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DEFLUORIDATION OF DRINKING WATER: STATE-OF-THE-ART TECHNIQUES AND FUTURE OUTLOOK

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ABSTRACT

Access to safe drinking water remains a global concern, particularly in regions affected by excessive fluoride concentrations. Various treatment methods, such as precipitation, adsorption, ion exchange, and membrane-based technologies, have been developed to mitigate fluoride contamination. Precipitation techniques convert soluble fluoride into insoluble compounds, while adsorption methods employ low-cost materials like activated alumina, bone char, and bio-adsorbents to capture fluoride ions. Ion exchange and membrane systems further enhance fluoride removal efficiency through selective ion substitution and physical separation, respectively. Despite their proven effectiveness in reducing fluoride to permissible limits and preventing dental and skeletal fluorosis, these technologies face notable challenges, including high operational costs, energy consumption, sludge generation, and limited applicability in rural or low-resource settings. Future research should focus on developing sustainable, energy-efficient, and low-cost treatment technologies using eco-friendly adsorbents, hybrid filtration systems, and nanomaterials to enhance efficiency while minimizing environmental impacts. Overall, ensuring long-term access to fluoride-free water demands an integrated approach combining technical innovation, economic feasibility, and environmental stewardship. Advancements in material science, automation, and circular economy strategies hold promise for overcoming current limitations and achieving sustainable water quality management in the future.

Keywords: Fluoride removal, Drinking water treatment, Adsorption, Ion exchange, Membrane technology, Reverse osmosis, Electrocoagulation

Abbreviation

RO	Reverse Osmosis
TDS	Total Dissolved Solids
MOFs	Metal-Organic Frameworks
RSM	Response Surface Methodology
ANN	Artificial Neural Network
SVM	Support Vector Machine
PCA	Principal Component Analysis
NF	Nanofiltration
TFN	Thin-film Nanocomposite
UF	Ultrafiltration
MOFs	Metal-organic Frameworks
WHO	World Health Organization

INTRODUCTION

Water, an essential resource for sustaining life and ecosystems, as well as supporting agriculture and human well-being, faces a significant threat from elevated fluoride concentrations (Achour et al., 2002; Youcef and Achour, 2004; Tabouche and Achour, 2004; Ghazali and Zaid, 2013; Chadee et al., 2024). The contamination of water with excessive fluoride levels poses risks to both the environment and human health. Elevated fluoride in drinking water has been associated with various health issues, such as dental and skeletal fluorosis (Solanki et al., 2022). In areas where natural fluoride levels exceed recommended limits, the process of becoming crucial to ensuring access to safe drinking water with a better governance (Achour and Chabbi, 2014; Ayari and Ayari, 2017; Yoboué et al., 2019); Ihsan and Derosya, 2024; Pandey et al., 2025), involves the removal or reduction of fluoride ions to meet regulatory standards for safe consumption (Chen et al., 2022). Over time, researchers and engineers have explored various techniques to achieve efficiency, each with its own set of advantages, limitations, and environmental implications (Ayoob et al., 2008; Jamwal and Slathia, 2022; Moradi et al., 2025). This comprehensive review examines the diverse methods used in water, their mechanisms, and the current and future consequences associated with their application (Remini and Amitouche, 2023; Remini, 2010; Aroua, 2018; 2022; 2023).

Fluoride plays a crucial role, in minimal amounts, in promoting bone mineralization and preventing dental cavities (Everett, 2011). However, elevated fluoride intake can lead to enamel deterioration known as fluorosis (Table 1) (Waghmare and Arfin, 2015) and is associated with various serious health conditions, including osteoporosis, brittle bones, arthritis, brain damage, cancer, infertility, Alzheimer's syndrome, and thyroid disorders (Kumar et al., 2021; Fadaei and Amiri, 2013). However, human-made activities, industrial and agricultural processes, and geological sources contribute to the presence of fluoride in aqueous environments. All-natural water sources contain some level of fluoride, with groundwater fluoride levels being influenced by minerals such as calcium and the type of rock (Dhillon et al., 2017). Table 2 provides information on the characteristics of fluoride materials.

One prominent method for addressing high fluoride levels is reverse osmosis (RO). This technique has gained considerable attention since the 1960s due to advancements in membrane materials and technologies (Ousman et al., 2023; Brião et al., 2019). RO is known for its lower energy consumption and ability to effectively separate nearly all total dissolved solids (TDS) from seawater, meeting established guideline standards (Brião et al., 2019; Yadav et al., 2024; Sahu et al., 2024). However, commonly used methods have their limitations, including high initial installation costs, lack of selectivity, low capacity, and challenges with regeneration or utilization (Bejaoui et al., 2014). Furthermore, the World Health Organization (WHO) has set the optimal fluoride concentration in drinking water for general well-being between 0.5 and 1.5 mg/L, within a temperature range of 12 to 25°C (Edition, 2011).

