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Review article

Review on accessible and innovative techniques for monitoring, analysis, and sustainable management of fluoride in drinking water

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ABSTRACT

Since more than 2.5 billion people worldwide depend on groundwater for their drinking needs, the availability of clean water is one of the biggest problems facing human civilization. Higher levels of fluoride in drinking water pose health risks to people all over the world because of the increased reactivity of fluoride ions that enter the water from both geogenic and anthropogenic sources. The effects of excessive fluoride concentrations on human health and how it regulate, have also been hotly debated in several nations. To solve the ever-increasing worldwide issue of fluoride contamination from groundwater, cost-effective, environmentally acceptable methods must be developed immediately. Adsorption, nano-filtration exchange, reverse osmosis precipitation/coagulation, etc., are examples of conventional techniques for removing fluoride. The materials applied in adsorption method is one of the current approaches that works well for rural populations since it is accessible, affordable, recyclable, and readily available. In contrast to other approaches, adsorbing materials are non-toxic and do not release toxic materials, secondary waste generation, high expense, and limited availability to the poor. This review focuses on the fluoride concentration range in fluoride-affected countries and recently developed defluoridation techniques using modified sustainable and environmentally friendly bio-geomaterials. This review covers advanced analytical methods, cost-effective detection strategies, sustainable management approaches, health implications, and policy recommendations for fluoride for safe water practices.

1. Introduction

Water is a vital natural element that sustains every living organism and is necessary for economic development. Out of 70 % of the whole earth's water resources, only 0.002 % of water is fit for safe drinking (Belotti and Frazao, 2022; Yousaf et al., 2013). A major source of drinking water for people all around the world is groundwater. However, in the past few decades, rapid industrialization, deforestation, unplanned urbanization, open landfills, improper waste management, and deteriorated groundwater resources with various inorganic and organic contaminants, including fluoride, have deteriorated drinking water quality. (Choubisa, 2024; He et al., 2020). Fluorine, located at position 9 in the periodic table, is recognized as the lightest element in the halogen family and ranks as the thirteenth most prevalent element in the earth crust (Basu, 2024; Ibrahim et al., 2019; Goschorska et al., 2018). The strong attraction of fluoride to solid phases increases its reactivity with various elements in aquatic environments, resulting in contamination. Fluoride in groundwater naturally leached from earth's crust, fluoride-containing rocks (fluorspar, cryolite, fluorapatite apatite, mica, hornblende, rock phosphate, and others), climatic circumstances, geochemical deposits, volcanic emission, nature of hydro-geological strata, and time of contact between rocks (Kabir et al., 2020; Pratha and

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Prabakar, 2020; Yadav et al., 2018; Garg and Sharma, 2016). Anthropogenic sources such as industrial discharge from aluminum, glass, ceramics, semiconductor, manufacturing industries, semiconductor manufacturing industries, and some fluoride-containing chemical compounds also contribute to fluoride pollution in groundwater (Pratha and Prabakar, 2020; Wu et al., 2016). According to epidemiological research, the primary route fluoride takes to enter the human body and enter the food chain is consuming contaminated food and water. (Dehghani et al., 2018).

Fluoride is a vital micronutrient that contributes to the development of the human body's skeletal and dental tissues within an acceptable range in water of 0.5 to 1.5 mg/L (Uddin et al., 2019). The high concentration of fluoride (>1.5 mg/l) may hurt the human body. The fluoride level in drinking water (1.5 to 3.0 mg/l) may enhance the risk of dental fluorosis (Chowdhury et al., 2022; Plattner et al., 2017), Whereas 3 - 6 mg/L concentration may be responsible for structural changes in bone tissues and beyond ten mg/L concentration will develop severe of skeletal fluorosis (WHO, 2011). The widespread reliance on fluoride-contaminated groundwater resources has resulted in dental and skeletal fluorosis in many countries. A substantial population of approximately 0.2 billion people residing in about 25 developing and developed nations, including India, China, Afghanistan, Argentina, Spain, Sweden, Iran, Iraq, Turkey, South Korea, Thailand, Mexico, South Africa, Tanzania, Malavi, and the United States, etc., are worst affected with fluoride contamination (Deshmukh et al., 2018). The global fluoride concentration range was found 0.01 to 69.7 mg/L (Park et al., 2024; Mumtaz et al., 2015). Prolonged fluoride exposure has become a matter of concern as it is responsible for many harmful health impacts on humans.

