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# Fluoride toxicity in groundwater of Rajasthan: A regional review of environmental and health complications

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**Abstract**
Fluoride contamination in groundwater poses a significant environmental and public health challenge in Rajasthan, India. This review critically examines the widespread fluoride toxicity in various districts of Rajasthan, elucidating the hydrogeological factors contributing to fluoride enrichment and the resultant health effects, particularly dental and skeletal fluorosis. This review synthesizes data from national and international studies, discussing fluoride distribution, permissible limits, and the most vulnerable communities. Despite several government and scientific interventions, sustainable mitigation remains elusive. In order to lessen the health effects of fluoride in Rajasthan, the study highlights the pressing need for integrated community awareness, legislative changes, and the implementation of cost-effective and efficient defluoridation methods.

**Keywords:** Fluoride contamination, fluorosis, groundwater, public health

## Introduction
Fluoride is a naturally occurring ion found in soil, rocks, and water, released into groundwater through geological processes. While fluoride is essential in trace amounts (0.5 to 1.0 mg/l) for dental health and prevention of caries, chronic ingestion of fluoride above the safe threshold (1.5 mg/l as per WHO guidelines) can lead to severe health disorders (Ayoob & Gupta, 2006) [2]. Regions with arid to semi-arid climates, such as Rajasthan, experience fluoride accumulation in groundwater due to slow recharge, intense evaporation, and mineral dissolution (Arif *et al*., 2013) [1]. This review focuses on Rajasthan, highlighting fluoride toxicity as a critical health and environmental issue, analyzing its causes, effects, and mitigation efforts.

## Hydrogeological and Climatic Context of Rajasthan
Rajasthan's geology is dominated by Precambrian crystalline rocks, including granites, gneisses, and schists, which contain fluoride-bearing minerals such as fluorite and biotite. Weathering and leaching of these minerals release fluoride ions into aquifers (Saxena & Ahmed, 2001; Choubisa, 2022) [6, 25]. The semi-arid climate with low rainfall combined with high temperatures causes excessive evaporation, concentrating dissolved solids, including fluoride, in groundwater the hard rock aquifers, being relatively impermeable, promote prolonged water-rock interactions, further elevating fluoride levels (Trivedi, 2022) [31]. Moreover, over-extraction of groundwater for agriculture and domestic use leads to lowering of water tables and concentration of contaminants (Khatri and Tyagi, 2015) [14]. Thus, hydrogeology and climatic factors synergistically exacerbate fluoride contamination in Rajasthan's groundwater.

## Fluoride Distribution in Rajasthan
Extensive hydrochemical surveys reveal alarming fluoride concentrations exceeding the WHO permissible limit of 1.5 mg/l in many districts of Rajasthan. Districts such as Nagaur, Jodhpur, Barmer, Jhunjhunu, and Dausa often recorded fluoride concentrations ranging from 3.5 to 8 mg/l or higher (Kumar & Singh, 2015; Ozha, 2022) [15, 23]. Choubisa (2001) [4] documented endemic fluorosis in southern Rajasthan districts like Dungarpur, Udaipur, and Banswara, confirming fluoride's widespread prevalence. The problem is exacerbated in rural areas where groundwater is the primary drinking water source and alternative safe sources are limited (Tiwari *et al*., 2020) [29]. Studies have also reported temporal variations, with fluoride concentrations rising during dry seasons due to reduced recharge and increased evaporation (Choubisa *et al*., 2010). This uneven distribution poses challenges for water management and public health protection.

## Health Impacts of Fluoride Toxicity
### Dental Fluorosis and Skeletal Fluorosis
Dental fluorosis is the earliest visible sign of fluoride toxicity, characterized by mottling, discoloration, and pitting of enamel in domestic animals. Mild fluorosis manifests as white opaque spots, while severe cases lead to brown stains and enamel loss, affecting aesthetics and dental function (Panchal and Sheikh, 2017; Choubisa, 1999) [3, 24]. In Rajasthan, high prevalence rates are reported among children in endemic zones, with surveys indicating fluorosis rates exceeding 30% in some villages (Choubisa, 2001) [4]. Prolonged ingestion of high fluoride levels causes skeletal fluorosis, a crippling disease with symptoms like joint pain, stiffness, bone deformities, and impaired mobility in animal as well as in human beings. Early stages involve mild joint discomfort, but advanced fluorosis leads to calcification of ligaments and skeletal deformities, often disabling the affected individuals (Sheikh Z and Panchal L, 2018; Kruland *et al*., 2007) [26]. Skeletal fluorosis is prevalent among adults in high-fluoride regions of Rajasthan, especially that consuming groundwater as the sole drinking source for decades (Choubisa *et al*., 2010).