Recent studies emphasize two complementary pathways for affordable, effective defluoridation: engineered low-cost adsorbents and advanced membrane systems. On the adsorbent side, researchers have reported increasingly sophisticated biomass-derived materials (e.g., rice-husk nanocellulose, modified biochar, metal-doped activated carbons) that combine high fluoride affinity, rapid kinetics, and reusability under realistic pH and ionic conditions; batch and column tests show removal efficiencies frequently in the 60-90% range for moderate concentrations and demonstrate good regeneration potential (Sihag et al., 2023). In parallel, membrane approaches have progressed from pure pressure-driven NF/RO toward hybrid and functionalized systems, thin-film nanocomposite (TFN) membranes, adsorptive ultrafiltration (UF) membranes doped with lanthanum- or metal-oxide functional groups, and integrated RO–membrane-crystallization units, which achieve very high fluoride rejection (often > 95% for RO/NF) while addressing fouling through surface modification and adsorptive preremoval (Xue et al., 2024). Reviews synthesize these advances and highlight practical challenges, cost/scale of adsorbent production, competing anions, concentrate management, and membrane fouling while proposing hybrid, site-tailored solutions as the most promising route for safe, low-cost defluoridation in resource-limited settings (Choksi et al., 2015a).

This study presents a comprehensive and forward-looking assessment of defluoridation of water, emphasizing the integration of emerging technologies with sustainable treatment approaches. Unlike traditional reviews, it combines a comparative analysis of adsorption, membrane, and electrochemical methods while critically identifying their operational limitations and scalability challenges. The novelty lies in proposing a hybrid, low-cost, and energy-efficient framework that merges nanomaterial-based adsorbents with renewable-driven electrochemical systems. This holistic perspective not only advances scientific understanding but also establishes practical pathways for future decentralized defluoridation solutions, aligning with global sustainability and safe drinking water objectives.

Table 1: Fluoride concentration in drinking water affects human health (Siaurusevičiūtė and Albrektienė, 2021).

Fluoride concentration in (mg/L)	Consequences
< 0.5	Dental cavities
0.5-1.5	Optimum dental health
1.5-4.0	Dental fluorosis
4.0-10.0	Dental and skeletal fluorosis
> 10.0	Crippling fluorosis

Table 2: Properties of fluoride materials (Siaurusevičiūtė and Albrektienė, 2021).

Materials	Compositions	Concentration rate (%)
Fluorapatite	$Ca_3 (PO_4) F$	4
Bastnaesite	$(Ce, La) (CO_3) F$	9
Cryolite	Na_3AIF_6	45
Fluorite (fluorspar)	CaF_2	49
Villianmitte	NaF	55
Sellaite	MgF_2	61

The study of is crucial because of the vast prevalence of fluoride pollution, which presents significant health hazards, such as dental and skeletal fluorosis (Ayoob et al., 2008). This problem is especially critical in areas with high natural fluoride concentrations in groundwater. We extensively employ conventional techniques, such as adsorption (Verma et al., 2024; Choksi et al., 2015b) with activated alumina, bone char, and ion-exchange resins, but frequently encounter obstacles such as restricted capacity, regeneration complexities, and problematic waste management. Reverse osmosis and nanofiltration membrane technologies, despite their great removal efficiency, face limitations due to their high energy consumption, membrane fouling, and brine disposal.

Emerging innovations to tackle these issues include the creation of sophisticated adsorbents such as metal-organic frameworks (MOFs) and nanomaterials, which provide even more selectivity and capacity. People are increasingly pursuing electrochemical processes like electrocoagulation and electrodialysis because they can reduce operational costs and environmental impact. Biosorption, which utilizes biological resources such as algae and agricultural waste, offers a sustainable alternative.

Despite the substantial societal benefits of water defluoridation technologies, the study faces certain limitations that must be acknowledged. Many current techniques, while effective at reducing fluoride levels, often involve high operational costs, complex maintenance requirements, and energy-intensive processes, which can restrict their implementation in resource-limited communities. Additionally, most research has been conducted at laboratory or pilot scales, leaving uncertainties about large-scale performance and long-term sustainability. Future research should prioritize the optimization of these technologies to achieve broader applications, enhance cost-effectiveness, and minimize environmental impacts. Moreover, adopting adaptive management approaches such as integrating hybrid treatment systems with real-time monitoring has the potential to significantly improve operational efficiency, ensuring that safe drinking water is reliably available to vulnerable populations. By addressing these limitations, the study underscores both the promise and the ongoing challenges of delivering community-level solutions for fluoride-contaminated water.

Fluoride concentration from a groundwater perspective

Controlling the fluoride concentration in groundwater is a crucial factor directly impacting water quality for human consumption (Nakayama et al., 2022). While fluoride occurs naturally in various geological formations, excessive levels can have adverse health effects. Therefore, it is essential to monitor and regulate fluoride concentrations in groundwater. However, geological factors play a significant role in determining fluoride levels, with minerals like fluorite, apatite, and mica contributing to elevated concentrations (WHO, 2004). As water passes through rock formations, it can dissolve these minerals, releasing fluoride ions into the groundwater. Regions with abundant fluoride-rich minerals, particularly those with volcanic or sedimentary rock formations, are more likely to have elevated fluoride levels in groundwater. However, apart from natural sources, human activities can also contribute to increased fluoride concentrations. To ensure public health and safety, the WHO has established guidelines for fluoride concentrations in drinking water. The optimal range is 0.5 to 1.5 milligrams per liter (mg/L) (Ali et al., 2016). Concentrations below 0.5 mg/L may lack dental benefits, while concentrations above 1.5 mg/L can lead to dental and skeletal fluorosis (Al-Ahmed et al., 2021; Ahmad et al., 2022; Ahmad, 2022).