A unified global approach is imperative for establishing standardized regulations to govern the amount of fluoride in drinking water. Affordable and sustainable solutions are required to ensure access to safe drinking water in communities affected by fluoride. Several conventional (liming, electrodialysis coagulation, and iron (III), alum, oxides of calcium, and other metals-based precipitation of fluoride) and emerging de-fluoridation methods (Adsorption, ion exchange, membrane filtration technology) are used by researchers globally. Based on the literature studies, adsorption methods, including various adsorbents derived from agricultural and industrial waste, biopolymers, algae, fungi, nanoparticles, and nanocomposites, are one of the emerging techniques for sustainable fluoride elimination owing to their simplicity, broad availability, and affordability. Over the last few decades, numerous studies have investigated fluoride distribution and defluoridation techniques. Yet, high fluoride concentrations in drinking water remain a persistent concern, with many parts of the world experiencing adverse health and socioeconomic impacts. This review offers a thorough and current examination of novel and easily available methods for monitoring, analyzing, and managing fluoride levels in sustainably drinking water. In contrast to earlier assessments, this study incorporates new developments in ecologically benign bio-geomaterials for defluoridation while highlighting the global fluoride concentration range in impacted areas. The novel aspect is the careful evaluation of new sustainable materials that provide affordable, non-toxic, recyclable substitutes appropriate for resource-constrained and rural environments. This analysis opens the door for workable, scalable, and community-driven defluoridation strategies to reduce fluoride contamination in groundwater by emphasizing the relative benefits of these environmentally benign alternatives to traditional techniques.

2. Status of fluoride in drinking water

Fluoride contamination in groundwater varies from place to place, primarily depending on the geographical structure, local factors, and anthropogenic activities (Vithanage and Bhattacharya, 2015). As shown in Table 1 (Mereta, 2017), about 70% of water bodies and 200 million people are affected by fluoride contamination worldwide. Most African, American, and Asian countries have higher concentration of fluoride in ground water (beyond the permissible limit, i.e., 1.5 mg/L) (Kabir et al., 2020).

The names of affected countries in the whole world are given in Fig.1. Fluoride contamination is a widespread issue, affecting a total of 100 countries across various continents. Specifically, 28 countries in Asia, 38 in Africa, 24 in Europe, 3 in North America, 5 in South America and 2 in Australia/Oceania have reported fluoride contamination (Shaji et al., 2024).

India is a severely affected country amongst Asian nations with 22 states with higher fluoride concentrations, namely, Karnataka, Kerela, Tamil Nadu, Andhra Pradesh, Telangana, Maharashtra, Manipur, Assam, Chhattisgarh, Bihar, Delhi, Gujrat, Haryana, Jammu & Kashmir, Jharkhand, Madhya Pradesh, Orissa, Punjab, Rajasthan, Tripura West Bengal and Uttar Pradesh (Shaji et al., 2024; Biswas et al., 2017). Geological surveys have revealed that the northwestern parts of Gujarat and Rajasthan in the India, are characterized by a high incidence of fluoride-containing aquifers, in contrast to the southern regions of Karnataka, Andhra Pradesh, and Tamil Nadu, where quartzite, limestone, and shale aquifers are more prevalent, often in conjunction with alluvial aquifers (Dutta et al., 2019). One of the areas of the nation most badly impacted by fluoride contamination is Uttar Pradesh (UP). In the Unnao and Pratapgarh districts of UP, most of the population (about 90%) has deleterious impacts on health due to severe fluoride exposure through fluoride-contaminated water ingestion (Tiwari et al., 2017). Raebareli district of UP also has severe fluoride contamination intensity with >10 mg/L fluoride occurrence in groundwater (Sahu et al., 2018).

3. Fluoride impacts on human being

The excessive fluoride concentrations in water used for cooking and drinking have become a global concern due to the fluoride-governed ill effects on the human body. High fluoride water sources can be found in areas with marine-derived geological deposits and at the base of tall mountains. Approximately 260 million people live in fluoride-affected zones (>1.5 mg/L), according to a WHO estimate (Alhaj et al., 2020). The global distribution of fluorosis is extensive, with endemic regions identified in at least 25 countries, including Asia, Europe, Africa, North America, and South America (Yadav et al., 2014).

