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Fluoride contamination a silent global water crisis: A Case of Africa

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ABSTRACT

Fluoride contamination in drinking water poses a global health risk, affecting millions worldwide, with Africa bearing a disproportionate burden due to unique geological factors like the East African Rift Valley. High fluoride levels in groundwater in these regions contribute to widespread health problems, notably dental and skeletal fluorosis, which impair quality of life and economic productivity. This study aims to evaluate the scope of fluoride contamination across continents, examining how Africa compares to regions like Asia, North America, and Europe. While some countries have mitigated contamination through advanced water treatment and regulatory measures, Africa still faces significant challenges due to limited infrastructure and resources. Findings highlight that addressing fluoride contamination in Africa requires a targeted approach, involving affordable treatment solutions, regulatory reforms, and community awareness programs. By outlining these strategies and emphasizing international cooperation, this study underscores the urgency of safeguarding health and well-being across affected African communities.

Introduction

Fluoride is a naturally occurring element in various geological formations, and its presence in groundwater and surface waters can lead to contamination [1], and impairing ecological health. In its natural formation, fluoride exists in form of complex minerals in the soil. These complex compounds are merely inert in their own, however, processes such as weathering and dissolution of fluoride-containing minerals such as fluorite (CaF₂), apatite, and micas found in rock formations, leaching, dissolution, ion exchange, and anthropogenic activities such as the use of phosphate fertilizers highly contribute to their existence in the water [2]. Dynamic water sources such as rivers, and percolation have a dynamic concentration of fluoride. Stagnant water sources such as closed lakes and water wells have a high concentration of fluoride due to natural saturation processes [2]. In its natural form, fluoride undergoes a

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noticeable chemical reactions that contribute to its abundance in the water [2]. Some of these reactions are presented in chemical Equations 1–2. Anthropogenic sources, such as effluents from industrial activities [3,4], agricultural runoff [3,4], and improper disposal of fluoride-rich waste [3,5], significantly contribute to contamination. Fluoride-containing minerals, such as fluorite (CaF_2) and apatite [$\text{Ca}_5(\text{PO}_4)_3(\text{F},\text{OH},\text{Cl})$], undergo natural weathering, releasing fluoride ions into the soil and groundwater.



Phosphate rocks contain fluoride as a contaminant. During the processing of these rocks to produce fertilizers like superphosphate, fluoride is released into the environment.



Water is often celebrated as the source of life, habitat, energy, transportation, domestic uses, agriculture, and industrial uses, a fundamental human right [6], and a symbol of purity [6]. Water has spiritual and religious accountability [7,8]. It is believed that Earth's water is likely a combination of both internal (primordial) sources and external sources (comets and asteroids) [9]. The asteroid theory, especially involving carbonaceous chondrites, is strongly supported, but Earth's initial formation also likely trapped water-bearing materials [9]. Natural water is pure, clean and safe yet, beneath the serene surface of rivers, lakes, and groundwater lies an alarming and often unnoticed menace among others, the fluoride contamination. While this issue is gaining an attention on the global stage, it poses a significant environmental and public health challenge, quietly affecting millions of people across the globe, which imperatively require immediate actions. According to the World Health Organization (WHO) fluorosis, a disorder caused by high fluoride in drinking water, affects over 200 million people globally [10–12]. In Africa, it is estimated that over 40 million people suffer from dental or skeletal fluorosis, primarily in countries such as Kenya, Tanzania, and Ethiopia [13]. Similarly, in Asia [14], especially countries like India and China [15], around 80–90 million people are affected by various forms of fluorosis [16]. Fig. 1 presents effects of fluoride contamination of dental.

These regions tend to have high natural fluoride levels in groundwater, particularly in arid and semi-arid regions, where long-term exposure leads to health complications [16,18], with children and expectant mothers being more vulnerable. Fluoride pollution can have a variety of harmful consequences on both human and ecological health, especially when it occurs in drinking water or other sources in excess levels [38,111,112], their effects vary depending on the levels and exposure duration. Health implications of fluoride pollution and exposure are significant and multifaceted [112–118]. Prolonged exposure to elevated fluoride levels, often within drinking water, may lead to dental fluorosis, this condition is particularly prevalent among children, impacting their dental health and self-esteem [112–118]. Moreover, long-term exposure may result in skeletal fluorosis, causing painful joint and bone problems, diminishing quality of life. Mainly, fluoride can enhance bone density by promoting the formation of fluoroapatite, but excessive exposure leads to skeletal fluorosis, characterized by impaired bone quality and increased brittleness [119]. While fluoride does not directly deplete calcium and phosphorus, it disrupts their metabolism [119], affecting normal bone remodeling and mineralization processes.

Table 1 presents reported effects of fluoride contamination on human and ecological well-being. Vulnerable populations in affected



Fig. 1. Effects of fluoride contamination, dental fluorosis (A-D), and skeletal fluorosis (E-F). (Source: [17]).

areas, often lacking access to alternative water sources, bear the brunt of these health risks [10–12]. Vulnerable populations, especially in resource constrained regions like Africa bear a disproportionate burden of health effects resulting from fluoride contamination [12, 42]. When it comes to accessing safe drinking water and healthcare [11,91,118,121], these marginalized communities many of which are found in rural or underdeveloped areas face difficulties. This is due to lack of access to clean drinking water alternatives, which increases their exposure to fluoride [1], and unaware of the risks associated with fluoride contamination, hence depend on local water supplies that may be contaminated with high amounts of fluoride [28]. Communities may lack access to educational resources or information campaigns that can inform them about the importance of safe water practices. Therefore, measures are required to ensure availability of clean, safe and affordable drinking water for all to ensure safety.

Table 1
Reported impacts of fluoride pollution and exposure to human and ecological health.

Effects	Cause	Characteristics	Affected countries or location	Implication	References	
Dental	Dental Fluorosis	Prolonged exposure to elevated fluoride levels above 1.5 mg/L during tooth development, especially in childhood, can lead to dental fluorosis	Visible dental changes such as staining, pitting, and enamel discoloration	Kenya, Tanzania, Ethiopia, India, Pakistan, Morocco, Algeria, Tunisia, China, Mexico, USA, Saudi Arabia and Yemen	Dental fluorosis is primarily a cosmetic issue, severe cases can result in enamel loss and structural damage to teeth	[19–21]
Skeletal	Skeletal Fluorosis	Long-term exposure to high fluoride levels ranging from 4.0 mg/L to 10.0 mg/L or higher	Affects bones and joints, including joint pain, limited mobility, and bone deformities	India, China, Kenya, Tanzania, Ethiopia, Turkey, Morocco, Algeria, Tunisia, Mexico, Morocco and Algeria	In severe cases, skeletal fluorosis can lead to disability and decreased quality of life	[22,23]
Neurological	Neurodevelopment Effects	Long-term exposure to high fluoride levels ranging from 3.0 mg/L to 11.0 mg/L	Fluoride exposure and adverse effects on neurological development, mainly in children linked	India, China, Mexico, USA, Kenya, and Tanzania	Symptoms such as nausea, vomiting, and abdominal pain	[4]
Gastrointestinal	Gastrointestinal Distress	High fluoride levels ranging from 1.0 mg/L to 5.0 mg/L can lead to gastrointestinal distress	Kidney associated symptoms	India, China, Ethiopia, Sri Lanka, Mexico, Kenya, and USA	Research in this area is ongoing, and more evidence is needed to establish causation definitively	[24]
Renal	Kidney Damage	Prolonged exposure to elevated fluoride ranging from 2.0 mg/L to 8.0 mg/L	Potentially affecting hormone production and function.	India, China, Ethiopia, Kenya, Sri Lanka,	Measures are necessary for ecological safety	[25,26]
Endocrine	Endocrine Disruption	High fluoride exposure may disrupt the endocrine system, ranging from 0.7 mg/L to 6.0 mg/L	Ecological disruption	China, India, Mexico, USA, Ethiopia, Kenya and Sri Lanka	This effect is generally associated with extremely high and chronic exposures.	[26,27]
Environmental	Ecosystem Disruption	Fluoride contamination in aquatic ecosystems can harm aquatic life	Ecological disruption	Japan, Russia, China, India, South Africa, Brazil, Canada, Norway, and USA	Research in this area is ongoing, and the exact mechanisms are not fully understood	[27]
	Soil Contamination	Excessive fluoride in soil can affect crop growth	Reduced agricultural yields		It can interfere with the growth and reproduction of aquatic plants and animals, disrupting the balance of ecosystems	[28]
	Air Pollution	Some industrial processes release fluoride into the air, contributing to air pollution	Ecological disruption		This is of particular concern in regions where fluoride-rich water is used for irrigation.	[29]
Cumulative Health Effects	Cumulative Impact	Prolonged exposure to even moderately elevated fluoride levels can result in health problems, particularly in regions where multiple sources of fluoride exposure exist	Ecological disruption	Globally	In extreme conditions, it may adversely damage several other delicate parts of a human being	[5,30,31]