Monitoring fluoride levels is crucial for identifying areas with elevated concentrations and implementing appropriate mitigation measures. Regular water testing helps authorities and communities understand the extent of fluoride contamination and take preventive measures to ensure safe drinking water (Swarnkar et al., 2024). Various methods can be employed to mitigate high fluoride concentrations, such as water treatment technologies like activated alumina, bone char, and reverse osmosis. Implementing land-use practices that minimize the use of fluoride-containing substances, proper disposal of industrial waste (Swarnkar et al., 2023), and promoting sustainable agriculture also contribute to preventing further contamination (Hajiani et al., 2022). In addition, public awareness and education are essential components of any strategy to address fluoride concentration in groundwater. Therefore, managing fluoride concentration in groundwater involves understanding geological, industrial, and agricultural factors. Through monitoring, effective mitigation measures, and public awareness, communities can ensure access to safe groundwater, protecting the health and well-being of their populations (Kanduti et al., 2016).

Contamination in groundwater

Groundwater contamination stands as a critical environmental challenge, posing substantial risks to public health, ecosystems, and overall water security (Saadi et al., 2014; Bahir et al., 2015; Belhadj et al., 2017; Carrard et al., 2019; Zegait et al., 2021).

Situated beneath the Earth's surface in saturated soil and rock layers, groundwater serves as a crucial source of drinking water for a significant portion of the global population, especially under climate fluctuations (Ouis, 2012; Kouassi et al., 2013). However, groundwater quality and safety are in danger due to the introduction of contaminants brought about by both human activity and natural processes (Freeze, 1984; Kheliel et al., 2015). The groundwater quality must be assessing using modern and strong tools (Koussa and Berhail, 2021; Lachache et al., 2023). Among the leading contributors to groundwater contamination are industrial activities encompassing manufacturing, mining, and chemical processing (Bouchemal and Achour, 2015; Lancellotti et al., 2023). Inadequate disposal of industrial waste, leakage from storage tanks, and accidental spills can release hazardous substances, such as heavy metals (Zoufri et al., 2024), solvents, and toxic chemicals, into the soil (Jeschke, 2016; Hallberg, 1987). Once these contaminants infiltrate the ground, they can percolate downward, reaching the groundwater and causing enduring pollution. Agricultural practices also play a substantial role in groundwater contamination. The application of fertilizers, pesticides, and herbicides in farming can lead to the leaching of harmful substances into the ground. Nitrate contamination, often linked to excessive fertilizer use, is a prevalent issue with adverse effects on human health, particularly in infants, leading to conditions like methemoglobinemia or "blue baby syndrome" (Zwolak et al., 2019; Shaban et al., 2023).

Improper disposal of household waste, including septic tank leaks and the disposal of household chemicals, poses another threat to groundwater quality (Abdel-Shafy et al., 2023). Additionally, the leakage of underground storage tanks at gas stations and fueling facilities presents a risk of introducing petroleum hydrocarbons into the groundwater, further compromising its quality.

Natural processes, such as mineral weathering and geological leaching, can also contribute to the presence of naturally occurring contaminants in groundwater. Certain geological formations may naturally contain elevated levels of substances like arsenic or fluoride, posing health risks when concentrations surpass recommended levels (El-Saadony et al., 2023; Brindha and Elango, 2011). Therefore, addressing groundwater contamination necessitates a comprehensive approach, encompassing proper waste management practices, stringent regulations on industrial discharges, the adoption of sustainable agricultural practices, and the implementation of effective monitoring and remediation strategies.

METHODS

Different techniques used for fluoride removal

Various techniques are frequently employed to eliminate fluoride from drinking water, with the selection of a specific method contingent upon factors like the fluoride concentration in the water, financial considerations, and local circumstances. Below are several commonly used methods for fluoride removal.

It is an essential water treatment method employed to eliminate surplus fluoride, which can lead to health problems associated with dental and skeletal fluorosis. Adsorption techniques utilizing activated alumina, bone char, and ion exchange resins are frequently used because of their high efficiency and cost-effectiveness. Although membrane techniques such as reverse osmosis and nanofiltration provide excellent fluoride removal rates, their effectiveness is generally constrained by operational expenses. The eco-friendliness and scalability of emerging technologies such as electrocoagulation and biosorption have attracted considerable interest (Tolkou et al., 2021).

This study assumes that fluoride removal efficiency primarily depends on parameters such as pH, contact time, adsorbent dosage, and temperature, which remain constant under controlled laboratory conditions. It is also assumed that the fluoride present in the tested water samples exists mainly as soluble fluoride ions and that interference from other ions is negligible. Additionally, the economic and environmental feasibility of emerging defluoridation techniques is evaluated under ideal operational conditions. These assumptions provide a standardized basis for comparing existing technologies and identifying sustainable pathways for efficient fluoride mitigation.

