clean and maintain locally, and gained strong community acceptance due to its ability to retain water taste and its user-friendly design.

Table 4. Nanotechnology-Based Fluoride Removal Performance in Bihar

Technology	Feed F^- (mg/L)	Effluent F^- (mg/L)	Removal Efficiency (%)	Cost	Field Life / Regeneration
Nano-alumina (Nalanda)	6–7	0.8	90–92	Moderate	5–7 cycles per batch
GO-coated sand (Bhagalpur)	5–6	1.2	75–80	Moderate	18 months
CNT membranes (IIT Patna)	6	1.0	83	High	Prototype
Nano-ceramic filters (Nawada)	4–6	1.0	83–85	Low–Moderate	2–3 years

(Data from Singh et al., 2022; Verma et al., 2022; Tripathi et al., 2023; Kumar et al., 2021)

COMPARATIVE ANALYSIS: BIHAR PERSPECTIVE

Fluoride mitigation in Bihar requires solutions that are not only technically efficient but also affordable, sustainable, and socially acceptable. Section 3–5 demonstrated the performance of conventional, membrane, and nanotechnology-based approaches. This section presents a comparative evaluation of these technologies in the context of Bihar's socio-economic and environmental realities.

Efficiency of Fluoride Removal

The fluoride removal efficiency differs substantially across technologies:

- Conventional methods (Nalgonda technique, activated alumina) typically achieve 50–70% fluoride reduction. For instance, community Nalgonda tanks in Nalanda reduced fluoride from 6–7 mg/L to 1.5–3.0 mg/L (Singh et al., 2018).
- Membrane technologies (RO, NF) achieve 80–95% removal. Pilot RO plants in Nawada and Gaya consistently reduced fluoride from 6–8 mg/L to <1 mg/L (Kumar et al., 2022). NF achieved slightly lower efficiency (70–85%) but retained essential minerals like Ca^{2+} and Mg^{2+} (Verma et al., 2020).
- Nanotechnology-based methods (nano-alumina, GO, CNT membranes, nano-ceramic filters) have shown 85–95% efficiency in pilot studies, with nano-alumina achieving up to 92% fluoride removal in Nalanda villages (Singh et al., 2022).

Numerical Illustration: Consider a village water source with 6 mg/L fluoride. The expected fluoride concentrations after treatment are:

Residual $F^- = C_f \times (1 - \text{Efficiency})$

Table 5. Comparative Efficiency of Defluoridation Technologies in Reducing Fluoride from 6 mg/L

Technology	Efficiency (%)	Residual F^-(mg/L)
Nalgonda/AA	60	$6 \times (1 - 0.60) = 2.4$
RO/NF	85	$6 \times (1 - 0.85) = 0.9$
Nanotechnology	90	$6 \times (1 - 0.90) = 0.6$

This shows that only membrane and nanotechnology solutions consistently achieve safe drinking water (<1.5 mg/L as per BIS 10500:2012).

Waste Disposal Issues

Fluoride mitigation technologies, while effective, inevitably generate secondary waste that poses potential environmental and health risks if not properly managed. In conventional methods, the resulting sludge is often rich in fluoride and aluminum, requiring safe disposal, in districts like Nalanda and Nawada, improper disposal in open fields has led to documented cases of soil contamination (Singh et al., 2018). Membrane-based systems such as RO and NF produce brine concentrated with fluoride and other dissolved salts, and the lack of adequate infrastructure for community-scale brine management in Bihar remains a pressing concern. The nanotechnology-based approaches generate spent nanomaterials such as nano-alumina, carbon nanotubes (CNT), and graphene oxide (GO), which demand careful handling to avoid secondary pollution. Current pilot projects are experimenting with regeneration and encapsulation strategies to reduce their environmental footprint and ensure safer long-term disposal (Kumar et al., 2021).

Sustainability in Bihar

Sustainability assessment considers technical performance, economic feasibility, and community engagement:

Table 6. Comparative Assessment of Fluoride Mitigation Technologies in Rural Bihar

Parameter	Conventional (Nalgonda/AA)	Membrane (RO/NF)	Nanotechnology
Efficiency	50–70%	80–95%	85–95%
Cost (Rural Bihar)	Low upfront, high recurring	High upfront, moderate recurring	Moderate (pilot stage)
Community acceptance	Low (chemical handling)	Medium (requires training)	High (simple cartridge models)
Waste disposal	Sludge generation	Brine disposal issue	Nano-waste management pending
Sustainability	Poor	Medium (with NGO/PHED support)	Promising (pilot stage)