Fig. 2 presents predicted areas with probability of fluoride concentration in the groundwater exceeding the WHO guideline for drinking water of 1.5 mg/L. Map shows area with poor prediction indicating the need for further studies to update the status. High fluoride levels in ground and drinking waters are particularly common in regions with fluoride-rich geological formations [16] such as the North Africa, Asia, Australia and the Lower tip of Southern America. Excessive fluoride intake, primarily through drinking water, can have adverse health effects. Damage to the enamel and tooth discolorations are symptoms of dental fluorosis, which is a prevalent dental health issue. Long-term exposure to excessive fluoride levels can cause skeletal fluorosis, leading to issues with the bones and joints [16,18,32,33], requiring intervention to ensure safety. Among the intervention includes to ensure access to clean and safe drinking water to communities. This agrees with SGD 6, with primary focus of ensuring access to clean and safe drinking water [34,35]. This includes improving water quality by reducing pollution, eliminating dumping, and minimizing the release of hazardous chemicals and materials. SDG 6 also emphasizes the need for adequate and equitable sanitation and hygiene for all [34]. Further, provision of clean water, sanitation, and hygiene are critical for preventing waterborne diseases such as cholera, dysentery, and typhoid [34].

By reducing the incidence of these diseases, communities can achieve better overall health and well-being, SGD 3. Similarly, lack of access to clean water and sanitation can perpetuate poverty by increasing health care costs and reducing productivity [37], SGD 1. By addressing these issues, communities can break the cycle of poverty and improve their economic prospects. Addressing fluoride contamination is crucial to prevent these health concerns [37]. Fig. 3 presents published articles globally on fluoride contamination of ground, surface, and drinking waters, soils, and sediments, including reports of ecological exposure and health implications, requiring intervention to ensure ecological safety. Widespread contamination highlights the need for global monitoring, mitigation efforts, and public health interventions to manage fluoride exposure and prevent its ecological and health impact.

While some regions in the world contains other forms of natural water contaminants such as hardness, soda and salts, about 5–10 % of global fresh water contains fluoride that necessitate global efforts to mitigate fluoride contamination, employing both prevention and treatment measures [28]. Identifying contamination sources and regulating industrial discharges is essential. Water treatment technologies like defluoridation filters and chemical coagulation can effectively reduce fluoride levels in drinking water [3,28]. Community awareness and education programs [38,39], plays a pivotal role in promoting safe water consumption practices and raising awareness of the risks associated with fluoride contamination. Fluoride contamination poses a multifaceted challenge that necessitates a holistic approach encompassing source identification, regulation, and treatment that inherently call for SDG 17 (working together). Protecting human health and safeguarding the environment require concerted efforts at the local, national, and global levels. The negative impacts of fluoride contamination can be lessened to enhance the wellbeing of communities all over the world by putting into practice efficient mitigation techniques and providing access to safe drinking water. This review explores the multifaceted challenges of fluoride contamination in African water sources, its causes, health implications, and the urgent need for comprehensive solutions for ecological resilience and adaptability.

Methodology

This narrative review focuses on fluoride contamination and its health implication globally focusing on Africa. The selected countries are based on the availability of data regarding fluoride contamination, health implications and related anthropogenic activities. The literature search employed keywords such as "fluoride contamination," "impacts of fluoride contamination," "fluoride exposure," "groundwater fluoride contamination," "health impacts of fluoride contamination," "high fluoride levels," along with the names of individual countries. Various databases, including Web of Science, Scopus, Google Scholar, Wiley Online Library, ScienceDirect, Taylor & Francis Online, Sage Publishing, and PubMed, were queried to identify relevant scientific journal articles. The review

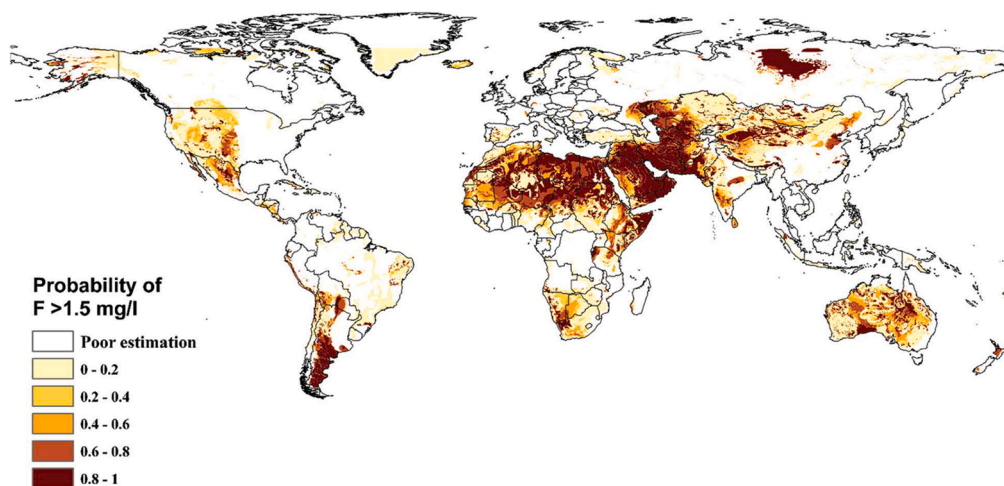


Fig. 2. Predicted probability of fluoride concentration in the groundwater exceeding the WHO guideline for drinking water of 1.5 mg/L according to Amini et al., 2008b) [36].

mainly a localized issue in parts of Spain, Italy, and Hungary, where natural geological factors cause groundwater fluoride levels to occasionally exceed 1.5 mg/L [68,69]. While health impacts like dental fluorosis can occur, skeletal fluorosis is rare [70,71] due to widespread access to alternative water sources and strict EU water quality regulations. In addition, negative effects of using fluoride containing groundwater for irrigation include decreased crop productivity [62]. Moreover, high fluoride levels may affect neurodevelopment and have been linked to other health concerns [72]. Vulnerable populations, particularly those in impoverished communities with limited access to clean water, bear the brunt of these health risks [72]. Fluoride contamination is a global issue, affecting countries across Asia, Africa, South America, and even some developed regions. The burden of addressing this problem lies in implementing both preventive and remedial measures. Table 2 presents report of global fluoride contamination of soils, sediments, ground, surface, and drinking water.

Fluoride occurrences in Africa water sources

Naturally fluoride occurs in various geological formations [42,112,113], with regions having high levels in their groundwater [113, 114]. However, the problem is exacerbated by anthropogenic factors including mining, agricultural runoff with fluoride-rich fertilizers, and industrial discharges, resulting into pollution of African water sources. Inadequate waste disposal practices exacerbate the situation. The consequences of fluoride contamination on human and ecological health are alarming, whereby prolonged exposure to elevated fluoride levels, often through drinking water, can lead to dental and skeletal fluorosis [18,33]. Vulnerable populations in Africa, particularly in rural and impoverished communities with limited access to clean water sources, are at risk of fluoride exposure and suffer from associated health problems [52]. Fluoride contamination is a complex challenge, efforts to address it are hampered by various factors, including limited resources, lack of awareness, and poor water infrastructure, to mention few. According to a study by Sunkari and Coallegues, the northern regions of Ghana are the only ones where fluorosis is endemic. There, communities with elevated groundwater fluoride levels have been reported in the North East Region, Northern Region, Upper East Region, and surrounding areas [60]. The high water-rock contact, ion exchange processes, and mineral dissolution from the Bongo Granitoids and Voltaian sediments are the causes of the elevated groundwater fluoride concentrations [60]. Children are at increased non-carcinogenic risk in Ghana's fluorosis-endemic regions [60], because they drink more water that has been fluoridated than other age groups. Fluoride contamination affects over 100 countries, with Africa (38 countries) most impacted. Groundwater with fluoride above 1.5 mg/L leads to dental and skeletal fluorosis, among other health issues [10].