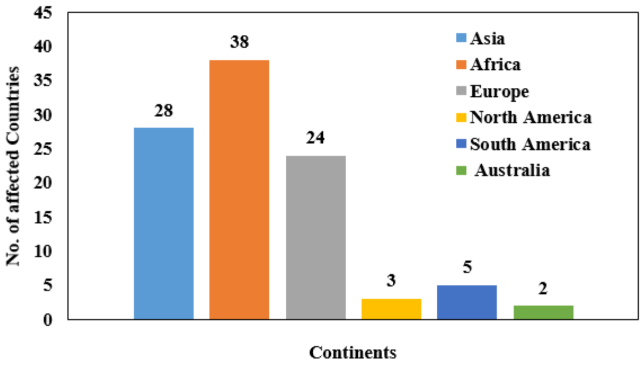

Fig. 1. Number of affected countries among different continents

Based on existing literature, the information on Indian states with fluorosis incidence from 1930 to 2022 is given in Fig.2 as the first case of fluorosis was observed in south India (Nellore district) in the 1930s (Tiwari et al., 2023; Chowdhury et al., 2022; Singh et al., 2018; Golgire et al., 2016). Few Indian cities like Unnao, Raebareli, Fatehpur, Kanpur, Jaunpur, etc, are the most severely affected zones of UP, with comparatively high incidences of fluorosis cases but (Bhadja et al., 2016). The most detrimental effects of excess fluoride include Dental fluorosis, Skeletal fluorosis, and linked disorders (Fig. 3).

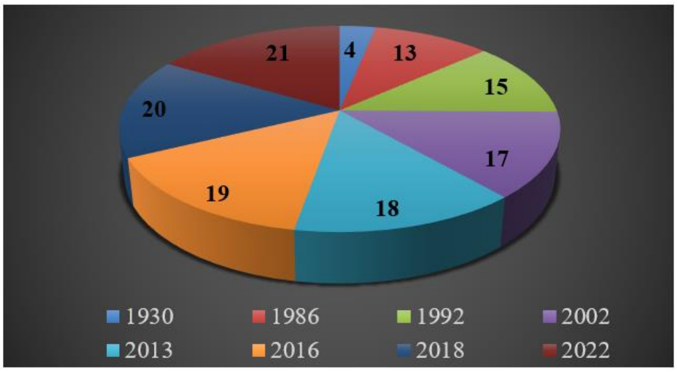

Fig. 2. Number of fluorides affected states in India from 1930 to 2022.

3.1. Dental fluorosis

The substitution of hydroxide ions with fluoride ions in hydroxyapatite, the primary constituent of tooth enamel, leads to the formation of fluoroapatite, resulting in dental fluorosis (Bhan and Singh, 2022). Dental fluorosis is frequent with severe fluoride exposure (He et al., 2020). It is characterized by hypo-mineralization of the enamel because of excessive fluoride exposure during enamel mineralization. Children are particularly susceptible to dental fluorosis due to their developing teeth and bones, but continuous fluoride exposure during childhood can cause dental fluorosis in adults. In children of more than 8 years of age, the discoloration on teeth is visible due to excessive fluoride consumption (Biswas et al., 2017).

Table 1 A range of fluoride concentration in different countries.

S. No.	Country	Range of F^- concentration (mg/L)	References
1	**Argentina**	1.9 -7.0	Liu et al. (2011)
2	**China**	0.1-15.36	Luo et al. (2013)
3	**Turkey**	1.5-15.2	Un et al. (2013)
4	**Saudi Arabia**	0.01-5.4	Alabdulaaly et al. (2013)
5	**Maxico**	1.8 -18.0	Sandoval et al. (2014)
6	**Brazil**	5-20	Bhadja et al. (2016)
7	**Japan**	0.0-12	Uddin et al. (2019)
8	**Thailand**	0.01-14.12	Uddin et al. (2019)
9	**Iran**	0.25-5.0	Uddin et al. (2019)
10	**Egypt**	00-10	Uddin et al. (2019)
11	**Ethopia**	00-75	Uddin et al. (2019)
12	**Kenya**	0.02-21.5	Uddin et al. (2019)
13	**Sri Lanka**	0.0-5.30	Uddin et al. (2019)
14	**Pakistan**	08-21	Yasar et al. (2021)
15	**Ghana**	0.35- 3.95	Zango et al. (2021)
16	**Malawi**	2.4-16	Belotti & Frazão (2022)
17	**India**	0.5 – 69.7	Park et al. (2024)

