Fluoride Toxicity through Groundwater Consumption and Its Rural Health Consequences: Field Evidence from Western Uttar Pradesh

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DOI: https://doi.org/10.51584/IJRIAS.2026.11050202

Received: 20 May 2026; Accepted: 26 May 2026; Published: 16 June 2026

ABSTRACT

Drinking water drawn from shallow aquifers across several belts of rural India carries dissolved fluoride at concentrations that silently damage teeth, bones, kidneys, and developing brains over years of daily consumption. In Western Uttar Pradesh, this problem is acute yet poorly documented at the district level, and most affected villages have no access to treatment or even basic information about the risk they face. This study was conducted across five districts — Agra, Mathura, Aligarh, Bulandshahr, and Etah — with the twin purpose of measuring fluoride concentrations in 214 groundwater sources and recording the health status of households that depend on them. Water was collected during April–May 2025, a period of peak groundwater stress, and analysed using the SPADNS colorimetric method. Simultaneously, 1,200 households across 42 villages were surveyed and children were clinically examined for signs of fluorosis. The data revealed that 52.3 percent of sources exceeded the 1.5 mg/L safety threshold, with a peak observation of 5.1 mg/L recorded in Aligarh district. Dental fluorosis was confirmed in 63.4 percent of children aged 5–14 years in high-exposure zones. Skeletal fluorosis was documented in 28.7 percent of middle-aged adults, while neurological screening flagged cognitive deficits in nearly one in five children under ten years of age in the most contaminated villages. Thyroid irregularities and early renal stress were also observed at clinically significant rates. The hydrochemical profile of contaminated sources — characterised by alkaline pH, low dissolved calcium, and elevated sodium bicarbonate — points to natural rock leaching as the primary source, compounded by intensive irrigation pumping that has deepened aquifer drawdown over decades. Practical, low-cost defluoridation approaches including the Nalgonda technique and community rainwater harvesting are evaluated and recommended for immediate deployment.

Keywords: Groundwater Fluoride Contamination, Fluorosis, Rural Health Impact, Western Uttar Pradesh, Defluoridation Methods

INTRODUCTION

A hand pump installed by the government in a village courtyard is, in most people's minds, a symbol of progress — proof that clean water has arrived. In a substantial number of villages across Western Uttar Pradesh, however, the water coming out of that pump carries a chemical burden that causes slow, cumulative damage invisible to the naked eye until it has already left permanent marks on children's teeth, stiffened adults' spines, and blunted young children's capacity to learn. The chemical in question is fluoride, and the problem it creates is not the result of industrial pollution or careless waste disposal. It is geological — the aquifer that feeds the pump passes through rock formations that have been releasing fluoride into the surrounding water for centuries, at rates that have been intensified in recent decades by the sheer volume of extraction needed to support one of India's most intensively farmed agricultural landscapes.

The western districts of Uttar Pradesh form part of the upper Yamuna-Ganga doab, a broad flat plain where generations of farmers have depended on groundwater not just for drinking but for growing wheat and sugarcane through long dry winters and scorching pre-monsoon months. The cumulative effect of this extraction, scaled up enormously since the Green Revolution of the 1960s and 1970s, has been a steady decline in water table depths across much of the region. As the water table drops, groundwater spends longer periods in contact with fluoride-bearing minerals, dissolving more fluoride before it is pumped to the surface. The result is a slow but consistent increase in fluoride concentrations in shallow wells and hand pumps — a trend that has been noted in state-level water quality reports but has not been translated into systematic district-level action.

This study was motivated by three observations that together pointed to the need for new, localised field evidence. First, existing fluoride data for Western UP is largely aggregate and dated, making it difficult for district administrations to prioritise specific blocks or habitations for intervention. Second, the health dimension of fluoride exposure in this region has rarely been investigated alongside water quality data, leaving the clinical burden invisible in public health records. Third, the remediation options that exist on paper — defluoridation units installed under various schemes — have a poor track record of continued operation in rural India, and any realistic proposal for improving the situation must account for this history. The present study was designed to address all three gaps through original fieldwork conducted across five representative districts of the affected region.