Climate change and environmental degradation exacerbate the fluoride contamination problem in Africa through several mechanisms. Rising temperatures and altered precipitation patterns lead to increased droughts and water scarcity, particularly in arid and semi-arid regions [115]. This results in greater dependence on groundwater, in which if contains higher levels of fluoride increases risks [115]. Additionally, environmental degradation, such as deforestation and soil erosion, affects the natural filtration process of water, leading to elevated fluoride concentrations. It has been demonstrated that ecological factors have a significant impact on fertility, distribution, and abundance in different areas [116]. The abundance data collected over the course of the investigation revealed a notable seasonal change, with a greater number of parasitoids detected in 2016 compared to 2015 [116]. Every month, there was a noticeable decline in the populations of parasitoids and pests. Parasitoids such as *T. chilonis*, *Cotesia flavipes*, *Sturmiopsis inferens*, and *Isotima javensis* were found to have a significant impact on pests [116]. The rainfall had the highest value among temperature, humidity, and predators. Over-exploitation of groundwater for agriculture and domestic use further concentrates fluoride levels as aquifers become depleted.

A comparative fluoride contamination

Fluoride contamination is a pressing concern in Africa, particularly in areas where groundwater is the primary source of drinking water. The continent's geological composition plays a significant role in this issue, as high fluoride concentrations are naturally present in many groundwater aquifers [10]. For instance, the East African Rift Valley is notably susceptible due to its unique geological formations [1]. The health impact is severe, with millions suffering from dental and skeletal fluorosis. These conditions arise from prolonged exposure to high fluoride levels, leading to tooth decay and bone deformities [1]. The situation is exacerbated by limited access to safe drinking water, compelling communities to depend on fluoride-rich groundwater [1]. Compounding the problem is the lack of infrastructure for effective water treatment and purification [117], leaving many communities without the means to mitigate the contamination. Comparatively, Asia faces similar challenges, particularly in India and China, where high fluoride levels in groundwater are prevalent [118–120]. However, these countries have made significant strides in addressing the issue through government initiatives and large-scale water treatment projects.

Africa's severe fluoride contamination compared to regions like Asia, Europe, and North America is rooted in distinct geological, infrastructural, and socioeconomic factors [121,122]. Unique geological formations, particularly in the East African Rift Valley, are rich in fluoride-bearing minerals, resulting in high fluoride levels in groundwater [121, 122]. Unlike Europe and North America, where robust water treatment and regulatory measures manage fluoride risks, many African regions lack similar infrastructure, leaving rural communities reliant on untreated groundwater, which often has the highest contamination levels. Water scarcity and high temperatures in Africa further concentrate fluoride in groundwater [43,107], compounding exposure levels. Socioeconomic constraints also limit mitigation efforts, as Africa has fewer resources for large-scale defluoridation projects, unlike India and China, which have undertaken significant government-funded initiatives [123]. These combined factors highlight the unique challenges Africa faces in managing fluoride contamination, underscoring the need for targeted solutions. In contrast, North America and Europe encounter less frequent and less severe fluoride contamination [124]. When it does occur, these regions efficiently manage and mitigate the problem

Table 2

Reports of global fluoride contamination in ground, surface, soils, sediments, and drinking waters.

Study	Year	Country	Matrix	Results	Implication	Remarks	Ref.
Prediction of fluoride contamination	2018	India	Groundwater	Presence of fluoride above WHO recommended limit	Potential health impacts, such as dental and skeletal fluorosis	Around 120 million, or 9 % of the population where at a greater risk	[73]
Assessment of fluoride concentration of groundwaters	2021	India	Groundwater	Contamination of groundwater with fluoride through natural and anthropogenic sources	Higher fluoride levels in groundwater, threatens ecological health	For mitigation reasons, processes like adsorption, must be considered.	[74]
Groundwater fluoride contamination was investigated	2018	India	Groundwater	The main causes of fluoride availability in groundwater are the presence of fluoride-bearing aquifers, geological variables, rate of weathering, ion-exchange reaction, residence time, and leaching of subsurface contaminants.	High levels of fluoride ion in groundwater, may impact human and ecological health.	Fluoride pollution requires immediate attention for ecological health	[75]
Assessment of fluoride pollution in water, soil, and plants	2018	India	Water, soil, and plants	Fluoride widely distributed, with higher levels in soils and originates from anthropogenic and geogenic sources	Potential harm to human and entire ecology, through food chain	Mitigation strategies are necessary, like use of physiochemical and biological to ensure ecological safety and sustainability	[76]
Fluoride contamination in groundwater evaluated	2017	Southern India	Groundwater	Fluoride in the groundwater originates from fluorapatite dissolution, with fluoride contents ranging from 0.67 to 2.9 mg/L	Water quality deterioration poses serious threat to human and ecological health.	Treatment strategies and regulatory framework on groundwater extraction are required for ecological safety and sustainability	[77]
Prediction of geogenic groundwater fluoride contamination.	2022	China	Groundwater	Results show that the area is contaminated with fluoride	This steer up threats to human and ecological health	Appropriate mitigation measures are to be applied for water improvement and defluoridation projects.	[78]
Presence of fluoride in groundwater investigated	2020		Groundwater	Presence of fluoride in waters	The contamination of fluorine leads to fluorosis	Advanced measures should be implemented for improvement of water quality	[79]
Assessment of fluoride pollution of drinking water	2017	Northwest China	Drinking water	Results show that groundwater fluoride levels ranged from 0.10 to 6.34 mg/L	Fluoride contamination may pose adverse effects to children and infants.	Instant need to mitigate impacts of fluoride pollution and exposure	[80]
Fluoride pollution of groundwater evaluated	2017	Pakistan	Groundwater	Presence of fluoride above WHO recommended levels, with Lahore 24 mg/L, Quetta 24.5 mg/L, and Tehsil Mailsi 6 mg/L	This cause potential health risks that include atrocious fluorosis	The need to mitigate impacts of fluoride pollution and exposure is prevalent	[81, 82]
Fluoride pollution of drinking water evaluated	2003		Drinking water	Naranji village have 14 mg kg ⁻¹ , exceeding WHO permissible limit (1.5 mg kg ⁻¹)	Potential health threats as the fluoride concentration have exceeded the WHO permissible limits	The need of urgently taking the remedial measures for mitigation purposes	[83]
Fluoride pollution of groundwater evaluated	2008		Groundwater	Fluoride ion concentrations ranged between 0.09 and 11.63 mg/l with mean values of 3.64 and median 3.44 mg/l	High fluoride levels exceeding WHO limit, may impair ecological health	Mitigation measures should be applied to prevent the hazardous effects of fluoride contamination.	[84]

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Table 2 (continued)