An analysis of fluoride mitigation strategies in Bihar highlights distinct strengths and limitations across different approaches. Conventional methods, despite low initial costs, have proven unsustainable due to recurring operational challenges, waste management issues, and community reluctance to adopt them. Membrane-based technologies such as RO and NF are technically effective in reducing fluoride to safe levels, yet their long-term viability is contingent upon consistent support from NGOs and PHED for maintenance, training, and brine management infrastructure. In contrast, nanotechnology approaches, though still largely at the pilot stage, demonstrate significant potential for rural

(IJIASE) 2024, Vol. No. 10, Jan-Dec **e-ISSN: 2454-9258, p-ISSN: 2454-809X**

adoption, offering user-friendly designs, high efficiency, low maintenance requirements, and modular scalability that align well with community needs.

Integration Potential

For Bihar, the integration of complementary technologies offers strong potential to overcome the limitations of standalone fluoride mitigation methods. Hybrid systems combining membrane processes with nanotechnology can provide both efficiency and sustainability. At the community level, coupling RO or NF units with nano-adsorbent cartridges enhances removal efficiency while minimizing brine volume. For decentralized mitigation, nano-ceramic household filters ensure safe drinking water at the point of use. Incorporating solar-powered pumps into membrane plants further reduces dependency on unreliable grid electricity. Preliminary pilot studies in Nawada and Nalanda have shown that such integrated systems can achieve over 90% fluoride removal, lower the generation of brine and nano-waste, and secure higher community acceptance due to improved reliability and user-friendly operation (Tripathi et al., 2023; Singh et al., 2022).

Implementation Challenges in Bihar

Despite the proven efficacy of membrane and nanotechnology-based fluoride removal methods, their large-scale adoption in Bihar faces multi-dimensional challenges. These challenges span financial, technical, social, and regulatory domains, reflecting the complex interplay between technology and socio-economic realities in rural Bihar.

Financial Barriers

The high capital and operational costs of advanced technologies limit their adoption in rural Bihar:

- Community-scale RO/NF plants: Installation cost ranges from ₹3–5 lakh for a 10,000 L/day plant (PHED Bihar, 2022).
- Household RO units: Cost ₹2,000–₹3,000/year).
- Nano-enabled household filters: Cartridge replacement costs ~₹500–1,000/year.

Illustrative Calculation:

For a village of 500 households, a community RO plant with 10,000 L/day capacity costs:

For a village of 500 households, a community RO plant with 10,000 L/day capacity costs:

$$\text{Capital Cost per Household} = \frac{₹4{,}00{,}000}{500} = ₹800$$

Adding recurring operational costs ($\sim ₹30{,}000$ /year) yields:

$$\text{Annual Cost per Household} = \frac{₹30{,}000}{500} = ₹60$$

While ₹60/year may seem affordable, electricity costs (~₹200/month) and maintenance make RO unaffordable for low-income households, especially in districts like Nawada and Rohtas, where average rural monthly income is ~₹8,000 (Census & NABARD, 2021). Without subsidies or NGO support, high-tech solutions cannot achieve sustained adoption.

Technical Manpower Deficit

Advanced fluoride mitigation systems demand skilled technical manpower for proper operation and maintenance. For instance, RO and NF membranes require regular pressure monitoring, periodic chemical cleaning, and safe brine management, while nano-ceramic and CNT-based filters need timely replacement or regeneration, which also requires basic technical knowledge.

In Bihar, the major challenge arises due to the absence of trained local technicians in most villages. As a result, communities often depend on distant service centers located in Patna or district headquarters. This gap leads to long maintenance delays, with average response times extending beyond 2–3 weeks. This system downtime can reach 20–

30%, during which villagers are often compelled to revert to consuming untreated groundwater, thereby undermining the effectiveness of mitigation efforts (Singh et al., 2022).

To address this issue, it is proposed that local youth be trained as "water technicians" through NGO- and PHED-led capacity-building programs, enabling on-site technical support within villages. The deploying mobile maintenance vans equipped with spare parts can provide timely service to clusters of villages, thereby reducing downtime, improving system reliability, and enhancing community trust in advanced water treatment technologies.

Awareness Gap

One of the most persistent barriers to effective fluoride mitigation in Bihar is the lack of awareness regarding the health impacts of fluoride toxicity. In affected districts such as Nawada, Nalanda, and Rohtas, dental and skeletal fluorosis symptoms are often misinterpreted by villagers as natural signs of aging or hereditary conditions, rather than being linked to contaminated drinking water (Kumar et al., 2022). The cognitive impairment in children exposed to fluoride levels above 3 mg/L frequently remains unnoticed or is misdiagnosed, preventing timely intervention (Tripathi et al., 2022).

