Fluoride contamination in groundwater of Birbhum district, West Bengal: A scientific review

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Abstract: Fluoride contamination in groundwater is a pressing environmental and public health issue, particularly in the semi-arid western blocks of Birbhum district, West Bengal. This review explores the extent, geochemical mechanisms, spatial distribution, health impacts, and mitigation strategies related to fluoride in the region. The problem is primarily geogenic, driven by the dissolution of fluoride-bearing minerals such as fluorapatite and biotite within the district's Precambrian crystalline rocks. These processes are intensified by high evapotranspiration, low rainfall, and extensive groundwater extraction, especially in blocks like Rajnagar and Dubrajpur. Groundwater fluoride concentrations in some areas exceed the WHO guideline of 1.5 mg/L, resulting in widespread dental and skeletal fluorosis, particularly among children and the elderly. Spatial and seasonal variability is influenced by geology, hydroclimatic conditions, and aquifer characteristics. Despite the availability of defluoridation technologies like the Nalgonda technique, activated alumina filters, and reverse osmosis, implementation challenges persist due to economic, technical, and social barriers. The review highlights critical research gaps in fluoride geochemistry, health risk assessment, and community-level awareness. A multidisciplinary approach combining hydrogeological assessment, public health strategies, and policy intervention is essential to mitigate the crisis and ensure safe drinking water access in fluoride-prone areas of Birbhum.

Keywords :Fluoride Contamination**,** Groundwater**,** Birbhum District**,** Geogenic Sources, Defluoridation Techniques.

1. Introduction:

The most precious natural resources that are very essential for sustenance of life on the globe are air and water. Surface water and groundwater are two major sources of water. Most of the population of the world depends on groundwater for their daily needs, especially for drinking purposes [1] because of inadequacy of surface water. India is the largest user of groundwater in the world. Annual usage is around 230 cubic kilometers (World Bank, 2012) which seems that 80% of domestic needs in rural areas and 60% in urban areas are met by ground water. But due to high population growth, industrialization, urbanization and intensive agriculture, the groundwater resources are under high risk and are now the major impacts on human health as well as on ecosystem and economy.

Fluoride and Arsenic are two geogenic lethal elements threats to health from the world's drinking-water resources. More than 300 million people (Bhattacharya et al., 2020; Bibi et al., 2017) across the globe is threatened by arsenic concentration above the 10 micrograms per liter (μg/L) WHO guideline value [2] and 200 million or more are considered at risk from fluoride concentrations above the 1.5 mg/L WHO guideline value [3] in drinking water.

Fluoride is one of the essential elements for humans; however, the excessive concentration may cause serious health hazards. prolonged exposure to concentrations exceeding 1.5 mg/L can result in dental and skeletal fluorosis, particularly in children and young adults (WHO, 2017). In many parts of India, including regions of West Bengal like Birbhum, fluoride levels in groundwater have been recorded well above the permissible limits. The factors influencing groundwater fluoride contamination include pH-dependent dissolution [4], aqueous ionic concentrations [5], rock-water interactions and contact time [6], atmospheric deposition [7], and mobilization through carbonate and bicarbonate ions [8].

Birbhum district, located in the western part of West Bengal, is geologically unique. Its terrain transitions from lateritic uplands and crystalline rocks in the west to alluvial plains in the east, influencing both groundwater chemistry and contaminant profiles. In recent decades, reports of endemic fluorosis in villages such as Khayrasole, Rajnagar, and Suri have drawn attention to the growing fluoride crisis in the region [9]. This review aims to comprehensively assess the extent, geochemical causes, health implications, and mitigation strategies of fluoride contamination in Birbhum's groundwater.