Study	Year	Country	Matrix	Results	Implication	Remarks	Ref.
Groundwater fluoride contamination evaluated	2022	Rajasthan, India	Groundwater	Groundwater contained fluoride ranging from 0.1 to 34.0 ppm, in the villages of Ajmer division and the lowest 0.1 to 7 ppm in the Kota	The maximum prevalence of dental and skeletal fluorosis., F-induces diverse adverse health consequences to entire ecology Agriculture crops, fluoridated with groundwater irrigation, harming and reduces crops productivity	Preventive measures for control of F intoxication are to be applied.	[57]
Fluoride pollution of drinking waters evaluated	2007	Northern Rajasthan, India	Drinking water	Presence of fluoride ranging from 1 to 5 mg/l.	Potential risk of pollution and exposure	Mitigation measures should be applied to prevent the hazardous effects of fluoride contamination.	[85]
Fluoride levels in drinkingwater investigated	2011	Central Rajasthan, India	Drinking water	Presence of toxic level (above 3.0 mg/l) of luoride in groundwaters	Potential ecological impacts, with cases of dental and skeletal fluorosis	Mitigation measures should be applied to prevent the hazardous effects of fluoride contamination.	[86]
Presence of fluoride in groundwater investigated	2010	Nalgonda district, India	Groundwater	Presence of fluoride in groundwaters, levels ranged from 0.1 to 9 mg/l	Potential ecological impacts, with cases of dental and skeletal fluorosis	Measures should be applied to mitigate hazardous effects of fluoride	[87]
Hydrogeochemical characterization of groundwaters	2010		Groundwater	Groundwaters in the watershed have an average fluoride level of 2.8 mg/l in pre-monsoon and 2.84 mg/l in post-monsoon.	Potential ecological hazards	Mitigation measures should be applied to prevent the hazardous effects of fluoride contamination.	[88]
Kurmapalli watershed groundwater fluoride levels assessed	2009		Groundwater	Levels of fluoride varied from 0.8 to 20 mg/l	Potential health hazards to villagers	Mitigation measures should be applied to prevent the hazardous effects of fluoride contamination.	[89]
Fluoride pollution and exposure dose assessment	2014	West Bengal	Soil and waters	Reported variations in fluoride levels with aquifer depths: 0.2 to 0.5 mg/L in dug wells, 0.01 to 0.17 mg/L in shallow tube wells, and 0.07 to 1.6 mg/L in deep tube wells. Soil fluoride levels ranged from 50 to 400 mg/kg	Potential ecological impacts	Mitigation measures should be applied to prevent the hazardous effects of fluoride contamination.	[90]
fluoride pollution in drinking groundwaters sessed	2008		Groundwater	Water fluoride levels ranged from 0.01 to 1.18 $\mu\text{g mL}^{-1}$	Potential ecological impacts	Strict mitigation policies are to be applied	[91]
Groundwater fluoride levels investigated	2014		Underground water	There were 1.24 mg/L in the villages of Kapileswar, Haringhata; 1.75 mg/L in Palta, 24 Parganas (North); 1.61 mg/L in Rondia, close to Panagarh; 1.38 mg/L in Midnapore; 1.08 mg/L in Hijli; and 1.06 mg/L in Laxmanpur, Purulia.	Potential ecological impacts	Strict mitigation policies are to be applied	[74, 92]

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Table 2 (continued)

Study	Year	Country	Matrix	Results	Implication	Remarks	Ref.
Groundwater fluoride levels assessed	2022	Bangladesh	Groundwater	About 25 % of groundwater samples from East coast and 22.39 % from West coast surpassed the tolerable limit with a maximum level of 16.12 mg/L	Potential ecological impacts	Strict mitigation policies are to be applied	[93]
Drinkingwater fluoride levels evaluated and associated ecological impacts	2020	Coastal region, Bangladesh	Drinking water	Potential fluoride pollution, surpassing permissible limit	Potential ecological impacts	Strict mitigation policies are to be applied	[94]
Assessment of geogenic fluoride contamination of water	2021	Tanzania	Water, rift valley.	Results indicate that fluoride, a well-known groundwater contaminant, existence of fluoride-rich minerals	Potential health effects to human and other animals	Formulation of environmentally friendly policies for purification of water.	[1]
Evaluation on the variability of fluoride concentration	2022		Ground water	Reported variability in fluoride levels, with depth to groundwater in Sanya flood plain	Potential health effects to human and other animals	Implementation of policies to mitigate effects of fluoride accumulation	[95]
The potential health risks of fluoride concentration assessed	2020	North Tanzania	Groundwater	Fluoride levels above 1.5 mg/L	Potential health effects to human and other animals	Water not safe for human consumption	[96]
Assessment of fluoride levels and ecological risks	2021		Drinking water	Results indicates variations in fluoride contamination in Arusha and Kilimanjaro regions	Potential health effects to human and other animals	Reduction of the geogenic occurrence of fluoride	[97]
Assesment on the occurrence of fluoride.	1993	Kenya	Natural water	Surface waters in Kenya had 1.3 ppm fluoride level, within the recommended level for potable water. Ground and surface waters show considerably higher fluoride contents	Susceptibility to dental caries Potential health effects to human and other animals	The need for minimizing fluoride content in water	[98]
Occurrence of fluoride in groundwater investigated	2018		Groundwater	Highest fluoride content was 72 mg/l, with a mean of 11 mg/l	Potential harm to entire ecology	Necessary measures are required for ecological safety	[99]
Assessment of fluoride in food chain around fluorspar mining	2019		Fluorspar in mining plant	Caprine had 6.4 mg/Kg of fluoride and mutton had 9.6mg/Kg	Potential harm to entire ecology	Necessary measures are required for ecological safety	[100]
Geogenic fluoride in shallow aquifers in groundwater assessed	2022		Aquifers from rift valley	Shallow groundwater had up to 23.5 mg/L of fluoride	Potential harm to entire ecology	Necessary measures are required for ecological safety	[42]
Aanalyses of fluoride levels in drinking water	2017	Namibia	Groundwater	Fluoride in potable water and appraised the population at risk for high fluoride intake.	Potential harm to entire ecology	Necessary measures are required for ecological safety	[101]
Fluoride levels of geothermal springs assessed	2015		Groundwater	High concentrations of dissolved fluoride, with values up to 18.9 mg/l.	Potential harm to entire ecology	Necessary measures are required for ecological safety	[102]
Analysis on water sources and its threat to human health	2014		water	The water is in many places inappropriate for human consumption	Potential harm to entire ecology	Necessary measures are required for ecological safety	[103]
Fluoride in groundwater assessed	2016	Mozambique.	Groundwater	Fluoride levels exceeding the 1.5 mg/L	Potential harm to entire ecology	Necessary measures are required for ecological safety	[104]

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Table 2 (continued)

Study	Year	Country	Matrix	Results	Implication	Remarks	Ref.
Fluoride levels groundwater from Sukulu Hills assessed	2020	Uganda	Groundwater	Groundwater fluoride levels from 0.4 to 3 mg/L, whereas in springs it was from 0.2 to 2.4 mg/L	Potential harm to entire ecology	Necessary measures are required for ecological safety	[105]
Assessment of fluoride levels in drinking water	1970		Drinking water	Fluoride levels in drinking water was 0.6 ppm	High prevalence of dental fluorosis.	Necessary measures are required for ecological safety	[106]
Fluoride levels in Surface and Groundwater investigated	2017		Surface and groundwater.	Reported that Lake Nakuru had 2800 mg/l in of fluoride	High prevalence of dental fluorosis.	Necessary measures are required for ecological safety	[107]
Hydrochemistry and fluoride contamination in Ndali-Kasenda assessed	2021		Surface water	Presence of fluoride contamination	Potential ecological impacts	Necessary measures are required for ecological safety	[108]
Investigation of sources of ground water fluoride contamination	2021	South Africa	Ground water	Groundwater fluoride concentration ranged from 3.92 to 4.95 mg/L. TF content of the rocks and soils ranged from 10 to 2000 mg/L. Leachates were obtained by making a slurry from the samples at a predetermined temperature and time. TF in leachates ranged between 0.27 and 14.88 mg/L and 0.05 to 10.40 mg/L at induced, and non-induced temperatures, respectively	Fluorite minerals occurring at greater depth was found to be the source of contamination. However, this study proves that fluoride decreases with depth and the elevated fluoride in the groundwater is caused by smectite-kaolinite clay, muscovite and chlorite minerals abundant in the area.	The need for technological innovation for remediation of fluoride to ensure ecological safety.	[109]
To examine the appropriateness of groundwater resources for drinking purposes in the Bilate River Basin of Southern Main Ethiopian Rift, Ethiopia	2021	Ethiopia	Groundwater	The fluoride concentration in groundwater ranges from 0.2 to 5.60 mg/L (mean, 2.10 mg/L). 59 % (i.e., 17 wells) of the groundwater samples were not suitable for drinking, because they surpassed the drinking water quality limit of 1.5 mg/L.	The FPI indicates that 51.72 % of the wells were highly polluted by fluoride.	The noncarcinogenic health risk varies from 0.75 to 8.44 for children (83 %), 0.34–3.84 for women (62 %), and 0.27–3.01 for men (52 %), which indicates that children are at higher health risk than women and men due to the physiological condition and the rates of ingestion.	[110]
The anomalous fluctuation of halogens with respect to the pollution status of Lake Mariout was investigated	2020	Egypt	Surface water, pore water, and sediments	Fluoride minerals, especially, fluorapatites and carbonate-fluorapatite (FAP and CFAP), had high Saturation Index (SI) values in surface water (42.77–51.95 and 16.04–60.89, respectively) and in pore water (51.26–54.60 and 17.52–78.33, respectively).	Multivariate analysis showed that in the long run, the fluoride precipitation in FAP and CFAP can significantly adsorb and absorb various pollutants and can protect the lake from pollution.	The river was not polluted.	[111]

through extensive water treatment facilities and regulatory frameworks. South America, while also dealing with fluoride contamination [124], experiences it on a smaller scale compared to Africa and Asia. Countries like Argentina and Chile have implemented successful community-based water treatment projects. In Australia, fluoride contamination is localized to specific areas with high geological fluoride levels [125].