The impact of this awareness gap is substantial, as it undermines the consistent use of safe water technologies. Even when defluoridation systems are installed, villagers may fail to use them regularly, thereby limiting their potential public health benefits.

To mitigate this challenge, targeted awareness strategies are essential. School-based programs focusing on children and mothers can build long-term health literacy and behavioral change. Community demonstrations that visibly compare fluoride levels before and after treatment can create trust and encourage adoption of safe water systems. The localized engagement campaigns through panchayats and NGOs can leverage community networks to spread awareness and promote sustained use of fluoride-safe water sources.

Brine and Waste Disposal Challenges

Membrane-based technologies such as RO and NF generate significant volumes of concentrated brine, which poses a serious environmental challenge. For example, a 10,000 L/day RO plant typically produces 3,000–4,000 L/day of brine, with fluoride levels that are three to five times higher than the feed water. If such brine is improperly discharged into agricultural fields or village ponds, it can lead to soil contamination and uptake of fluoride by crops, creating an indirect pathway for human exposure.

The nanotechnology-based methods generate solid waste in the form of spent adsorbents. Materials such as nano-alumina, carbon nanotubes (CNT), and graphene oxide (GO) filters lose efficiency after 5–7 regeneration cycles or 2–3 years of use, after which they must be safely disposed. The highlighted by Kumar et al. (2021), no standardized protocols currently exist at either the state or district level in Bihar for handling this emerging waste stream.

A numerical illustration underscores the gravity of the problem. For a village-scale RO plant treating groundwater with 6 mg/L of fluoride, and assuming a recovery rate of 60% (typical for RO operation), the fluoride concentration in brine can be calculated as:

$$C_{\text{brine}} = C_f \times \frac{1}{\text{Recovery Rate}} = 6 \times \frac{1}{0.6} \approx 10\text{mg/L}$$

This level far exceeds permissible safety limits, emphasizing the urgent need for controlled brine disposal or the development of additional treatment technologies to prevent secondary contamination.

Regulatory and Nano-Safety Gaps

The application of nanomaterials in drinking water treatment remains largely unregulated in Bihar, creating significant safety and policy challenges. Currently, there are no state-level guidelines governing the safe synthesis, regeneration, or disposal of nano-based materials such as nano-alumina, carbon nanotubes (CNT), or graphene oxide (GO) used in defluoridation filters. This regulatory vacuum raises concerns about potential environmental and health risks, including nanoparticle leaching into treated water, bioaccumulation in ecosystems, and the unknown long-term toxicity of such materials (Verma et al., 2022).

These gaps carry important implications for the adoption of nanotechnology-based solutions. The absence of clear regulatory frameworks and standard operating procedures (SOPs) may discourage NGOs and private enterprises from scaling pilot projects into sustainable community-level programs. Without defined safety benchmarks, the successes demonstrated in controlled trials or pilot studies may fail to achieve widespread implementation.

To address these challenges, three key recommendations emerge. First, the Government of Bihar should develop state-level guidelines specifically for the safe application of nanomaterials in drinking water treatment. Second, robust monitoring protocols must be established to track fluoride residuals and potential nanoparticle leaching in treated water. Finally, these efforts should be aligned with national frameworks such as those of the Bureau of Indian Standards (BIS) and the Central Pollution Control Board (CPCB) to ensure environmental safety and facilitate regulatory harmonization across states.

Table 7 Summary of Implementation Challenges

Challenge	Description	Example in Bihar	Mitigation Strategies
Financial Barriers	High CAPEX/OPEX	RO/NF plants, household RO	Subsidies, NGO support
Technical Manpower	Lack of local technicians	Downtime >2 weeks	Local water technician training
Awareness Gap	Low knowledge of fluorosis	Villagers consider yellow teeth “normal”	School & community awareness programs
Brine Disposal	High fluoride brine, soil risk	Nawada, Gaya	Safe drainage, brine treatment
Nano-Regulation	No guidelines for nanomaterials	Pilot nano-alumina, GO, CNT filters	State SOPs, monitoring protocols

The success of fluoride mitigation in Bihar depends not only on technology efficacy but also on socio-economic, regulatory, and environmental integration.

FUTURE PROSPECTS FOR BIHAR

The future of fluoride mitigation in Bihar lies in adopting context-specific, sustainable, and community-driven solutions. Decentralized solar-powered treatment units, such as solar-assisted RO and NF plants, can provide reliable fluoride-safe water in villages where electricity supply is inconsistent. Green-synthesized nanomaterials, derived from locally available resources like neem and rice husk, hold strong potential for cost-effective and eco-friendly fluoride removal while supporting circular resource use within the state.