2. Geological and Hydrogeological Context of Birbhum

Birbhum district spans an area of approximately 4,545 km² and comprises 19 development blocks. It is bounded by the Santhal Parganas of Jharkhand to the west and Murshidabad district to the east. Geologically, Birbhum features a dual landscape- Western part is characterized by Precambrian crystalline formations, including granite, gneiss, and laterites, while the eastern region is defined by Quaternary alluvial deposits composed of sand, silt, and clay [10]. The groundwater regime in Birbhum consists primarily of two aquifer systems: the Shallow Aquifers ranging from 20-50m deep which are more vulnerable to seasonal fluctuations and microbial contamination, and the deep Aquifers extending from 50–150m, ate typically tapped for rural drinking water supply and more influenced by geogenic contamination like fluoride [11]. The region's semi-arid climate results in significant evaporation and reduced recharge, especially in the western blocks. These hydroclimatic conditions favor long residence times and greater rock-water interactions, increasing the mobilization of fluoride ions into groundwater systems [9].

3. Distribution and Spatial Trends of Fluoride Contamination

A wide range of studies and government surveys have documented the spatial distribution of fluoride in Birbhum's groundwater [12-16]. Based on data from the Public Health Engineering Department (PHED) and recent hydrogeochemical investigations, the fluoride concentration in the district is ranges between 0.1 and 19 mg/L.

Block-Wise Trends

The Geological Survey of India (GSI**)** has carried out groundwater quality assessments in various districts across India, including Birbhum district of West Bengal. Zone with varying fluoride concentration across the different parts of the district are clearly marked (Figure 1) [17] Based on available data Rajnagar, Khayrasole, Dubrajpur, Suri-I and II are the High fluoride contaminated blocks. Nalhati, Murarai-I and II and Labhpur are Moderate contaminated blocks while Bolpur-Sriniketan, Rampurhat I & II and Mohammad Bazar are low contaminated blocks [12-16]. A detailed summary of GSI-based fluoride zoning in the groundwater of Birbhum are given bellow (Tasble1 & 2).

Table 1. Fluoride Zoning in Birbhum District (Safe, Moderate, High-Risk Zones)

Zone	Fluoride Concentration (mg/L)	Location (Blocks/Areas)	Remarks
Safe Zone	< 1.0	Rampurhat I & II, Nalhati I, Mohammad Bazar, Rajnagar (most areas)	Suitable for drinking
Moderate Zone	1.0–1.5	Parts of Dubrajpur, Suri I & II, Khoyrasol	Borderline for long-term consumption
High-Risk Zone	> 1.5	Parts of Dubrajpur, Khoyrasol, Suri II, Nalhati II	Not suitable for drinking; fluorosis-prone zones