Defluoridation of water involves several critical parameters that influence the efficiency and feasibility of various treatment methods. These include the initial fluoride concentration, pH, temperature, and the presence of competing ions, which can affect the adsorption capacity and kinetics of defluoridation processes. The choice of adsorbent material, such as activated alumina, bone char, or hydroxyapatite, plays a significant role in determining the removal efficiency and regeneration potential. Additionally, factors like contact time, flow rate, and the specific surface area of the adsorbent are crucial in optimizing the defluoridation process. Understanding and controlling these parameters are essential for developing effective and sustainable defluoridation technologies, particularly in regions with high fluoride contamination levels

Activated alumina

Activated alumina, characterized by its porous nature, can adsorb fluoride ions (Tang et al., 2009). As water traverses a column filled with activated alumina, the fluoride ions attach themselves to the alumina's surface.

Ion exchange

Ion exchange entails substituting fluoride ions with other ions that exhibit a lesser attraction to the exchange resin. Typically, a resin containing chloride or hydroxide ions is employed for this process (Strathmann et al., 2013). While effective, this method can incur significant costs.

Reverse osmosis

Reverse osmosis involves the filtration of water through a semi-permeable membrane, where pressure is applied to allow water molecules to pass through while preventing the passage of most dissolved ions (Joo and Tansel, 2015; Greenlee et al., 2009), including fluoride.

Bone char

Bone char, derived from animal bones, exhibits a strong attraction to fluoride. When water is filtered through a layer of bone char, fluoride ions adhere to the char's surface through adsorption.

Electrocoagulation

This process entails applying an electric current to water to disrupt and coalesce impurities, such as fluoride. The aggregated particles can subsequently be eliminated through sedimentation or filtration (Mollah et al., 2001).

Adsorption with aluminium salts

Aluminum-based coagulants, like aluminum sulphate (alum) (Wallis et al., 1963), can combine with aluminum fluoride to form insoluble complexes that are easier to remove through settling or filtering.

Lime softening

Water is treated with lime (calcium hydroxide) (Randtke et al., 1982; Liao and Randtke, 1986), causing the formation of precipitates of calcium fluoride, which can be eliminated through either sedimentation or filtration processes.

Distillation

Distillation entails heating water to create steam, which is then cooled and returned to a liquid state. Since fluoride has a relatively low vaporization point, the distilled water is expected to exhibit decreased fluoride concentrations.

Solar

This approach harnesses solar energy to warm water within shallow ponds or channels (Anjaneyulu et al., 2012). As the water undergoes evaporation, residual fluoride is deposited, leading to diminished fluoride concentrations.

Precipitation

The precipitation processes entail introducing chemicals and generating fluoride precipitates, with calcium and aluminum salts being prominent in these reactions (Jagtap et al., 2012). Daily, chemicals must be added in batches during the precipitation, resulting in the daily production of a certain quantity of sludge.

Membrane technologies

Membrane technology, including reverse osmosis (RO), nanofiltration (NF), and electrodialysis (Brose et al., 2002), is extensively employed because of its exceptional efficacy in eliminating fluoride. Reverse osmosis (RO) and nanofiltration are very efficient approaches, but they encounter obstacles such as significant energy consumption, membrane fouling, and the production of brine waste. The possibility for reduced energy use and selective ion removal has made electrodialysis a subject of increasing investigation. Emerging developments strive to enhance membrane selectivity, mitigate fouling, and decrease operational expenses, thus enhancing the sustainability and accessibility of these methods for large-scale applications (Lacson et al., 2021).

New methods used for fluoride removal

Various methods are utilized for eliminating fluoride from drinking water, each presenting its own set of advantages and limitations (Tiwari et al., 2023).

Electrodialysis

Electrodialysis is a treatment process that utilizes ion-selective membranes and an electric field to selectively eliminate fluoride ions. However, its energy-intensive nature may limit its applicability in certain water treatment situations.

Ion exchange resins

Ion-exchange resins exhibit the capacity to selectively eliminate fluoride ions through an exchange process with other ions within the resin. Regeneration of the resin becomes imperative once it reaches its saturation point for fluoride ions.

Nano-filtration

Nano-filtration represents a membrane-driven filtration technique capable of selectively eliminating ions according to their size and charge. While it may not match the efficacy of reverse osmosis in removing fluoride, it proves to be a more economically viable alternative.

Biological defluoridation

Scientists have been investigating the capacity of specific microorganisms and plants to gather fluoride from water. Ongoing research aims to assess the practicality of employing biological approaches on a large scale for the removal of fluoride.

Crystalactor

The crystal reactor represents an innovative solution for the efficient removal of fluoride from drinking water. Through a distinctive crystallization process (Aldaco et al., 2008), Crystalactor attains high removal rates while keeping operational costs to a minimum (Xuechu et al., 2009). The system involves the creation of calcium fluoride crystals that are easily separable to yield purified water. This groundbreaking technology addresses the increasing concern of elevated fluoride levels in drinking water, a prevalent issue in numerous regions. The accompanying illustration elucidates the Crystalactor process, highlighting the crystallization of calcium fluoride and its subsequent separation. Crystalactor not only offers an environmentally friendly remedy but also ensures the provision of safe and compliant drinking water (Silva, 2023).