3.2. Skeletal fluorosis

Skeletal fluorosis is a pathologic disease caused by prolonged consumption of high fluoride concentrations that accumulate in bones and joints, and symptoms can appear in children and adults (Wu et al., 2016). High fluoride deposition results in osteoclast genesis and altered calcium levels in bone tissue, which upsets the equilibrium of bone mineral metabolism (Divyadeepika et al., 2024). Fluoride quickly enters the bones and other calcified tissues of the body, resulting in osteosclerosis, osteoporosis, and degenerative joint changes (Chen et al., 2017). Fluoride predominantly affects the synovial joints of the cervical spine, pelvic girdle, vertebral column, knee, and shoulder, with small joints in the hands and feet (Sellami et al., 2020). Thus, there are various stages in the development of the skeletal changes brought on by chronic fluoride poisoning (Biswas et al., 2017).

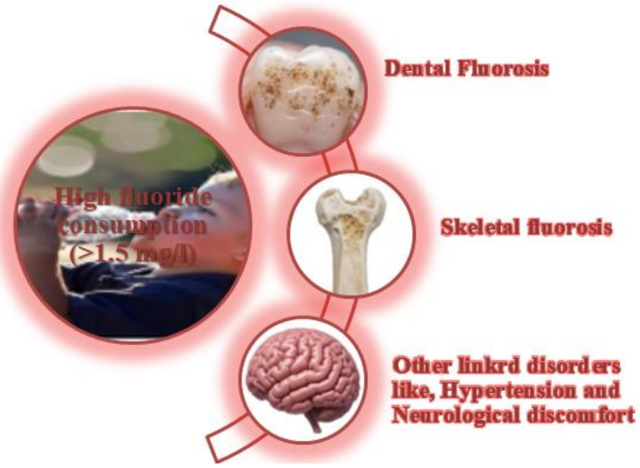

Fig. 3. Effect of Fluoride on human heal

Skeletal fluorosis severity is divided into three categories, which correspond to the disease's progression: mild, moderate, and severe. The symptomatic details of all the categories are as follows:

a. **Mild fluorosis:** Generalization bone, joint pain and osteosclerosis.
b. **Moderate fluorosis:** Periosteal bone formation, calcification, restricted movements at pine and joints and osteosclerosis.
c. **Severe fluorosis**: Exostoses osteophytosis deformities of spine and limb (Park et al., 2024; Choubisa, 2024; Cook et al., 2021).

3.3. Other Fluoride linked disorders

The term "Fluorosis and Linked Disorders" is appropriately used to describe the earliest signs of fluorosis that affect soft tissue. Unfortunately, "Linked disorders" were not given enough attention for nearly 50 years due to soft tissue involvement. To suspect fluorosis, the earliest symptoms are essentially necessary. They are arranged chronologically.

- Discomfort in the gastrointestinal tract (40–50% of people may have IBS)
- Fatigue and weakness are symptoms of muscular injury, and 30–40% of people may experience them.
- Polyuria and polydipsia, which are excessive thirst and urination tendencies that affect 2–20% of people.
- A significant portion of people experience low hemoglobin and anemia.
- Most people (10–30%) may experience pain in their primary joints.

Despite the above conditions, hypertension and neurological disorders have also been included in fluorosis-linked disorders (Susheela and Toteja, 2018).

3.3.1 Hypertension

Elevated fluoride concentration in the body’s hard and soft tissues affects the circulatory system and accelerates the heartbeat. There is no conclusive proof of the increasing risk of high blood pressure on fluorine exposure through food, water, and air, despite research showing that fluoride exposure can cause chronic cardiovascular disease, hypertension, and an increase in heart rate (Panda et al., 2015).

3.3.2 Neurological discomfort

Few studies have demonstrated adverse effects at low fluoride concentrations; the majority of in vitro experiments employing high fluoride levels have consistently shown neurotoxicity to brain cells (Liu et al., 2011). Several studies explain that low concentrations of fluoride like 0.5 µmol/L (10 µg/l) were sufficient to induce biochemical changes and lipid peroxidation in the cells present in the brain, whereas three µmol/L (57 µg/L) induced inflammation reactions in the cells of the brain (Goschorska et al., 2018; Swamy et al., 2024).