Table 2. Fluoride Hotspot Areas in Birbhum

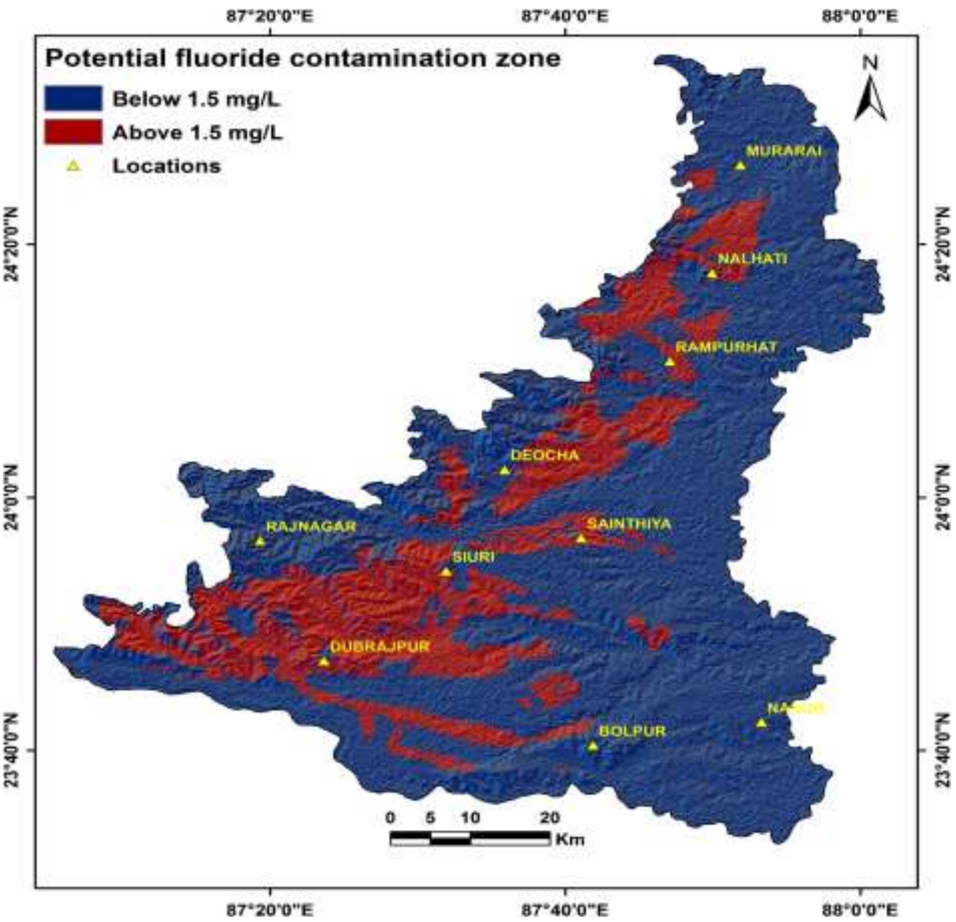
Block/Area	Fluoride Range (mg/L)	Source
Khoyrasol	2.0 – 4.5	[12]
Dubrajpur	1.8 – 3.9	[13,14]
Nalhati II	1.5 – 2.2	[15]
Suri II	1.4 – 2.5	[16]

Seasonal Variation

Seasonal variations significantly influence the concentration of fluoride in the groundwater of Birbhum district. Empirical studies and hydrochemical surveys have consistently reported that fluoride concentrations are notably higher during the pre-monsoon period compared to post-monsoon seasons. This seasonal disparity is primarily attributed to reduced dilution of groundwater by rainwater recharge, which is naturally higher during the monsoon. During the pre-monsoon months (March–June), evapotranspiration rates are intensified due to high ambient temperatures and semi-arid climatic conditions, particularly in the western and northwestern blocks, such as Dubrajpur, Khoyrasol, and parts of Nalhati II [18]. This leads to a decrease in the water table and concentration of dissolved ions, including fluoride, in the groundwater.

Additionally, GIS-based spatial analyses and temporal monitoring have revealed a persistent pattern of elevated fluoride concentrations in the western and northwestern parts of Birbhum throughout the year, with a peak in pre-monsoon. These regions are underlain by Precambrian granitic and gneissic formations, which contain fluoride-bearing minerals such as fluorite, apatite, and biotite. The longer residence time of groundwater in these hard rock aquifers during the dry season enhances rock-water interaction, promoting the dissolution and mobilization of fluoride into the aquifer systems [11]. Furthermore, limited monsoonal recharge in these areas restricts natural dilution, thereby exacerbating the fluoride enrichment.

Figure 1. Potential fluoride contaminated zone of Birbhum District. Reported from Thapa et al. (2017). [17]



4. Geochemical Controls on Fluoride Mobilization

The primary origin of fluoride in groundwater is geogenic source [8]. The majority of fluoride in groundwater comes from weathering of granites and felsites rocks, which contain fluoride-bearing minerals such as fluorspar, cryolite, fluorapatite, and hydroxyapatite, leaching processes, and subsequent percolating through soil and sediments. A number of anthropogenic activities also significantly increase the concentration of fluoride in groundwater with fluorinated industrial waste from iron, steel, glass, and aluminum industries, or agricultural activities by using phosphate fertilizers and certain pesticides [19]. The following processes are responsible for fluoride release in Birbhum's aquifer systems:

Mineral Dissolution

In the western region of Birbhum district**,** which is geologically dominated by Precambrian crystalline rocks such as granite**,** gneiss**,** and associated pegmatitic intrusions**,** fluoride-bearing minerals like fluorapatite ($Ca_5(PO_4)_3F$)**,** biotite**,** and amphiboles are naturally present. These minerals undergo chemical weathering when they interact with percolating groundwater, especially in fractured and weathered zones of the rock.