Reported fluoride contamination in Africa and its impacts

Fluoride contamination has significant environmental consequences, particularly in aquatic ecosystems and agricultural settings [126,127]. A study by Wambu et al. [128], reported that Lake Victoria served as the primary water source in the area, though other sources including dams and open pans (39.5 %), boreholes and shallow wells (23.5 %), and streams (18.5 %) were the main alternatives at greater distances from the lake [128]. The average fluoride content across these water sources exceeded recommended drinking water limits [128], but lake and river water did not show high fluoride concentrations. The data from Malawi shows that 83 % of water samples were below the WHO fluoride limit of 1.5 mg/l, while 14 % fell between the former (pre-1993) and current WHO limits of 1.5–6 mg/l [64]. Only 3 % of samples exceeded Malawi's guideline of 6 mg/l (based on the former WHO standard). Although these fluoride levels are lower than in other East African Rift System (EARS) areas, they indicate the need for policy revisions and management strategies by the Malawian government, especially given reported cases of dental fluorosis near high-fluoride groundwater sources [64]. The link between increased fluoride and warmer groundwater highlights the influence of geothermal sources, this may lead to ecological impacts and related health impacts globally. Elevated fluoride levels in water bodies can harm aquatic life by disrupting metabolic processes [129–131], impacting reproduction, and reducing species diversity. Fluoride from contaminated irrigation water accumulates in crops, vegetables, and fruits, adding to the population's fluoride exposure through the food chain [132]. This bioaccumulation heightens the risk for communities already affected by fluoride poisoning, as it introduces an additional source of fluoride beyond drinking water [132]. Fluoride-contaminated water used for irrigation can accumulate in soils, affecting crop growth, reducing agricultural yields, and contributing to soil degradation, which compromises food security [133]. Data indicates fluoride contamination across various regions in Ghana, with concentrations ranging from 0.05 mg/L to 13.29 mg/L [67]. High fluoride levels in the Bongo District in the north exceed the WHO safety limit of 1.5 mg/L. Additional findings in Sekyere South and Nalerigu reveal concentrations between 0.3 mg/L and 4.0 mg/L, and 0.35 mg/L to 3.95 mg/L, respectively [67]. Contamination probabilities range from 50 % to 90 % in the north and northeast. Although data for southern areas is limited [67], the identified hotspots highlight the need for further investigation, to ensure ecological safety. Low-income households may struggle to afford water treatment technologies or alternative water sources [126,127], limiting their ability to effectively mitigate exposure. Addressing fluoride contamination is imperative to prevent these adverse effects and ensure the well-being of communities and the entire ecology. Fig. 4 presents reported cases of health impacts related to fluoride toxicity and injury.

Similarly, fluoride in water sources in northern Tanzania, within the East African Rift Valley, significantly impacts human health, causing conditions like dental, skeletal, and crippling fluorosis [1]. A study by Mureth et al. reported that the fluoride concentration tested ranged from 1.37 to 48 mg/L, indicating potential harm to entire ecology [134]. These environmental consequences underscore the urgency of addressing fluoride contamination to protect ecosystems and ensure sustainable agricultural practices. The severity of these effects depends on several factors, including the concentration of fluoride [133,135,136], the duration of exposure, and individual susceptibility. Public health authorities and environmental agencies monitor and regulate fluoride levels in drinking water to ensure they fall within safe limits.

Environmental consequences

Fluoride contamination has significant environmental consequences that affect ecosystems, agriculture, and soil health, with effects that cascade through the food chain and contribute to broader ecological stress [137]. Studies indicate that fluoride, especially when it accumulates in high concentrations in water or soil, can harm aquatic life, vegetation, and soil composition [76,138]. The environmental accumulation of fluoride can have cascading effects on wildlife and food webs. Animals grazing on

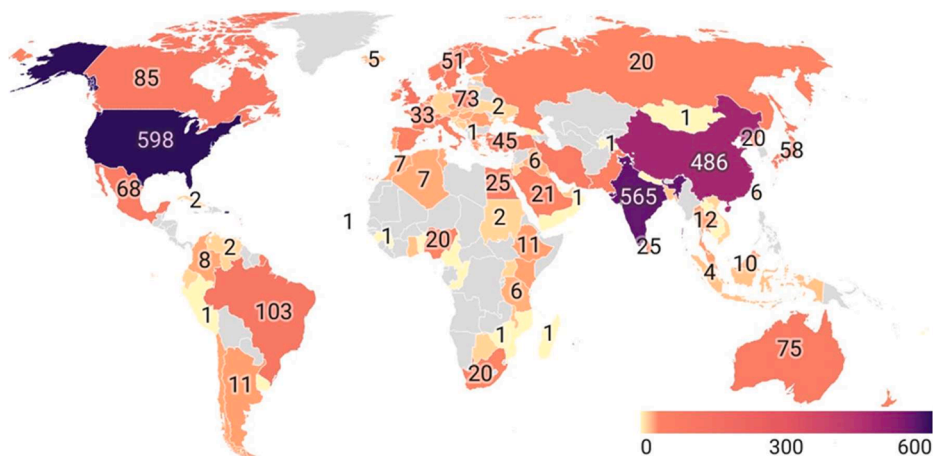


Fig. 4. Reported cases of health impacts related to fluoride toxicity and injury. Global map shape file source: <https://app.datawrapper.de/>, publication data from SCOPUS database.

fluoride-contaminated forage can suffer from chronic fluorosis, a condition that affects bone density and joint health, leading to reduced mobility and, in severe cases, mortality [139,140]. This problem has been reported among livestock in areas with fluoride-rich groundwater, where fluoride bioaccumulates in forage plants, exacerbating health risks for grazing animals [139,140]. Consequently, ecosystems with higher fluoride exposure may see declining populations of herbivores, which can disrupt predator-prey dynamics and lead to further ecological imbalance.

Impacts on aquatic ecosystems

In aquatic environments, elevated fluoride levels can be toxic to fish, invertebrates, and microorganisms, disrupting ecological balance. Previous studies reported that fish exposed to high fluoride concentrations exhibit stunted growth, skeletal deformities, and organ damage [132,141,142]. Fish in these habitats exhibited abnormalities in bone structure and impaired metabolic functions due to fluoride toxicity [143–146]. Plants and microorganisms, which are important players in nutrient cycling, are also sensitive to high fluoride levels, which can inhibit photosynthesis and reduce species diversity [138]. These may weaken food webs, threatening biodiversity and the stability of the ecosystem.

Effects on agriculture and crop health

Fluoride contamination affects crop health when contaminated groundwater is used for irrigation, leading to fluoride accumulation in plants [76,138,142]. Crops such as rice, maize, and vegetables have shown reduced yields and compromised nutritional quality when exposed to high fluoride concentrations [57]. Fluoride accumulates in edible plant tissues, introducing fluoride into the food chain and raising health risks for both animals and humans [132,142,143,145]. Researcher reported that the use of fluoride-contaminated water for irrigation, resulted into bioaccumulation in leafy greens and other vegetables [1,17,129,134], posing chronic health risks to communities that depend on these foods. Crop plants sensitive to fluoride [147–149], show reduced photosynthesis and growth rates, leading to lower agricultural productivity, which has socioeconomic implications for farmers especially in Africa where agriculture is the main economic activity.