The Crystalactor is a crystallizer utilizing a fluidized bed design (Fig. 1). In contrast to traditional water treatment methods, this cost-efficient crystallization approach generates a valuable by-product instead of producing waste.

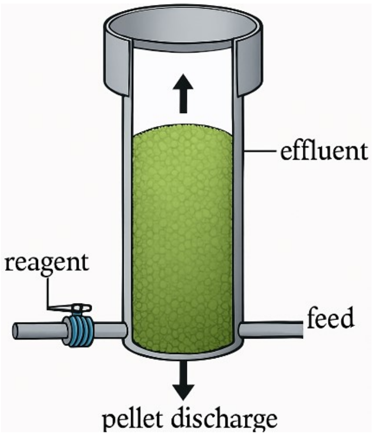

Figure 1 Crystalactor (Giesen, 1999).

Memstill technology

Memstill technology emerges as a state-of-the-art remedy for eliminating fluoride from drinking water, addressing the critical issue of water contamination (Tolkou et al., 2021). This innovative approach seamlessly merges membrane filtration and distillation, providing an effective and sustainable method to ensure water safety. The process begins with specialized membranes that selectively segregate fluoride ions from water, preventing their passage and allowing only water molecules to permeate. This design ensures contaminants are retained. Following this, the concentrated fluoride solution undergoes a distillation process (Ying et al., 2020), where water is vaporized and then condensed back into a liquid state. This dual-stage method guarantees the precise removal of fluoride, resulting in purified water. The accompanying Fig. 2 illustrates the integrated design of the Memstill system, showcasing the membrane filtration unit and distillation chamber working cohesively. Memstill technology represents a significant stride in pursuing clean and safe drinking water, providing an environmentally friendly and sustainable solution to combat fluoride contamination.

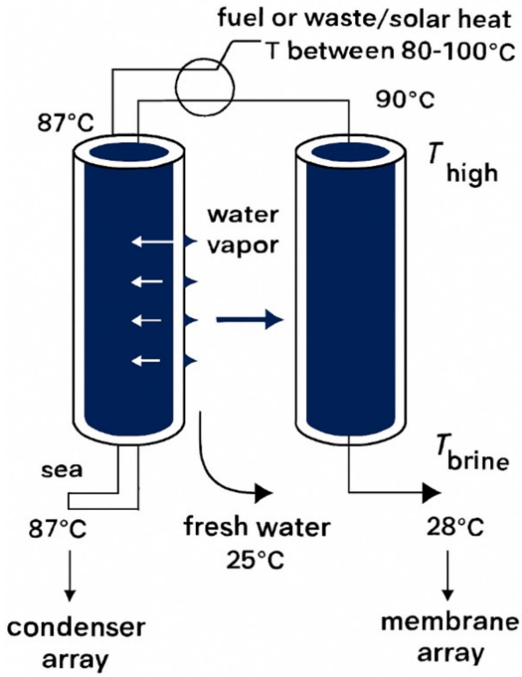

Figure 2: Integrated design of Memstill technology.

Water pyramid solution

The Water Pyramid stands out as an innovative remedy for the pressing issue of fluoride contamination in drinking water, a problem that poses significant health risks such as dental and skeletal fluorosis (Sankhla and Kumar, 2018). This forward-thinking and cost-efficient technology integrates traditional water purification methods with state-of-the-art techniques. Located at the foundation of the Water Pyramid, a pre-treatment chamber utilizes activated charcoal and sand filtration to eliminate impurities and particulate matter. Subsequently, the water progresses through a sequence of chambers featuring advanced ion exchange resins specially designed to target and capture fluoride ions. This thoughtful combination ensures a comprehensive removal of fluoride, rendering the water safe for consumption.

The modular design of the Water Pyramid allows for scalability and adaptability to different water quality conditions. The pyramid's shape enhances water flow efficiency, optimizing the overall treatment process. Additionally, the system is suitable for installation in off-grid or rural areas because it can use solar energy. Furthermore, accompanying this description is a visual representation (Fig. 3) illustrating the Water

Pyramid's layered structure, emphasizing the filtration stages and the precise removal of fluoride.

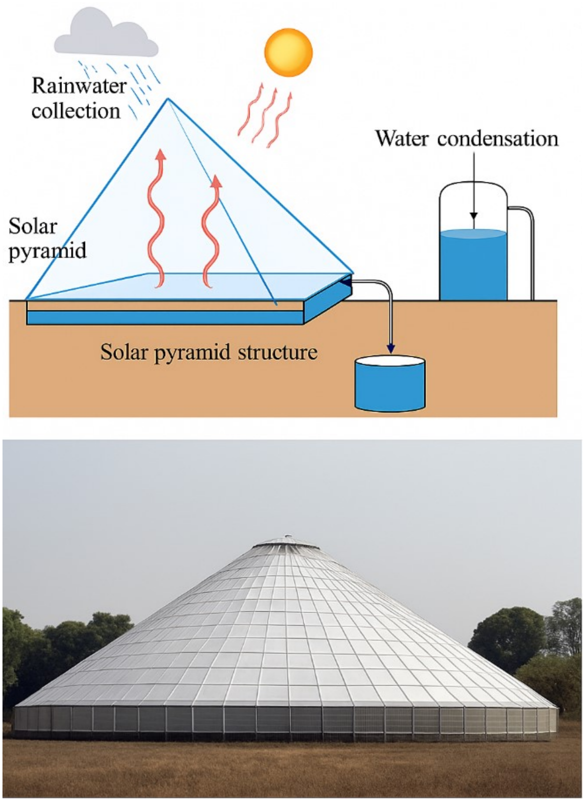

Figure 3: Visual representation of the Water Pyramid's layered structure.