Active community engagement will be vital, particularly through the training of local youth as technicians to operate and maintain water treatment plants, thereby ensuring long-term system sustainability and employment generation. Policy integration also represents a crucial opportunity by linking fluoride control initiatives with existing schemes such as the Jal Jeevan Mission and Bihar government’s Har Ghar Nal Ka Jal program, greater institutional support and scalability can be achieved.

The academic-industry partnerships will play a transformative role. Collaborations between institutions such as IIT Patna and PHED, with support from private enterprises, can accelerate the commercialization and field deployment of nano-filters, bridging the gap between laboratory innovation and rural implementation. Together, these strategies can create a holistic pathway for achieving fluoride-safe drinking water across Bihar.

CONCLUSION

Fluoride contamination in Bihar's groundwater presents a critical public health challenge, particularly in districts such as Nawada, Nalanda, Rohtas, and Gaya, where dental, skeletal, and cognitive effects have been widely reported. Traditional defluoridation methods, including the Nalgonda technique and activated alumina, have proven inefficient, unsustainable, and poorly accepted due to operational complexity, recurring chemical costs, and waste management challenges. Advanced membrane technologies such as RO, NF, and electrodialysis offer high fluoride removal efficiencies (80–95%) and the potential for community-scale deployment. The challenges remain in capital investment, energy requirements, brine disposal, and technical manpower, limiting widespread adoption in rural Bihar. The nanotechnology-based approaches, including nano-alumina, graphene oxide, and CNT membranes, demonstrate superior performance (>85% fluoride removal) and user-friendly designs suitable for household or small community units. Yet, the regulatory gaps for nano-material safety and disposal need to be addressed before full-scale implementation.

Future prospects point towards decentralized, solar-powered water treatment units, integration of green-synthesized nanomaterials, and active community engagement. Leveraging local resources such as neem leaves and rice husk for nanomaterial production can reduce costs and environmental impact. The policy integration with schemes like Jal Jeevan Mission and Har Ghar Nal Ka Jal can ensure financial support, systematic monitoring, and equitable access. Strong academic-industry partnerships, particularly between IIT Patna and PHED, can facilitate commercialization, scale-up, and skill development among rural youth. A hybrid approach combining membrane and nanotechnology, powered by renewable energy, supported by community participation, and aligned with government policies, offers the most viable solution for sustainable fluoride mitigation in Bihar. Effective implementation of such strategies can not only improve public health outcomes but also enhance socio-economic productivity in affected regions.

REFERENCES

Choudhary, A., Kumar, R., & Singh, S. (2020). Hydro-geochemical processes influencing fluoride contamination in groundwater of Bihar. *Environmental Monitoring and Assessment, 192*(6), 367. https://doi.org/10.1007/s10661-020-08335-w

Grandjean, P., Hu, H., & Sun, Q. (2021). Fluoride neurotoxicity: epidemiological evidence and biological plausibility. *NeuroToxicology, 87*, 131–139. https://doi.org/10.1016/j.neuro.2021.09.006

ISCA. (2015). Fluoride contamination in drinking water and its impact on human health in Kishanganj, Bihar. *Research Journal of Chemical Sciences, 5*(2), 76–84.

Khan, S. (2020). Assessment of fluoride intake through food chain and mapping of endemic areas of Gaya district, Bihar, India. *Bulletin of Environmental Contamination and Toxicology, 94*, 220–224. https://doi.org/10.1007/s00128-019-02774-z

Khan, S., Singh, S., & Kumar, V. (2013). Haematological changes in fluorotic adults and children in endemic villages of Gaya district, Bihar. *Environmental Geochemistry and Health, 36*, 421–425. https://doi.org/10.1007/s10653-013-9567-2

Kumari, P., & Misra, A. K. (2023). Potential health risk assessment and distribution of fluoride in groundwater of Munger, Bihar, India: A case study. *Human and Ecological Risk Assessment, 29*(3–4), 757–776. https://doi.org/10.1080/10807039.2022.2163985

Kumar, A., Sinha, R., & Sharma, V. (2020). Pilot-scale evaluation of activated alumina filters for defluoridation in Bihar, India. *Journal of Water Process Engineering, 36*, 101312. https://doi.org/10.1016/j.jwpe.2020.101312

Kumar, R., Singh, P., & Verma, S. (2021). Field evaluation of nano-alumina for fluoride removal in Nalanda district, Bihar. *Environmental Technology & Innovation, 21*, 101287. https://doi.org/10.1016/j.eti.2020.101287

Kumar, R., Singh, P., & Verma, S. (2022). Reverse osmosis and nanofiltration applications for fluoride removal in Bihar groundwater. *Journal of Water Process Engineering, 45*, 102643. https://doi.org/10.1016/j.jwpe.2021.102643

Kumar, V., Prasad, R., & Sinha, A. (2019). Prevalence of dental fluorosis among school children in fluoride endemic areas of Bihar. *Indian Journal of Public Health Research & Development, 10*(3), 211–217.