The reaction of fluorapatite ($Ca_5(PO_4)_3F$) in groundwater leads to fluoride dissolution, especially in alkaline pH environments. Under alkaline conditions **(**$pH > 7.5$**)**, the solubility of fluorapatite increases because phosphate and calcium ions are removed from solution via secondary precipitation (e.g., calcite or hydroxylapatite), which shifts the equilibrium to release more fluoride ions (F^-) into groundwater [11].

$$Ca_5(PO_4)_3F\ (s) \rightleftharpoons 5Ca^{2+} + 3PO_4^{3-} + F^- \quad (1)$$

Ion Exchange

The geochemical behavior of fluoride in groundwater is closely tied to the presence of other major ions, especially calcium (Ca^{2+}) and bicarbonate (HCO_3^-). The replacement of bicarbonate (HCO_3^-) and calcium (Ca^{2+}) ions affects fluoride solubility. In Na–HCO_3-dominated groundwater**,** which is typical of weathered granitic and gneissic terrains**,** several geochemical processes change the equilibrium. When HCO_3^- concentrations are high**,** calcium ions preferentially react with bicarbonate to form calcium carbonate

$$Ca^{2+} + 2HCO_3^- \rightarrow CaCO_3(s) + CO_2 + H_2O \quad (2)$$

This reaction lowers the concentration of free Ca^{2+} in the groundwater. As Ca^{2+} is removed**,** the precipitation of CaF_2 is inhibited, which means that fluoride remains in the dissolved state [11].

Evaporation

In semi-arid regions, the high rate of evaporation leads to the concentration of dissolved ions, including fluoride, in soil and groundwater [20]. The Rajnagar and Dubrajpur blocks, located in the western part of Birbhum district, are underlain by hard crystalline rocks such as granite and gneiss, which contain fluoride-bearing minerals. These areas receive limited rainfall, while water loss through evaporation and plant transpiration is considerably high. This climatic imbalance results in reduced groundwater recharge and promotes the accumulation of dissolved salts, including fluoride, thereby elevating fluoride concentrations in the subsurface water [21].

5. Public Health Implications

Dental Fluorosis

Dental fluorosis is recognized as the earliest and most visible indicator of chronic fluoride toxicity, primarily resulting from the prolonged ingestion of fluoride-contaminated water during the critical years of tooth development, typically from birth to around eight years of age [22]. Excessive fluoride intake during this period disrupts the function of ameloblasts, the enamel-forming cells, leading to improper formation of the enamel matrix and delayed mineralization. This pathological process results in a hypomineralized, porous enamel structure with varying degrees of discoloration and surface irregularities [23].

In fluoride-endemic regions such as the Rajnagar and Dubrajpur blocks of Birbhum district**,** epidemiological studies have reported a high prevalence of moderate to severe dental fluorosis among children, which correlates with groundwater fluoride concentrations often exceeding the World Health Organization’s permissible limit of 1.5 mg/L [21]. These clinical findings reflect the long-term exposure to naturally occurring fluoride in the hard rock aquifers that dominate the geology of the area.

Skeletal Fluorosis

Skeletal fluorosis is a crippling bone disease caused by long-term ingestion of high levels of fluoride, typically through drinking water. Unlike dental fluorosis, which is visible in early life, skeletal fluorosis develops gradually over years or decades, primarily affecting bones and joints**.** Fluoride accumulates in the skeletal tissues, substituting hydroxyl ions in hydroxyapatite to form fluorapatite, thereby altering bone structure and density [24].