4. Analysis and monitoring of fluoride

Determining fluoride concentration in environmental samples is a matter of concern because of its significance for human health. Numerous conventional methods for fluoride determination have been used by the researchers, such as the Electrochemical method (Potentiometric and Voltammetry), Chromatography (Ion chromatography, Gas chromatography, and HPLC), Spectroscopy (ICP and molecular), Microfluid analysis (Flow and sequential injection analysis) (Dar and Kurella, 2023). In recent years, the development of reliable fluoride sensors has emerged as a novel research approach, driven by the need for accurate and efficient fluoride detection. Fluoride has been measured by researchers using a variety of sensors, such as fluorescent chemosensors, colorimetric chemosensors, and PVC membrane samarium (III) sensors (Kabir et al., 2020; Deng et al., 2016; Yadav et al., 2014; Gu et al., 2013). Chemosensors are an attractive option for fluoride detection due to their sensitivity, selectivity, and ease of use. They have recently attracted a lot of attention for these reasons. Other methods include laser-induced breakdown spectroscopy (LIBS), preformed molecular D4R zinc phosphate heterocubane, and microwave-assisted digestion (Quarles et al., 2014; Krishna et al., 2014).

Advanced fluoride detection systems combine digital platforms and biosensors for increased sensitivity and real-time analysis. Optical and fluorescence sensors employ Surface-Enhanced Raman Spectroscopy (SERS), colorimetric probes, and quantum dots for ultra-sensitive detection. Ion-selective electrodes (ISEs) and field-effect transistor (FET) sensors are examples of electrochemical sensors that provide accurate, low-concentration monitoring (Shaji et al., 2024; Pratha & Prabhakar, 2020). Portable, on-site fluoride testing is made possible by lab-on-a-chip (LoC) and microfluidic devices, while selectivity is enhanced by nanotechnology-based sensors like metal-organic frameworks (MOFs) and quantum dots. AI, IoT-based monitoring systems, and smartphone-integrated sensors all improve real-time tracking and data analysis for effective fluoride management (Park et al., 2024; Sahu et al., 2018).

5. Efficient techniques used by the researcher for fluoride removal

5.1. Conventional methods for fluoride removal

Over time, many technologies have been distinguished for fluoride removal and are emerging daily. Some techniques, like

Nalgonda, reverse osmosis, electro-dialysis, etc., have been identified earlier, whereas techniques like adsorption by various substrates are widely used nowadays.

5.1.1 Nalgonda Technique

The Nalgonda technique (oldest technique) is famous for reducing the fluoride problem in groundwater in India and originated from the Nalgonda place of Andhra Pradesh, India (Sahu et al., 2018). Nalgonda techniques for defluoridation are based on adsorption methods using alumina hydroxide, which is readily available in developing countries like India for household or community uses due to its low cost (Divyadeepika et al., 2024).

5.1.2. Reverse Osmosis (RO)

It is a physical mechanism based on the hydraulic system's pressure that uses a permeability layer solute flow from higher to lower concentration. Deng et al (2016) used this technology for water purification.

5.1.3. Electro-dialysis

Electro-dialysis employs an electrochemical process to remove excess salts from water, minimizing the risk of bivalent salt precipitation and reducing energy consumption. Dialysis is a process used to separate transported solutes through the membrane (Garg and Sharma, 2016).

5.2. Emerging techniques for de-fluoridation

5.2.1. Adsorption technique

Adsorption is a physicochemical technique for fluoride removal based on the attraction of molecules by the physical forces and nature of ionic interaction with the adsorbent surface. The technique is an economical procedure with remarkable effectiveness and is uncomplicated for fluoride reduction (Dar and Kurella, 2023). In recent decades, modified biogeomaterials for water purification have been an emerging technology. They can change the original adsorbent's physical and chemical properties and enhance water's purification capacity.