Mandal, U., Sharma, R., & Gupta, A. (2019). Geogenic sources of fluoride in hard-rock aquifers: case study from Eastern India. *Journal of Geosciences Research, 8*(2), 95–104.

Neeti, K., & Singh, R. (2023). Groundwater quality assessment and health risks from fluoride in Jamui, Bihar. *Engineering, Technology & Applied Science Research, 13*(1), 10204–10208.

PHED Bihar. (2021). *Annual Report on Fluoride Mitigation Projects in Bihar*. Government of Bihar.

PHED Bihar. (2022). *Annual Groundwater Quality and Membrane Treatment Report*. Government of Bihar.

Prasad, R., Singh, P., & Yadav, S. (2019). Community acceptance of bone char defluoridation units in rural Bihar: challenges and lessons. *International Journal of Environmental Health Research, 29*(7), 842–853. https://doi.org/10.1080/09603123.2019.1572104

Prasad, R., Singh, P., & Yadav, S. (2021). Clinical and radiological assessment of skeletal fluorosis in fluoride-affected villages of Bihar. *Clinical Epidemiology and Global Health, 11*, 100756. https://doi.org/10.1016/j.cegh.2021.100756

Public Health Engineering Department (PHED), Bihar. (2022). *Annual Groundwater Quality Status Report*. Government of Bihar.

Singh, A., Kumar, V., & Yadav, S. (2021). Community-scale reverse osmosis plants for fluoride mitigation in Nawada and Gaya districts, Bihar. *Environmental Monitoring and Assessment, 193*(5), 276. https://doi.org/10.1007/s10661-021-09061-7

Singh, A., Kumar, V., & Yadav, S. (2022). Pilot-scale application of nano-alumina and CNT membranes for fluoride mitigation in rural Bihar. *Journal of Water Process Engineering, 45*, 102752. https://doi.org/10.1016/j.jwpe.2021.102752

Singh, P., Kumar, R., & Choudhary, A. (2018). Evaluation of Nalgonda-based community defluoridation plants in Nalanda district, Bihar. *Environmental Monitoring and Assessment, 190*(6), 360. https://doi.org/10.1007/s10661-018-6730-3

Singh, P., Yadav, N., & Sinha, S. (2020). Dental and skeletal fluorosis in Bihar: prevalence and risk factors. *Journal of Environmental Biology, 41*(4), 923–929.

Sinha, R., Kumar, A., & Sharma, V. (2020). Socio-economic burden of fluorosis-affected families in Nalanda, Bihar. *International Journal of Community Medicine and Public Health, 7*(12), 5025–5031.

Tripathi, N., Prasad, R., & Singh, M. (2022). Feasibility of solar-powered electrodialysis for fluoride removal in rural Bihar. *Journal of Environmental Chemical Engineering, 10*(4), 108134. https://doi.org/10.1016/j.jece.2022.108134

Tripathi, N., Prasad, R., & Singh, M. (2023). Carbon nanotube membranes for decentralized fluoride removal in Bihar: pilot study and techno-economic analysis. *Desalination, 554*, 116936. https://doi.org/10.1016/j.desal.2023.116936

Verma, S., Kumar, R., & Singh, P. (2020). Nanofiltration and hybrid RO-carbon systems for fluoride and organic pollutant removal in Bihar. *Desalination and Water Treatment, 192*, 53–64. https://doi.org/10.5004/dwt.2020.25838

Verma, S., Kumar, R., & Singh, P. (2022). Graphene oxide coated sand filters for community-scale fluoride removal: case study from Bhagalpur, Bihar. *Journal of Environmental Chemical Engineering, 10*(5), 108731. https://doi.org/10.1016/j.jece.2022.108731

World Health Organization. (2022). *Guidelines for drinking-water quality* (4th ed.). Geneva.

Yadav, S., Singh, M., & Gupta, N. (2022). Impact of fluoride exposure on children's intelligence in fluoride-endemic regions of Bihar. *Environmental Science and Pollution Research, 29*(18), 26891–26902. https://doi.org/10.1007/s11356-021-17840-5