Solar dew collector system

The Solar Dew Collector System (Rajvanshi, 1981) is an innovative approach to combating fluoride contamination in drinking water, offering a sustainable solution that utilizes solar energy. This eco-friendly technology utilizes specially designed structures equipped with solar panels to capture sunlight. These panels generate heat, initiating the evaporation of water from contaminated sources. As the water vapor rises, it encounters a condensation surface within the collector, leading to the formation of dew droplets. These droplets, now free from fluoride and other impurities, are collected in a reservoir for safe consumption.

The simplicity and scalability of the Solar Dew Collector make it a practical solution for communities grappling with fluoride contamination (Rashid et al., 2022), particularly in areas lacking conventional water treatment facilities (Fig. 4). By effectively removing fluoride from drinking water, this system not only addresses a critical health concern but also demonstrates the integration of renewable energy into water purification technologies.

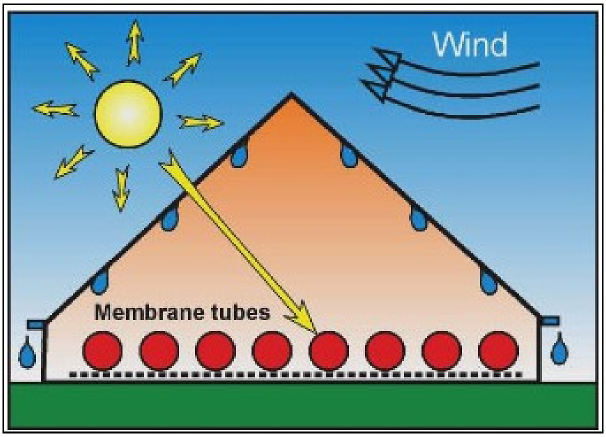

Figure 4: Solar dew collector system.

Boiling with brushite and calcite

The utilization of brushite and calcite in boiling water presents an innovative and efficient technique for eliminating fluoride from drinking water (Larsen and Pearce, 2002). The global concern over fluoride contamination in water sources, leading to potential health risks such as dental and skeletal fluorosis, has prompted the adoption of this method. Brushite, some crystalline material rich in calcium and phosphate, and calcite, a form of calcium carbonate, are employed due to their capacity to interact with fluoride ions.

As water undergoes the boiling process, brushite releases calcium ions into the water, facilitating the formation of calcium fluoride precipitates. These precipitates actively bind to fluoride ions, effectively diminishing their concentration in the water. Concurrently, calcite plays a crucial role in the removal process by elevating the alkalinity of the water, creating an optimal environment for fluoride precipitation. This approach not only provides a cost-effective solution but also aligns with environmental considerations, offering a sustainable alternative to fluoride removal. Particularly in regions where alternative water treatment technologies may be impractical or costly, boiling with brushite and calcite emerges as a straightforward yet robust method. By mitigating the adverse effects of excessive fluoride in drinking water, this technique ensures the provision of safe and potable water to communities grappling with fluoride-related health challenges.

A unique strategy put forth by Larsen and Pearce (2002) involved boiling a suspension of brushite ($CaHPO4.2H2O$) and calcite (calcium carbonate). The results of lab tests were encouraging, showing that quickly boiling a mixture of brushite and calcite makes it easier for these two salts to change into apatite. Notably, the fluoride present in the solution becomes incorporated into the apatite structure through this process.

New adsorbent for absorption of fluoride

In the pursuit of ensuring access to safe drinking water, researchers have actively delved into innovative solutions for the removal of fluoride, a prevalent contaminant known for its detrimental health effects. Emerging as promising candidates for effective fluoride adsorption, new adsorbents address the urgent need for dependable water purification methods (Bhatnagar et al., 2011). Noteworthy among these adsorbents are advanced materials like graphene oxide, metal-organic frameworks (MOFs), and various modified natural materials. In addition, graphene oxide, characterized by its high surface area and distinctive structure, demonstrates exceptional adsorption properties, efficiently capturing fluoride ions from water. In contrast, MOFs offer tunable structures that can be tailored to specific adsorption requirements, showcasing versatility and efficiency in fluoride removal processes. Additionally, modified natural materials, such as chitosan and activated carbon, have been investigated for their enhanced adsorption capacities.

The exploration of novel adsorbents signifies a critical stride towards achieving global standards for safe drinking water. As research continues to advance the frontiers of materials science and environmental engineering, the development of highly efficient adsorbents represents a promising milestone in the ongoing efforts to combat fluoride contamination in drinking water.