In Birbhum, particularly in the blocks like Rajnagar and Dubrajpur, prolonged consumption of groundwater with fluoride concentrations above 3–4 mg/L has been associated with cases of skeletal abnormalities, especially in older adults and those with high daily water intake. Although systematic health surveys in Birbhum are limited, anecdotal and field reports have indicated early symptoms of skeletal fluorosis in several villages where groundwater is the primary source of drinking water and fluoride levels often exceed WHO limits [21].

6. Remediation and Mitigation Strategies

Several techniques have been developed to mitigate fluoride contamination in drinking water, each with varying applicability based on scale, cost, and efficiency. The Nalgonda technique, widely used in rural India, involves the addition of lime and alum to precipitate fluoride as insoluble complexes; although cost-effective and simple, it generates fluoride-rich sludge requiring careful disposal [25]. Ion exchange resins, particularly those based on anion exchange, are effective at household levels but demand regular regeneration with brine solutions and are sensitive to pH fluctuations [26]. Reverse Osmosis (RO) systems offer high fluoride removal efficiency (95–98%) and are increasingly deployed in rural schools and health centers, though their high initial cost and maintenance needs pose barriers to widespread adoption [27]. Activated alumina filters are another common solution for point-of-use treatment; when properly maintained, they efficiently reduce fluoride levels and are used in government-promoted filters such as “JalKalp” in high-risk regions [27]. A more recent innovation, Subterranean Fluoride Removal (SFR), is currently under trial in parts of India; it involves injecting chemically treated water into aquifers to promote in-situ reactions that immobilize fluoride before it enters wells [28]. These methods offer promising solutions, but site-specific conditions, operational challenges, and sustainability must be considered when selecting the appropriate defluoridation strategy.

7. Research lacunae and Community awareness

Despite decades of investigation, several research lacunae persist in understanding and mitigating fluoride contamination in groundwater. Firstly, there is a lack of high-resolution spatial and temporal data on fluoride concentrations across many rural regions, including parts of Birbhum district, which limits effective risk mapping and intervention planning. Secondly, while the geogenic sources of fluoride are broadly recognized, the site-specific geochemical interactions, such as ion exchange, weathering kinetics, and the role of bicarbonate and calcium ions remain insufficiently understood in diverse hydrogeological settings. Thirdly, the long-term health impacts of chronic fluoride exposure beyond dental and skeletal fluorosis, including potential effects on the nervous, reproductive, and endocrine systems, require more in-depth epidemiological and toxicological studies and finally, community awareness, behavioral practices, and socio-economic barriers to the adoption of mitigation technologies are often overlooked in technical studies. Addressing these knowledge gaps is essential for developing holistic, region-specific fluoride management strategies that integrate hydrogeological science with public health, technology, and policy frameworks.

8. Conclusion

Fluoride contamination in the groundwater of Birbhum district, particularly in its western blocks such as Rajnagar and Dubrajpur, has emerged as a significant environmental and public health concern. The primary source of elevated fluoride levels is geogenic, resulting from the weathering and dissolution of fluoride-rich minerals in hard crystalline rocks like granite and gneiss. This natural process is further intensified by semi-arid climatic conditions, high evapotranspiration, and excessive groundwater extraction. As a result, fluoride accumulates in aquifers, posing long-term risks to the population. Sustained consumption of fluoride-laden water has led to widespread cases of dental and skeletal fluorosis, affecting both children and adults. Despite the availability of several defluoridation techniques, their implementation remains limited due to economic and infrastructural barriers. A comprehensive approach involving scientific monitoring, community awareness, safe water provision, and policy support is essential to mitigate the impact and ensure the health and well-being of affected populations.

Conflict of Interest

The author declares that there is no Conflict of interest.

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