LITERATURE REVIEW

Fluoride enters groundwater almost entirely through the weathering and dissolution of minerals in the rocks and soils that form the aquifer matrix. Fluorite, apatite, micas, and certain amphiboles are the primary source minerals, and their dissolution rate is governed by a set of chemical conditions that vary considerably from one aquifer to another. Alkaline groundwater, poor in dissolved calcium but rich in sodium and bicarbonate, creates precisely the conditions under which fluoride remains in solution rather than precipitating out. This combination — high pH, low calcium, high sodium bicarbonate — is the hydrochemical fingerprint that researchers working on fluoride-affected aquifers have come to recognise as a reliable predictor of elevated fluoride, and it describes a large proportion of the shallow groundwater in Western Uttar Pradesh.

The health consequences of chronic fluoride consumption have been documented across a spectrum from the cosmetic to the crippling. At concentrations marginally above the safety threshold, the first sign is typically dental fluorosis — a developmental defect of tooth enamel that occurs when children ingest excess fluoride during the years when their permanent teeth are forming. The severity ranges from faint white streaks that may be mistaken for calcium deposits to severe brown-black mottling accompanied by physical pitting and fragility of the enamel surface. Beyond the aesthetic damage, fluorosed teeth are structurally weaker and more susceptible to fracture and decay. At higher fluoride levels and with longer exposure, skeletal fluorosis develops as fluoride progressively replaces hydroxyl groups in bone mineral, causing abnormal density changes that can ultimately lead to painful and immobilising deformity of the spine, hips, and knees.

The neurological dimension of fluoride toxicity has attracted increasing research attention since the early 2010s, when a systematic synthesis of epidemiological data from several countries found that children growing up in high-fluoride areas consistently scored lower on cognitive tests than matched control populations from lower-fluoride areas. The biological mechanism proposed involves fluoride's ability to cross the blood-brain barrier, particularly in developing foetuses and young children whose neurological systems are still maturing. Thyroid function has also been implicated, with fluoride shown to interfere with iodine uptake and thyroid hormone synthesis, potentially compounding cognitive effects in areas where iodine intake is already marginal — a situation that describes many rural communities in UP.

Despite this evidence base, the policy response in Uttar Pradesh has been fragmented. Water quality testing programmes under successive rural drinking water schemes have flagged fluoride as a concern, but the data collected have rarely been used to drive block-level or village-level action. Defluoridation units installed under centrally sponsored schemes have frequently been documented as non-functional within months of commissioning, due to a combination of inadequate community training, broken supply chains for consumables, and the absence of any monitoring or accountability mechanism at the local level. The present study was undertaken in this context, with the understanding that documenting the problem clearly and proposing solutions grounded in local realities is a necessary first step toward meaningful action.

STUDY AREA

Five districts of Western Uttar Pradesh were selected for this investigation: Agra, Mathura, Aligarh, Bulandshahr, and Etah. Taken together, these districts span an area of roughly 18,400 square kilometres situated between approximately 27°N and 28.5°N latitude and 77.5°E and 79.5°E longitude. The terrain across most of this area is a flat to gently undulating alluvial plain broken only by the Yamuna riverfront ravines near Agra and Mathura and minor topographic rises in eastern Etah. Elevations generally range between 150 and 210 metres above sea level.

The climate follows a continental sub-tropical pattern with a pronounced dry season occupying the better part of eight months each year. Rainfall arrives almost entirely in the southwest monsoon between June and September, with annual totals ranging from about 620 mm in the western margins to around 780 mm in the eastern portions of the study area. Summer temperatures regularly exceed 45°C in May and June, driving high evapotranspiration rates that further concentrate dissolved ions in soil water and shallow groundwater. January minimum temperatures approach 3–5°C, suppressing recharge even during occasional winter fog events. The net result of this climate is an aquifer that receives intense but brief recharge and faces continuous, year-round extraction.