5.2.1.1 Natural materials

The term "natural mineral" refers to a single naturally occurring substance or compound created during a geological process with an essentially constant chemical composition. Natural minerals have significant advantages in terms of scope and cost, and they also show their impact on pollution control, making them particularly useful in pollution control and environmental remediation (Basu, 2024). The literature suggests the natural minerals that can remove fluoride are zeolite, SiO_2, clay, calcium-based minerals, and some other minerals (Nabbou et al., 2019; Gitari et al., 2015; Peng et al., 2013; Zhang et al., 2011). According to several studies, raw clay has been modified by metal oxide amendment, acid treatment, and thermal activation to increase the surface area, active sites, and adsorption capacity of fluoride, and clay-associated minerals are employed for the fluoride removal (Gitari et al., 2015; Maiti et al., 2011).

5.2.1.2 Carbon-based absorbent

Carbon-based materials with pore structure and surface chemical properties, such as graphite and activated carbon, are used extensively in adsorption, sensing, catalysts, and other applications. Because fluoride and carbon have a high affinity for one another (Divyadeepika et al., 2024). According to Balarak et al. (2016), single-walled carbon nanotubes can remove fluoride in the range of 87% to 100% performance efficiency. Choubisa (2024) reported that waste carbon slurry from the fertilizer industry has fluoride adsorption capability of 4.861 mg/g.

5.2.1.3 Metal materials

Multivalent metal oxides are believed to benefit fluoride adsorption due to their high electronegative, smaller size, and strong affinity for fluoride ions. Single metal, binary metal, and ternary metal are the three types of metal-based fluoride elimination materials. Yasar et al. (2021) conducted the modification in the structure of aluminum oxide and found a maximum percentage of fluoride removal (52.15 mg/g) by γ-Al_2O_3 as compared to other forms (θ-Al_2O_3 and α-Al_2O_3). According to a recent study, ethanol treated with manganese as well as zirconium (Mn–Zr–Et adsorbent) at 50 mg/L of fluoride amount demonstrated fluoride adsorption (32.87 mg/g adsorption capacity) (Ye et al., 2024).

5.2.1.4 Resins and polymers

Important adsorbents for eliminating cationic and anionic pollutants from contaminated water are polymers and resins. They are effective material for the fluoride removal because of their three-dimensional, macromolecular, and irregular hydrocarbon chain network organisation.

The polymers used in adsorption have drawn enhancing the attraction from researchers in recent years due to their high surface activity, adjustable surface characteristics, affordability, and efficiency in adsorbent production. Luo et al. (2013) used a carbon-carbon coupling procedure to create a conjugated microporous polymer (BCMP-3) from triaryl boron. At equilibrium fluoride concentrations of 16 mg/L at a temperature of 298 K, the highest adsorption capacity reached 24 mg/g. Wu et al. (2016) developed a novel calcium and aluminum-loaded dual-purpose alginate/carboxymethyl cellulose sodium composite adsorbent (SA/CMC-Ca-Al). The highest amount of fluoride that could be adsorbed at pH 2.0 and 298.15 K was 35.98 mg/g.

Additionally, resins are commonly utilised as fluoride removal adsorbents because of their excellent stability, significant adsorption capability, and adaptability in working environments. Mumtaz et al. (2015) eliminated fluoride from the aqueous phase using a modified chelating resin that contained bifunctional groups of sulfonated monophosphonic acid (S9570-Fe (III)). The efficiency of beads of Haix-Fe-Zr and Haix-Zr resin in fluoride removal was investigated (Goschorska et al., 2018). The findings demonstrated that Haix-Fe-Zr resin beads were more effective at removing fluoride from the tainted groundwater than Haix-Zr resin beads.

5.2.1.5 Industrial By-products

Industries produce a variety of wastes that must be disposed of. Using them appropriately can save costs associated with disposal, mitigate environmental harm at the dump site, and redirect resources to other uses. When utilised for the adsorptive removal of contaminants like fluoride, a variety of industrial waste products have demonstrated and they have exceptional efficacy in defluoridating contaminated water (He et al., 2020). The effectiveness of fluoride removal in flue gas desulfurization gypsum was examined by Sandoval et al. (2014). Fluoride concentrations were lowered by 93.31% using FGD, from 109 to 7.3 mg/L. Based on kinetic study, the theoretical fluoride capacity at one g/L FGD gypsum was roughly 96.90 mg/g. To produce ferric-modified chromium (III)-fibrous protein (Fe-CrFP) adsorbent from tanning leather waste for fluoride absorption, Deng et al. (2016) employed a crosslinking process.