Soil degradation and reduced fertility

Elevated fluoride levels in soil affect soil structure, nutrient availability, and microbial communities. Soils contaminated with fluoride can inhibit the activity of nitrogen-fixing bacteria, essential for maintaining soil fertility and supporting plant growth [150, 151]. Fluoride can also bind wial nutrients like calcium and magnesium, making them less available to plants, which further decreases soil productivity [150,151]. Over time, fluoride accumulation in soils, particularly in agricultural lands irrigated with fluoride-contaminated water, can reduce soil fertility, resulting in degraded land quality [149–151]. This reduction in soil health not only affects current crops but also impedes the recovery and productivity of soil for future use. Therefore, fluoride contamination poses multifaceted environmental risks that affect ecosystems, agricultural productivity, and soil health. Its impact is particularly pronounced in regions reliant on fluoride-rich groundwater for irrigation and drinking water, such as parts of East Africa, India, and China.

Economic implications

Fluoride contamination presents significant economic implications for affected communities in Africa, exacerbating existing challenges and deepening socio-economic disparities. Fluorosis, a result of excessive fluoride intake, leads to severe dental and skeletal issues, undermining the health of community members. The associated healthcare costs are substantial, particularly in regions with limited access to medical services and public health infrastructure [152]. The economic impact extends to productivity losses. Individuals suffering from fluorosis experience chronic pain and physical disabilities, which diminish their ability to work effectively [153]. This results in reduced household incomes and limits the economic output of communities. For example, in Ethiopia and Kenya, studies have shown that affected populations have lower participation in labor-intensive activities due to debilitating conditions caused by fluorosis [154]. The cost of implementing fluoride remediation technologies, such as de-fluoridation plants, poses a significant financial burden on already strained local economies [155]. These communities must allocate scarce resources to address contamination, often at the expense of other critical development projects. As water quality deteriorates, reliance on bottled water or other clean water sources increases, leading to higher household expenditures on safe drinking water. Therefore, fluoride contamination not only hinders economic development in African communities by imposing direct health costs and reducing productivity but also diverts funds from essential social and economic initiatives, thereby deepening the cycle of poverty and underdevelopment.

Existing policies on water fluoride levels in Africa

Existing policies on water fluoride levels in Africa vary significantly across countries, reflecting a range of regulatory frameworks and approaches to managing fluoride contamination. The World Health Organization (WHO) recommends a maximum allowable fluoride concentration of 1.5 mg/L in drinking water [124,156,157], a guideline many African nations strive to align with; however, enforcement and adherence to this standard are inconsistent. Countries like Kenya and Tanzania have developed national water quality standards [1,158,159], but implementation is often hampered by inadequate monitoring and limited resources. In some

regions, local governments lack the capacity to assess groundwater fluoride levels regularly, leading to unregulated consumption of contaminated water. Additionally, public awareness campaigns about the health risks associated with fluoride exposure are often insufficient, limiting community engagement in water quality management [160,161]. Although international organizations and NGOs have initiated various projects to address fluoride contamination, these efforts frequently face challenges related to policy coherence and coordination at national and local levels. Overall, while some frameworks exist, the lack of uniformity, comprehensive enforcement, and community involvement undermines the effectiveness of fluoride management policies in Africa.

Mitigation strategies

Fluoride contamination in Africa poses a significant public health and environmental challenge, particularly in regions with high natural fluoride levels in groundwater. To address this issue, various fluoride remediation approaches [112,162–165], have been proposed. These approaches aim to reduce fluoride levels in drinking water to safe and acceptable limits by WHO and governments for ecological safety and sustainability. Table 3 presents reported mitigation strategy that potentially reduced fluoride levels. Mitigation involves defluoridation techniques, increased public awareness, policy implementation, and alternative water sources to reduce exposure and ensure safe drinking water globally. Most of affected African countries lack the financial and technological resources to implement comprehensive mitigation strategies [166]. Inadequate public awareness and education about the risks of fluoride contamination often hinder preventive measures [166]. Poor water infrastructure in rural areas exacerbates the problem by limiting access to safe drinking water sources [166], insufficient monitoring and enforcement of water quality standards in some regions perpetuate the issue. To combat fluoride contamination in Africa, concerted efforts are needed. This includes, developing clean water infrastructure, particularly in rural areas, is essential to provide access to safe water sources and ensure ecological safety and sustainability. Public awareness campaigns [167], implementing affordable and sustainable water treatment technologies [163,168,169], may help to ensure fluoride free water for all and ensure ecological health.

Defluoridation processes

Defluoridation is the process of removing excess fluoride ions (F^-) from water to make it safe for consumption [188]. High levels of fluoride in drinking water can lead to dental and skeletal fluorosis, which are health problems caused by excessive fluoride intake [30]. There are several methods for defluoridation, and the choice of a method depends on factors like the initial fluoride concentration [189], available resources [189], and the specific requirements of the community [189]. These methods indicated in Fig. 5.

Activated alumina adsorption

Activated alumina (Al_2O_3) is a common adsorbent used for removing fluoride from water [190]. The water is passed through a column packed with activated alumina, which adsorbs the fluoride ions [190]. Periodically, the activated alumina needs to be regenerated by backwashing it with a caustic solution and then rinsing it. A study by Gao and Coallegues reported that in a short period of adsorption, the modified activated alumina maximum capacity increased from 38 % to 67 % [191], indicating that the diffusion of fluoride was primarily governed by adsorption onto the active sites and the adsorption of fluoride on activated alumina was single-layer physical adsorption [191]. Similarly, You and Coallegues reported similar effectiveness of activated alumina for defluoridation [192]. Activated alumina can be regenerated and reused for defluoridation [193], indicating potential for its use in mitigation of fluoride in water sources.

Bone char adsorption

Bone char is another adsorbent material made from animal bones mainly containing calcium and phosphate. It is effective for removing fluoride from water [172,173]. The process involves passing water through a bed of bone char [172]. A study by Gather and Coallegues used bone charcoal in water defluoridation in combination with eggshell powder and dry banana peel medium [194]. The use of eggshell powder and dry banana peel medium were found to increase the fluoride removal capacity of bone charcoal by more than 20 % [194]. Further report indicate that the highest fluoride removal was attained when a composite of bone charcoal, eggshell powder and dry banana peel medium used for defluoridation [194]. Like activated alumina, bone char needs to be regenerated periodically. A study by González-Ponce and Coallegues [195], reported that 0.075 mol/L of NaOH was effective in recuperating the defluoridation properties of bone char with a regeneration efficiency higher than 90 % during five adsorption/desorption cycles [195]. Bone char regeneration efficiency decreased up to 64 % after ten adsorption/desorption cycles with a maximum fluoride adsorption capacity of 0.18 mmol/g [195].

Calcium precipitation

This method involves adding calcium-containing compounds (such as calcium hydroxide or calcium carbonate) to the water [196]. The added calcium reacts with fluoride ions to form insoluble calcium fluoride, which can be removed through sedimentation and filtration [196]. A study by Lacson and Coallegues reported that even at extreme anion concentrations, the optimum condition ($Ca^{2+} = 105.0$ mM, seed dosage = 5.0 g., and pH = 3.79 ± 0.13) still reached a high defluoridation efficiency of about 98 % [196]. The range of the prevailing acidic pH (2.0–6.0) presumably deterred the potential precipitation of Ca^{2+} with other anions but still ensured CaF_2

Table 3
Reported mitigation strategy that potentially reduced fluoride levels.