The subsurface geology consists of layered Holocene and Pleistocene alluvial sediments — principally fine to medium sand interbedded with clay lenses — that form the shallow unconfined aquifer accessed by hand pumps and dug wells in most villages. Below this alluvial cover, which extends to depths of 60–100 metres in most of the study area, older Vindhyan sedimentary sequences and Pre-Cambrian metamorphic basement rocks occur, particularly in the southern parts of Agra and Mathura. These older formations contain higher concentrations of fluorite and apatite and contribute fluoride to the overlying alluvial aquifer through upward hydraulic gradients in areas where deep extraction creates a vertical head differential. The shallow aquifer itself accumulates additional fluoride through evaporative concentration of return irrigation flows during the long dry season.

METHODOLOGY

Groundwater Sampling Protocol

Groundwater samples were drawn from 214 sources — 162 India Mark II and III hand pumps and 52 open dug wells — spread across 42 villages in the five study districts. Villages were selected using a stratified approach to ensure representation of the major geological sub-units, depths of groundwater occurrence, and levels of agricultural intensity across each district. All sampling was completed between 7 April and 31 May 2025, deliberately timed to capture the peak drawdown period when ion concentrations in shallow aquifers are typically at their annual maximum. Before filling the collection bottle, each hand pump was operated continuously for four to five minutes to clear residual water from the casing and rising main. Samples were collected in pre-cleaned 500 mL HDPE bottles, sealed immediately, and assigned a unique field ID linked to GPS coordinates, source type, and estimated depth recorded from local knowledge or available borehole logs. All bottles were transported in insulated cooler boxes and reached the laboratory within 24 hours of collection.

Chemical Analysis

Fluoride concentration was measured using the SPADNS (sodium 2-parasulphophenylazo-1,8-dihydroxy-3,6-naphthalenedisulphonate) colorimetric procedure, which is the standard analytical method recommended by the American Public Health Association for both field and laboratory determination of fluoride in drinking water. Absorbance was read at 570 nm on a Hach DR3900 benchtop spectrophotometer. Every sample was analysed in triplicate and the mean of the three readings reported. A five-point calibration curve was prepared from sodium fluoride standard solutions at the beginning of each analytical session, and a reagent blank was run with each batch to correct for background absorbance. Complementary parameters — pH, electrical conductivity, total dissolved solids, calcium, magnesium, sodium, potassium, bicarbonate, and chloride — were measured on the same samples to characterise the hydrochemical environment and interpret the fluoride data in context.

Household Health Assessment

A structured questionnaire was administered face-to-face to one adult respondent per household across 1,200 homes in the surveyed villages. The instrument was designed in Hindi, piloted in one village outside the study area, and revised based on pre-test feedback before deployment. It captured data on household composition, length of residence, primary water source, any alternative sources used, and the health history of household members across seven fluorosis-related conditions. All children between five and fourteen years of age whose parents provided informed consent underwent a clinical oral examination conducted by a trained public health dental officer using the Dean's Fluorosis Index scoring system. For adults reporting joint pain, back stiffness, kidney discomfort, or thyroid-related symptoms, available records from the nearest primary or community health centre were reviewed to cross-check self-reported conditions against formal diagnoses where such records existed and could be accessed. Cognitive screening of children under ten years was conducted using a validated Hindi-language instrument assessing short-term recall, pattern recognition, and sustained attention.

Data Analysis and Mapping

Spatial interpolation of fluoride values across the study area was carried out in ArcGIS 10.8 using the inverse distance weighting method, which assigns predicted values to unsampled locations based on the weighted average of surrounding measured points. The resulting continuous surface maps were used to visually identify spatial clusters of high-fluoride groundwater and correlate them with geological and land-use features. Statistical relationships between fluoride concentration and health outcome prevalence across villages were assessed using Pearson's correlation coefficient for normally distributed pairs and Spearman's rho for skewed distributions. All analyses were conducted in SPSS Version 26 with a significance threshold of $p < 0.05$ applied consistently.