### Non-skeletal Effects
Recent studies highlight fluoride's impact beyond bones and teeth, including neurotoxicity, thyroid dysfunction, and reproductive health problems (Grandjean, 2019) [11]. Fluoride can cross the blood-brain barrier and potentially reduce IQ in children exposed to elevated fluoride during

developmental stages (Guth *et al*., 2020; Gosh and Gosh, 2020) [12]. Additionally, renal damage and gastrointestinal disturbances have been linked to chronic fluoride exposure (Malin *et al*., 2019; Dharmaratne, 2019) [8, 17]. These findings underline fluoride's systemic toxicity and demand comprehensive health risk assessments.

**Socioeconomic Impacts**

Fluoride toxicity disproportionately affects rural, low-income populations dependent on groundwater. The economic burden of fluorosis includes direct healthcare costs and indirect costs like loss of productivity due to disability (Khatri & Tyagi, 2015) [14]. Many impacted families in Rajasthan must pay for regular checkups, medical care, and in extreme situations, lifelong care (Choubisa, 2001) [4]. Physical deformities resulting from skeletal fluorosis lead to social stigma and reduced quality of life, compounding mental health issues. Women and children, often with limited access to healthcare, are the most vulnerable groups.

**Government and Scientific Interventions**

The Indian government has launched various initiatives such as the National Programme for Prevention and Control of Fluorosis (NPPCF), aiming to provide safe drinking water and raise awareness (Mukherjee *et al*., 2021) [20]. The Nalgonda technique, a chemical defluoridation method involving alum and lime, is promoted in some regions for household water treatment (Jamwal and Slathiya, 2022; Choubisa, 2023) [5, 13]. Additionally, schemes like rainwater harvesting and piped water supply under the Jal Jeevan Mission attempt to reduce groundwater dependency.

Despite these efforts, challenges remain in the scalability and maintenance of defluoridation units, lack of awareness, and funding constraints, especially in remote areas (Choubisa *et al*., 2010; Dubey *et al*., 2018) [9]. Scientific research continues to explore novel and low-cost techniques suitable for local adoption.

**Mitigation Strategies**

**Short-Term Measures**

Household-level defluoridation using activated alumina, bone char, or locally available adsorbents can reduce fluoride exposure effectively (Tomar and kumar, 2013; Meenakshi & Maheshwari, 2006) [18, 30]. Promoting rainwater harvesting also provides fluoride-free water during monsoons, supplementing contaminated groundwater.

**Long-Term Measures**

Sustainable groundwater management includes artificial recharge of aquifers to dilute fluoride concentration. Alkaline circumstances with a reasonable level of specific conductivity are favorable for fluoride dissolution from fluorite to water (Saxena & Ahmed, 2001) [25]. Crop diversification and water-saving irrigation reduce groundwater extraction pressure (Khatri & Tyagi, 2015). Community education campaigns are essential to increase awareness about fluoride risks and preventive actions.

**Comparative View**

Fluoride contamination is a global concern affecting regions such as parts of China, East Africa, and the Rift Valley, where geological and climatic factors are similar (Davies, 2008; Onipe *et al*., 2020) [7, 22]. Within India, apart from Rajasthan other states like Andhra Pradesh, Gujarat, and Tamil Nadu also report fluoride-related health issues (Dubey *et al*., 2018; Yasaswini *et al*., 2024) [9, 34]. Rajasthan's unique combination of arid climate, geology, and water scarcity intensifies vulnerability. International case studies emphasize community involvement and appropriate technology for effective mitigation, lessons valuable for Rajasthan's context (UNICEF, 1999; Meenakshi & Maheshwari, 2006) [18, 32].

**Conclusion**

Fluoride toxicity in Rajasthan's groundwater is a well-established environmental and public health challenge. Despite ongoing government programs and technological solutions, the problem persists due to geographical, socio-economic, and infrastructural constraints. Multi-pronged strategies including scientific research, low-cost defluoridation techniques, community education, and sustainable water resource management are imperative. Future efforts must prioritize vulnerable populations and ensure scalable, affordable, and culturally acceptable mitigation measures to safeguard public health in Rajasthan.

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