Mitigation strategy		Characteristics	Cost effectiveness			Areas applied	Challenges	Implication	References
			Initial Cost	Operating Costs	Effectiveness				
Defluoridation filters	Activated alumina filters	Maximal removal, compatible and thermally stable	Moderate	Moderate	High	Rural areas of India, China, and the U.S.	Regeneration, fouling, flow rate and pressure drop	Used for remediation of fluoride	[114,170,171]
	Bone char filters	Chemically stable	Low to Moderate	Low	Moderate to high	Developing countries such as Tanzania and Kenya	Saturation, Microbial growth, flow rate and pressure drop	Bone char is typically made from animal bones, and there may be health and ethical concerns associated with its use	[172,173]
	Hydroxyapatite Filters	Highly selective and biocompatible	Low to Moderate	Low	Moderate to high	Capacity, life span, operational complexity	Columns parking and material stability	Scale up challenges, need expertise and additional technology	[28,163,174]
	Biomass based adsorbents	Can be tailored to specific pollutants by proper choice and modification of adsorbent	Low to Moderate	Low	Moderate to high	Developing countries	Regeneration and reuse	Eco friendly, and can be used to target low level pollutants	[175]
Ion exchange resins		Can be tailored to specific pollutants	Low to high	Low to high	Highly efficient		Regeneration, pressure drop and chemical compatibility	These resins can remove all ions, where used for drinking water production the guidelines need to be adhered	[176–178]
Reverse osmosis		Most effective methods for reducing fluoride levels to safe limits, capable of removing nearly all fluoride content	High	High	Very high	Commonly used in urban areas and for bottled water production	Initial cost, energy consumption and fouling	Needs strict regulatory compliance	[179]
Chemical coagulation and precipitation such as Nalgonda Technique		Moderate. It can effectively reduce fluoride levels, but the process requires careful management to avoid other water quality issues.	Low	Low	Moderate	In rural India for community-level water treatment in community and industrial settings	Chemical selection, dosage control, sludge management, and pH adjustments	Stringent regulations regarding water quality and chemical usage	[180–182]
Solar water disinfection (SODIS)		No chemical use and effective against many types of bacteria, viruses, and protozoa, including those responsible for common waterborne diseases.	Low	Low	Moderate	SODIS is particularly valuable in remote or underserved areas where access to clean water and advanced treatment technologies is limited.	Weather, time, water clarity and container availability	SODIS is most suitable for small-scale applications	[183–185]
Community defluoridation plants		Large-scale plants are built to treat water at the community level, often using a combination of techniques like activated alumina, coagulation, or reverse osmosis.	High	High	Moderate to High	Very high	Effective in areas with widespread contamination and sufficient infrastructure support.	Cost-effective in densely populated areas where a centralized treatment system can serve many people, spreading out the high initial and operating costs.	
Rainwater harvesting		Weather, initial cost, maintenance, quality concerns	High	Moderate to high	Low to moderate	Suitable for water conservation if well maintained	The design of an RWH system should consider factors such as local rainfall patterns, roof area, storage capacity, intended water uses, and available budget	Rainwater harvesting offers a sustainable and cost-effective solution for water conservation and management, particularly in areas facing water scarcity or unreliable water supplies	[186,187]

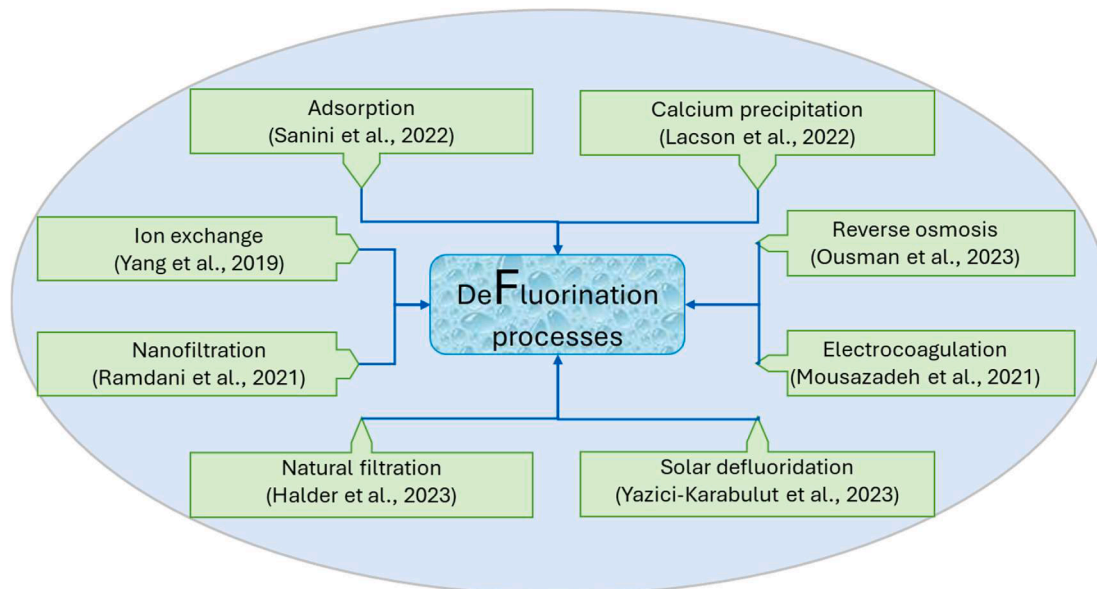


Fig. 5. Common defluoridation techniques (Source: Author's design).

precipitation [196]. This method can be improved by introducing medical stone-coated sponges as a microbial activity promoter and slow-release calcium source into an immobilized bioreactor for enhanced fluoride removal [197]. In a similar study Wang and Colleagues reported maximum adsorption of 5.10 mg g^{-1} and defluorination efficiency of 98.24 % [198], indicating that the method is potential for defluorination as reported by other researchers.

Ion exchange

Ion exchange resins can be used to remove fluoride ions by replacing them with other ions, typically chloride or sulfate ions [199]. The resin needs to be periodically regenerated with a concentrated brine solution. Singh and Colleagues prepared Zirconium impregnated hybrid anion exchange resin (HAIX-Zr) by impregnating ZrO_2 nanoparticles on polymeric anion exchanger resin [200]. Fluoride uptake by HAIX-Zr was quite rapid, 60 % removal was obtained within 30 min [200]. A study by Qiu and Colleagues prepared a nano-hydroxyapatite encapsulated inside an anion exchanger and used it for defluoridation [201]. The material exhibited almost constant defluoridation efficiency in a wide pH range, especially much higher. Fluoride removal efficiency under neutral and weakly alkaline conditions (pH 7–10) than currently available materials [201], indicating potential for improvement to increase the defluoridation efficiency to ensure public health safety.

Reverse osmosis

Reverse osmosis is a membrane-based filtration process that can effectively remove fluoride and other impurities from water [202, 203]. The largest daily water output, ranging from 26,000 to 50,000 m^3/day , is achieved by hybrid RO-MD (membrane desalination) systems with a specific energy consumption of 3.572 kWh/m^3 , with an energy cost varying between 0.85 and 0.9 $\$/\text{m}^3$ [204]. The RO-MSF (Multi-Stage Flash) systems produced 14.4 to 1000 m^3/day of water at a specific energy consumption of 5.2 to 6.7 kWh/m^3 , with energy costs ranging from 1.35 to 1.84 $\$/\text{m}^3$ [204]. The negative environmental effects of waste brine can be reduced and the cost of creating freshwater can be reduced with hybrid systems [204]. It uses a semi-permeable membrane to separate the water into purified and concentrated streams. This method reached fluoride rejection of 98 % and 90 % for Nanofiltration.

Electrocoagulation

Electrocoagulation involves passing an electric current through the water, which causes coagulation and precipitation of fluoride ions [205]. The precipitated fluoride can then be removed through sedimentation or filtration [205]. The electrocoagulation process were applied for T, Al/Al system achieves fluoride concentration within permissible limits ($0.72 \text{ mg L}^{-1} \text{ F}^-$) at 10min of treatment, 0.2 A (Current density 48.78 A m^{-2}) and 10 mL min^{-1} with a removal efficiency of 68.69 %, and after 160min, the removal increased to 99.56 % [205]. The 1 Mg/AlMg needs 10min to achieve a concentration of $0.75 \text{ mg L}^{-1} \text{ F}^-$ at 0.2 A ($j 25 \text{ A m}^{-2}$), 16 mL min^{-1} with a removal efficiency of 67.39 %, and after 100min, the removal is increased to 92.17 % [205]. This method can be combined with other methods such as adsorption for improved efficiency of defluoridation.

While these defluoridation techniques are viable and backed by evidence [163,164,206,207], implementing these strategies in

Africa requires overcoming significant practical challenges. Ensuring sustainable fluoride mitigation will depend on making technologies locally accessible, culturally acceptable, and economically feasible, coupled with strong governmental support, targeted policies, and ongoing community engagement.