RESULTS AND DISCUSSION

Spatial Pattern and Magnitude of Fluoride Contamination

Of the 214 sources tested, 112 returned fluoride values above the 1.5 mg/L threshold — a non-compliance rate of 52.3 percent across the combined dataset. The observed range extended from 0.5 mg/L at the lowest end to 5.1 mg/L in a dug well at Iglas, Aligarh, which represents 3.4 times the permissible limit. This upper extreme was not an isolated outlier: nine other samples in Aligarh and Etah exceeded 4.0 mg/L, a level associated in the clinical literature with measurable renal and neurological toxicity on prolonged exposure. District-wise results are presented in Table 1 below.

Table 1: Fluoride Concentration Data by District — Pre-Monsoon Survey, April–May 2025

District	Blocks Surveyed	Sources Tested (n)	F^- Observed Range (mg/L)	% Sources > 1.5 mg/L
Agra	Khandauli, Bah	48	0.6 – 4.2	54.2%
Mathura	Farah, Baldeo	42	0.8 – 3.8	47.6%
Aligarh	Iglas, Atrauli	50	0.5 – 5.1	62.0%
Bulandshahr	Siyana, Jahangirabad	38	0.7 – 3.5	42.1%
Etah	Jalesar, Kasganj	36	1.1 – 4.7	66.7%
Combined	—	**214**	0.5 – 5.1	**52.3%**

Etah district recorded the highest proportion of non-compliant sources at 66.7 percent, a figure that reflects the combination of older, fluorite-rich sedimentary geology in the Jalesar and Kasganj blocks and a relatively shallow water table sustained by intensive sugarcane irrigation return flows. Aligarh followed at 62.0 percent, with the Iglas block standing out as the most severely affected single area in the entire dataset. Bulandshahr showed the lowest non-compliance proportion at 42.1 percent, consistent with its location nearer to active Ganga recharge zones where fresher water dilutes fluoride accumulation in the shallow aquifer.

The hydrochemical data reinforced the geological interpretation. Contaminated sources consistently showed alkaline pH values between 7.9 and 8.9, elevated sodium and bicarbonate, and markedly depressed calcium — a $Na\text{-}HCO_3$ water type that is widely documented as the characteristic chemical environment of fluoride-enriched groundwater in alluvial plains. Pearson correlation between fluoride and dissolved calcium across the full dataset yielded $r = -0.64$ ($p < 0.001$), confirming that calcium limitation is a key driver of fluoride retention in solution. Electrical conductivity was positively correlated with fluoride ($r = 0.58$, $p < 0.001$), pointing to the role of evaporative concentration in shallower dug wells during the long dry season.

Disease Burden Recorded in Surveyed Households

The clinical and survey data painted a detailed and troubling picture of the health toll that chronic fluoride exposure is inflicting on these communities. Among the 1,200 households surveyed, dental fluorosis emerged as the most prevalent and visibly obvious condition. Dean's Index scoring of 847 children in the five to fourteen age bracket returned a fluorosis prevalence of 63.4 percent in villages where groundwater fluoride exceeded 2.0 mg/L — a proportion that dropped to 31.2 percent in villages where fluoride was between 1.5 and 2.0 mg/L, and fell to 9.4 percent in control villages drawing from sources below 1.0 mg/L. This dose-response gradient across the three exposure bands is among the clearest findings of the study and leaves little ambiguity about the causal relationship between water fluoride and dental damage. Health outcomes across all recorded conditions are compiled in Table 2.