5.2.1.6 Biogeosorbent

Biosorption is the most effective remediation method for eliminating fluoride from water-based systems. Biosorption is the process by which biomass binds ions. Biomass can be either living or dead. However, non-living biomass is preferable to biosorbent. Bio-adsorption technology has been more popular in recent years because of its excellent performance, affordability, and ease of operation (Tomar et al., 2014). Several bio-sorbents made from plant materials have been developed for defluoridating water, such as *Vitex negundo* leaf adsorbent (Saikia et al., 2017), Typha angustata plant adsorbent (Hanumantharao et al., 2012a; Hanumantharao et al., 2012b), Drumstick biosorbent (Parlikar and Mokashi, 2015), *Lagenaria siceraria* shell carbon (Hanumantharao et al., 2012b), root-based adsorbent of plant Cocos nucifera (George and Tembhurkar, 2019), and maize husk, fly ash adsorbent (Deshmukh et al., 2018). The waste from citrus limetta pulp was effectively converted into biogenic activated carbon, which was then used to extract fluoride from an aqueous solution (Ibrahim et al., 2019). These are the only bio-sorbents for defluoridation derived from plant biomass, and their effectiveness was found to be promising (Table 2).

6. Fluorosis Management and Prevention

The treatment of fluorosis does not require any drug/medicine prevention. Disease recovery can be possible upon early detection of fluoride symptoms. Prevention of fluorosis can be done by providing safe drinking water and nutritional intervention (Susheela, 2016). Monitoring water quality is crucial for knowing the level of contamination. Available methods should work on the ground, especially for poor people. The color or symbol should mark the fluoride-affected hand pump for non-drinking uses, and a de-fluoridation tank should be developed in the areas affected by fluoride. Awareness spread about the fluoride contamination in water and associated health issues in fluoride-affected areas.

7. Conclusion

Fluoride-contaminated groundwater is a serious global issue, and most issues are often natural and result from fluoride from natural sources. However, human activity has increased fluoride levels in the environment and worsened matters. Consequently, extremely efficient water management and environmental protection technologies are needed to solve this circumstance. It emphasized the efficient/suitable eco-friendly fluoride removal method from fluoridated water. Prevention of fluorosis is also discussed in this review. Previously available de-fluoridation methods have shortcomings such as being expensive, toxic, and complex processes. The modified Biogeoadsorbent showed promising results in the defluoridation, which was inexpensive, effective and eco-friendly.

Table 2. Fluoride removal by biogeosorbent

S.No.	Adsorbent materials	% Removal	Working pH	Reference
1	Modified lemon leaf	70	5	Tomar et al. (2014)
2	NaOH-treated neem leaves	90	2	Goswami, (2015)
3	Wheat straw	93	7	Romar-Gasalla et al. (2017)
4	Moringa estenopetala	95	7	Mereta, (2017)
5	$SnCl_2$Coated chistogen	90	6	Kahu et al. (2017)
6	Jamun leaf ash	70.8	6.5	Tirkey et al. (2018)
7	Tea ash powder	>90	7	Deshmukh et al. (2018)
8	Banana peel	86.5	2	Mondal and Roy, (2018)
9	Citrus Limetta (sweet lime)	86	4	Brahim et al. (2019)

Additionally, scientists must improve environmentally friendly fluoride removal technologies to increase their scalability and accessibility. Community leaders, scientists, and policymakers must collaborate to guarantee that everyone has access to clean water. By tackling the causes of contamination as well as its negative health impacts, a long-term solution can be developed that protect the environment and enhance people's lives.

Recommendation

Large-scale rainwater harvesting for groundwater recharge can reduce the groundwater fluoride concentration. The responsibility of providing safe drinking water to the fluoride-affected area should be the village administration, the handling of fluoride-rich water before consumption. Adopting an adsorption method to remove fluoride from drinking water provides safe water for drinking and cooking.

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Author contribution

Lata Verma: Writing original draft and conceptualization, **Vippan Kaur:** Writing work**, Aneet Kumar Yadav:** Writing work, **Atin Kumar Pathak:** Formal analysis of review**, Archana Dwivedi:** Writing and editing the draft**, Garima Singh:** Manuscript validation and correction.

Conflict of interest

The authors declare that there are no conflicts of interest.

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