STATISTICAL METHODS

Response surface methodology (RSM)

Purpose of RSM

a. Optimization: Response Surface Methodology (RSM) primarily determines the most favorable parameters for a specific process, such as optimally maximizing fluoride removal in water treatment.
b. Modelling and analysis: This study examines the correlation between independent factors, such as pH, adsorbent dosage, and contact time, and the response variable, such as fluoride removal effectiveness.

Application in defluoridation

a. Parameter optimization: To achieve maximum fluoride removal, Response Surface Methodology (RSM) extensively optimizes crucial parameters such as adsorbent dosage, pH, and contact time. To optimize procedures, an analysis of interaction effects is essential for determining the synergistic or antagonistic effects between factors.

b. Cost-effectiveness: RSM minimizes resource consumption and operational expenses by determining optimal conditions with a reduced number of trial runs.

Advantages of RSM

a. Efficiency: Demands a reduced number of trials in comparison to conventional approaches, therefore conserving both time and financial resources.
   Robust optimization techniques efficiently manage several variables and their inter actions, therefore enabling a thorough comprehension of the process.
b. Visual Insights: generates contour and surface plots that provide a graphical representation of the impact of variables on the answer, facilitating decision-making.

Limitations of RSM

a. Complexity: As the number of variables increases, the model and interpretation of the data can become increasingly difficult.
b. Quadratic Model Assumption: Response Surface Methodology assumes a second-order polynomial model, which may not accurately represent strongly non-linear connections until higher-order elements are incorporated.

Artificial neural network (ANN)

Artificial neural networks (ANNs) are computational models that draw inspiration from the human brain. They can represent intricate and non-linear dependencies between inputs and outputs. Artificial neural networks (ANNs) in research forecast the effectiveness of fluoride removal by considering factors such as adsorbent characteristics, water composition, and operating parameters. This is because artificial neural networks (ANNs) work well when regular statistical methods fail because of non-linearity and complicated variable interactions. Such models have exceptional predictive precision and are capable of processing extensive information, making them highly advantageous for process optimization and scale-up forecasts.

Machine learning algorithms

Machine learning algorithms such as support vector machine (SVM), random forests, gradient boosting, and decision trees are becoming more commonly employed in studies. These algorithms are capable of representing intricate interactions between parameters and offer a high level of predicted accuracy. For example, Random Forests are capable of processing vast quantities of data, including numerous variables, thereby providing valuable insights into the crucial aspects that have the greatest influence on fluoride removal. Support Vector Machine (SVM) is employed in classification and regression tasks to assist researchers in optimizing parameters for effective fluoride removal. These approaches are preferred because they can automatically adapt to the complexity of data without requiring significant manual adjustment.

Principle Component Analysis (PCA)

By expressing datasets as a smaller group of uncorrelated variables known as principle components, Principle Component Analysis (PCA) reduces the number of dimensions. In investigations, principal component analysis (PCA) is employed to determine and prioritize the most important aspects that influence the effectiveness of fluoride removal. This enables researchers to concentrate on crucial variables and streamline the optimization process. The Principal Component Analysis (PCA) method makes data less complicated, which makes results easier to understand and helps find the exact parts that affect the process.

Setup, scale of use, and location

Defluoridating drinking water is technically viable at the point of use and applicable to both small communities, such as wellhead installations, and larger water supplies. Point-of-use systems can generate ample treated water for the drinking and cooking needs of several individuals. Numerous small distillation units, designed for plumbing into existing systems, have undergone testing and demonstrated the ability to produce 10 liters per day or even larger quantities. Certified low-pressure reverse osmosis units, ranging in rated capacities from 30 to 100 liters per day, are readily available. Additionally, point-of-use activated alumina anion exchange can effectively eliminate fluoride from small water volumes, though international performance standards for this method have not yet been established.

In more developed regions, conventional water treatment is typically conducted in centralized water works with minimal user involvement. Skilled operators oversee the process, and the affordability of treatment is assumed. This approach is well-established and closely regulated, but it demands substantial resources and may pose challenges in less-developed countries, particularly in rural areas where water users are dispersed and local supply is the norm. In such scenarios, decentralized treatment becomes a more viable option, whether at the community village level or directly within households (Table 3).

Table 3: The characteristics of water treatment methods vary between conventional systems in industrialized nations and those in developing countries.

Criteria	Industrialized Countries	Developing Countries
Setups and constant flow	Frequently organized in vertical streams	Organize in non-uninterrupted vertical formations. Execute filling and drawing processes in batches.
Equipment and treatment location	Consistently positioned at waterworks, typically in proximity to water reservoirs.	Operational at the community level. Implemented at the household level.
Treatment media/process	Precipitation Activated alumina	Activated alumina bone charcoal

	Reverse osmosis Synthesis resins Electrodialysis	precipitation Nalgonda and other naturally occurring media.