Factors affecting defluoridation techniques

Defluoridation is influenced by various factors that can affect the efficiency and effectiveness of the process [208,209], these factors can vary depending on defluoridation method used. The initial fluoride levels of ions in the source water are critical factors [210], higher initial levels may require more extensive or specialized defluoridation techniques. The pH level of water can impact defluoridation methods such as coagulation and precipitation [180], adjusting the pH to the appropriate range can enhance the defluoridation process. Similarly, the temperature can affect the efficiency of certain defluoridation processes [211,212], such as activated alumina or bone char adsorption, generally, higher temperatures can improve adsorption. Some defluoridation methods [114,191], like adsorption, ion exchange, and precipitation, require sufficient contact time for adsorbate and adsorbent interactions [114,191], for better fluoride removal. Similarly, the presence of co-ions such as sodium (Na^+) and calcium (Ca^{2+}), in the water can compete with fluoride ions for binding sites on adsorbents or in ion exchange resins [213], with the type and concentration of co-ions [213], having influence on the defluoridation process. The rate at which water flows through the defluoridation system can affect its efficiency [180, 210], slower rates may allow for more effective contact between adsorbate and adsorbent resulting to effective removal.

The choice of adsorbent such as activated alumina [190], bone char [195], ion exchange resins [213], or coagulants [214], can significantly impact the efficiency of the defluoridation process. For methods that involve regeneration, such as activated alumina or ion exchange, proper maintenance and regeneration procedures are essential to ensure continued effectiveness [178,215]. Some defluoridation methods, like reverse osmosis and electrocoagulation, may require energy input [216,217]. The availability and cost of energy can affect the feasibility of these methods. The composition of the source water [203,218], including its mineral content and turbidity, can influence the choice of defluoridation method and the treatment process's effectiveness [196,219]. The availability of financial resources [220], infrastructure [221], and trained personnel [222], can significantly impact the selection and implementation of defluoridation technologies. The environmental impact of the chosen defluoridation method, including the disposal of spent treatment materials or brine solutions, should be considered. The acceptance and willingness of the local community [196,219, 223], to use and maintain the chosen defluoridation system can affect its long-term success.

Compliance with local, national, and international regulations and safety standards [224], is crucial to ensure the quality and safety of the treated water. For proper selection of a method to be used a thorough assessment of these factors when designing and implementing a defluoridation system to ensure that it effectively reduces fluoride levels in drinking water while considering local conditions and constraints. Apart from availability of all these methods [208,225,226] for defluoridation process, still there is a need for improvement for more sustainable option especially for resource contained areas like developing countries [208,209,226]. Among the potential option includes biosorption, and solar defluoridation methods. The choice of defluoridation method depends on various factors, including the fluoride concentration in the water, available resources, and the specific needs of the community or region. These methods may be used for monitoring treated water to ensure that fluoride levels remain within safe limits to ensure public health safety.

Community engagement and awareness

Community engagement is essential for the successful implementation of fluoride remediation approaches [169]. Educating communities about the risks of fluoride contamination and promoting safe water practices is crucial [18]. Ongoing research is essential to develop and improve fluoride remediation technologies suitable for resource-constrained settings like Africa. Innovation can lead to more cost-effective and sustainable solutions [163]. Governments in affected regions can play a vital role by setting and enforcing regulations for fluoride levels in drinking water [32,52]. Monitoring and compliance are crucial components of these efforts. Similarly, collaborations with international organizations and agencies can provide funding, expertise, and resources to support fluoride remediation projects in Africa. In Kenya's Rift Valley region, where fluoride levels are naturally high, community-led awareness programs run by NGOs have also helped reduce exposure [227]. Through local education initiatives, communities learned to identify safe water sources, prompting households to adopt rainwater harvesting and use fluoride-free sources for drinking [227]. Studies from these regions show improved health outcomes, such as decreased rates of dental and skeletal fluorosis, following these awareness campaigns [227–229]. Additionally, in Uganda, public health programs have combined awareness with training in low-cost defluoridation techniques [230,231]. The emphasis on educating communities about water safety and providing resources for water testing and treatment has empowered residents to take proactive measures in reducing fluoride exposure [230–232], ultimately demonstrating that well-structured public awareness campaigns can substantially reduce health risks from fluoride. Addressing fluoride contamination in Africa requires a multifaceted approach that combines technology, community engagement, policy initiatives, and international cooperation. Effective fluoride remediation not only improves the quality of drinking water but also contributes to better public health and the well-being of communities affected by this silent water crisis.

Recommendations

To ensure water quality there is the need for establishing comprehensive water quality assessment and monitoring programs to regularly test fluoride levels in water sources, especially for fluoride contamination hotspots. Timely data collection and analysis are

crucial for identifying affected areas and implementing appropriate measures to ensure the availability of fluoride-free water. The need to invest in and deploy effective water treatment technologies, such as defluoridation filters, activated alumina adsorption, and reverse osmosis systems [202], in areas with high fluoride contamination, these technologies can significantly reduce fluoride levels in drinking water and improve its safety. Similarly, launching public awareness campaigns to educate communities about the risks associated with fluoride contamination and the importance of accessing safe drinking water sources. Empower individuals and communities to make informed choices and adopt practices that mitigate exposure [233]. In areas where natural water sources are heavily contaminated with fluoride, consider providing alternative sources of safe drinking water, such as community wells, boreholes, or water supply systems with fluoride removal capabilities.

Moreover, community engagement, ensuring regular maintenance and monitoring of water treatment facilities to keep them in optimal working condition. This includes training local personnel to operate and maintain these systems effectively. Encourage the diversification of water sources to reduce reliance on a single contaminated source. Combining different water sources, such as surface water and groundwater, can help minimize fluoride exposure risks, and, hence ensuring safety. The governments, regulatory authorities and policy makers need to strengthen regulatory frameworks to limit industrial discharges and wastewater contamination. The need to enforce strict standards for fluoride levels in industrial effluents and encourage responsible waste disposal practices, underscores the importance of global collaboration. International support, both financial and technical, is vital to address fluoride contamination in regions with limited resources. Additionally, the establishment of healthcare programs for affected communities to provide early diagnosis and treatment of dental and skeletal fluorosis, along with the implementation of surveillance systems to monitor the prevalence of these conditions and track their progression, is essential.

Promoting research into innovative and cost-effective fluoride removal technologies suitable for use in resource-constrained settings, such as developing countries, is crucial. Supporting research on the long-term health effects of fluoride exposure, particularly in vulnerable populations, is essential. African governments must advocate policies prioritizing safe drinking water access and environmental protection. Engagement with local, national, and international authorities, is necessary to raise awareness and garner support for mitigation efforts, including the participation of affected communities in decision-making processes. Inclusion of local knowledge and community engagement is essential for the success and sustainability of fluoride contamination solutions. Addressing fluoride contamination is a complex challenge, but with concerted efforts from governments, NGOs, communities, and the international community, its adverse effects on public health and the environment can be mitigated. Prioritizing safe drinking water and promoting sustainable practices are essential steps towards a fluoride-free future.

Conclusion

Fluoride contamination is a global challenge that is often overlooked, with significant impacts on human and environmental health. Particularly in Africa, it represents a silent water crisis, stealthily undermining community well-being. The severe effects of fluoride exposure, such as dental and skeletal fluorosis, underscore the critical need for innovative and comprehensive solutions. To address the pressing issue of fluoride contamination in Africa, a paradigm shift is necessary. By integrating traditional knowledge with cutting-edge technology, communities can harness sustainable water treatment solutions tailored to local needs. Strengthening regulatory frameworks will ensure safe drinking water standards are not only met but exceeded. Community engagement and awareness, highlighting the health risks of fluoride and the value of safe water practices, empowers individuals to make informed choices and become active participants in the solution. Additionally, international partnerships can provide the vital resources and expertise required to develop robust strategies for tackling fluoride contamination. Through these innovative and comprehensive measures, Africa can turn the tide on fluoride pollution, transforming it from a pervasive threat into an opportunity for enhancing the health and prosperity of its communities.

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Consent for publication

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Availability of data and material

Used secondary data and cited within.

CRedit authorship contribution statement

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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