Table 2: Fluoride-Associated Health Outcomes Recorded Across Surveyed Villages

Disorder Recorded	Triggering F^- Level (mg/L)	Vulnerable Group	Village-Level Prevalence (%)	Prominent Clinical Feature
Dental Fluorosis	Above 1.5	Children 5–14 yrs	63.4	Enamel pitting, brown staining
Skeletal Fluorosis	Above 3.0	Adults 35–60 yrs	28.7	Spinal rigidity, genu valgum
Cognitive Deficit	Above 2.0	Children below 10 yrs	19.2	Poor recall, inattention
Renal Stress	Above 4.0	Adults above 40 yrs	14.5	Reduced GFR, flank discomfort
Thyroid Dysfunction	Above 2.5	Women 20–50 yrs	22.1	Sub-clinical hypothyroidism

Skeletal fluorosis was confirmed in 28.7 percent of adults aged 35–60 years in the surveyed households. A feature that struck the survey team repeatedly during field visits was how normalised these symptoms had become in affected communities. Respondents who described severe back pain, difficulty bending, and progressive stiffening of the knee joints typically attributed their condition to age or the physical demands of farming — not once did any of the 342 skeletal-fluorosis-positive respondents independently connect their condition to their drinking water. This finding has direct implications for health system design: primary care workers in fluoride-endemic areas need specific training to recognise and record skeletal fluorosis, and the data systems used by PHCs must include fluorosis as a codable diagnosis.

Cognitive screening of 614 children under ten years of age identified signs of memory impairment and attentional difficulty in 19.2 percent of children from high-fluoride villages. The proportion in control villages was 7.3 percent, a difference that was statistically significant ($\chi^2 = 18.4$, df = 1, $p < 0.001$). Thyroid irregularities, assessed primarily through symptom reporting and available health records, were documented in 22.1 percent of women aged 20–50 years in villages with fluoride above 2.5 mg/L. Early renal stress indicators, including self-reported urinary discomfort and GFR data available from a subset of PHC records, were noted in 14.5 percent of adults above forty years in the most contaminated locations.

Geochemical and Agricultural Drivers of Contamination

The geological inheritance of fluoride-bearing minerals in the aquifer matrix is the foundational cause of contamination across the study area. This much is established. What makes the situation in Western UP distinct, and what explains the higher fluoride values recorded here compared with earlier surveys conducted two or three decades ago, is the compounding effect of agricultural water use on aquifer chemistry. The region's water table has declined measurably over the past forty years as groundwater extraction for kharif and rabi crop irrigation has outpaced recharge. With shallower water tables, the saturated zone where dissolution actively occurs has expanded downward into older, more fluoride-rich formations. Simultaneously, the evaporative concentration of irrigation return water percolating back into the aquifer during the long dry months carries an elevated dissolved ion load, including fluoride leached from phosphate fertilisers applied in large quantities to sugarcane and wheat fields. Neither of these processes is immediately reversible, which means that even if extraction is moderated, residual fluoride concentrations in the shallow aquifer are likely to remain elevated for years. This long time horizon reinforces the case for prioritising household and community water treatment over waiting for natural aquifer recovery.

MITIGATION STRATEGIES

Any practical response to fluoride contamination in rural Western UP must work within the realities of the setting: variable electricity supply, low household incomes, limited technical capacity at the panchayat level, and a history of installed water treatment systems falling out of use within months of commissioning. With these constraints in mind, the study evaluated five defluoridation approaches on the basis of removal efficiency, operational simplicity, and realistic cost and maintenance burden in this specific context. Table 3 summarises the assessment.

Table 3: Comparative Evaluation of Defluoridation Options for Rural Western Uttar Pradesh

Technology	Mechanism of Action	Fluoride Removal (%)	Viability in Rural UP Context
Nalgonda Technique	Coagulation using alum and lime	70–80	Very High — materials locally available, no power needed
Activated Alumina	Ion-exchange adsorption on alumina beds	85–92	High — supported under Govt. schemes; needs regeneration
Bone Char Filtration	Fluoride uptake by calcium hydroxyapatite	75–85	Moderate — effective but faces cultural resistance
Reverse Osmosis	Pressure membrane separation	90–96	Low — electricity-dependent, high O&M cost
Rainwater Harvesting	Capture of naturally fluoride-free precipitation	~100 (source bypass)	Very High — seasonal but sustainable with storage

The Nalgonda technique stands out as the most immediately deployable option for the majority of affected villages. Its reliance on alum and lime — both cheap and available at any local input shop — means that households can start using it as soon as they receive basic training. The technique requires no electricity, no specialised equipment, and no imported components. Its limitations — primarily the need for disciplined and consistent application, the generation of a fluoride-laden sludge that must be disposed of safely, and a removal efficiency that may not be sufficient for sources above 4.0 mg/L — are manageable with proper community education and panchayat-level oversight.

Activated alumina filtration, increasingly supported through government-linked programmes, offers a higher and more consistent removal rate and is appropriate for community-level installations serving multiple households. The critical requirement is a functioning supply chain for regeneration chemicals and the presence of at least one trained operator per unit. Past experience in UP and neighbouring states suggests that state-level support for maintenance — ideally through a cluster-based service model in which one trained technician is responsible for a group of units across several villages — is the difference between systems that continue working for five years and systems that are abandoned in six months.

Rainwater harvesting deserves to be treated not as a supplementary option but as a strategic priority, particularly given the distinct seasonality of the contamination problem. Monsoon rainfall in this region is naturally free of dissolved fluoride. A household with a 10,000-litre ferrocement storage tank and a clean rooftop collection area can capture enough water during the four monsoon months to meet its drinking and cooking needs for much of the non-monsoon period. At the community level, larger storage structures serving multiple households offer even better economics. The Jal Jeevan Mission capital subsidy framework can be used to fund this infrastructure if gram panchayats are supported in preparing technically sound proposals.

CONCLUSION

This field investigation into groundwater fluoride contamination and its consequences for rural health in Western Uttar Pradesh yields three conclusions that, taken together, call for immediate and coordinated administrative action. The first is that the contamination is extensive: more than half of the groundwater sources sampled across five districts contain fluoride above the safety limit, and concentrations in a significant minority of sources are high enough to cause serious long-term damage to all physiological systems that fluoride is known to affect. The second is that the damage is already happening: dental fluorosis in children, skeletal fluorosis in adults, neurological impairment in young children, and thyroid and renal stress in women are all documented at rates that cannot be dismissed as isolated or coincidental. The third is that the affected communities are largely unaware of the connection between their water and their health — a gap in awareness that both deepens the human cost and represents an opportunity for relatively low-cost public health intervention.

The technical pathway to managing this problem is clear. Community-level defluoridation using the Nalgonda technique can be deployed quickly and cheaply. Activated alumina units can be installed and sustained where maintenance support is organised properly. Rainwater harvesting can reduce dependence on fluoride-contaminated groundwater for drinking during and after the monsoon. None of these solutions requires new technology or extraordinary budget allocations — they require sustained administrative attention and a commitment to following through beyond the installation stage.

What this study points toward, ultimately, is the need for district-level fluoride action plans — working documents that map contaminated habitations, assign defluoridation technologies matched to local conditions, define timelines for Jal Jeevan Mission piped water connections in the most severely affected areas, and establish a mechanism for monitoring both water quality and health outcomes over time. The science is available. The affected population is identifiable. The solutions are tested. The remaining variable is institutional will, and it is the one that this study, by placing field evidence on the table, hopes to help tip in the right direction.

ACKNOWLEDGEMENTS

Fieldwork of this nature depends on the goodwill and patience of the people it studies, and the author records sincere appreciation to the gram panchayat heads, village residents, and primary health centre staff across Agra, Mathura, Aligarh, Bulandshahr, and Etah districts who gave their time and trust to this investigation. Laboratory analysis was carried out with the support of the technical staff at Shobhit University, Gangoh, whose precision and diligence underpinned the reliability of the findings. Data on district-level water quality trends were provided by the State Water and Sanitation Mission, Uttar Pradesh, and the author gratefully acknowledges this institutional cooperation.

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