Evaluation criteria

The removal of fluoride from drinking water is essential for public health, and the evaluation criteria should prioritize efficiency, affordability, and environmental impact (Majumdar and Sundarraj, 2013). It is crucial to choose a method that consistently achieves fluoride levels within acceptable limits set by health authorities. Cost-effectiveness is vital for widespread implementation, especially in economically challenged regions. Additionally, environmentally friendly techniques should be favored to minimize ecological repercussions. Considerations such as simplicity, scalability, and compatibility with existing water treatment infrastructure also play crucial roles in selecting an optimal fluoride removal solution. In essence, a comprehensive evaluation must balance efficacy, accessibility, and sustainability to protect communities from the harmful effects of excess fluoride in drinking water (Boehmer et al., 2023).

There is no universally applicable method suitable for all social, financial, economic, environmental, and technical contexts. Moreover, none of the existing methods has been successfully implemented on a large scale in many regions worldwide. Each method comes with its own set of drawbacks, which are presented below:

High-cost technology

Advanced technologies with elevated expenses, encompassing both high initial costs and ongoing operational expenditures, often necessitate imported spare parts, a consistent power supply, costly chemicals, and skilled operation or regeneration. Examples of such high-cost technologies include reverse osmosis, ion exchange, and activated alumina.

Limited efficiency

The method's effectiveness is restricted, meaning it fails to adequately eliminate fluoride even when the correct dosage is applied. For instance, in the Nalgonda technique, the remaining concentration frequently surpasses 1 mg/L, unless the initial fluoride levels in the raw water are comparatively low.

Unobserved breakthrough

The fluoride levels in treated water can increase slowly or abruptly, especially when the medium in a treatment column becomes depleted or when the flow is not properly regulated. For methods involving bone charcoal and other column filters, regular monitoring of fluoride residuals is essential, or keeping track of the flow rate and treated water volume is crucial to prevent unnoticed breakthroughs or a decline in removal capacity.

Limited capacity

The removal capacity of bone charcoal or activated alumina is approximately 2 mg of fluoride per gram of medium, whereas significantly larger quantities of calcined clay.

Deteriorated water quality

Degraded water quality naturally leads to elevated pH levels, typically exceeding 10 (du Plessis, 2022; Chowdhury, 2018). The decline in water quality can stem from bacterial proliferation, inadequately prepared media such as bone charcoal, or leakage of the medium from the treatment container, including ion exchange, alumina, Nalgonda sludge, etc.

Taboo limitations

Certain cultural and religious restrictions exist regarding specific methods, such as the use of bone charcoal. In Hindu culture, the bone charcoal method is deemed culturally inappropriate. Likewise, Muslims may raise concerns about bone charcoal originating from pigs. Additionally, villagers in North Thailand have reported the charring of bones as unacceptable.

Selection of appropriate methods

The selection of an appropriate fluoride removal method is a pivotal decision with direct implications for public health in both industrialized and developing countries. Decision trees (Fig. 5) offer a methodical approach to guide this selection process, taking into account factors such as cost, efficiency, and technological feasibility. In industrialized nations with advanced infrastructure, decision trees serve as valuable tools for choosing the most appropriate fluoride removal method based on specific contextual factors. Variables like the degree of fluoride contamination, adherence to water quality standards, and available resources are considered in the decision-making process. For instance, in cases of relatively low fluoride concentrations, cost-effective technologies like activated alumina or ion exchange may be favored. In contrast, in developing countries, decision trees are instrumental in navigating the challenges posed by limited resources and infrastructure. The focus may shift towards low-cost, sustainable solutions that can be easily implemented in resource-constrained environments.

Ultimately, decision trees streamline the decision-making process, providing a systematic framework for evaluating diverse fluoride removal methods. By incorporating considerations specific to each context, these decision trees contribute to the development of tailored solutions that address the unique challenges faced by industrialized and developing countries in mitigating fluoride contamination in drinking water.

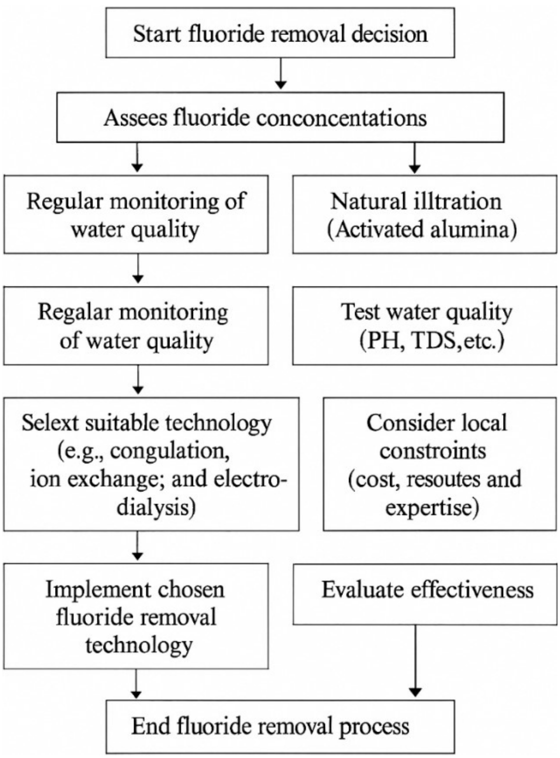

Figure 5: Decision tree flowchart for the selection of appropriate methods.

PRESENT AND FUTURE CONSEQUENCES OF FLUORIDE LEVELS

Present consequences of high fluoride levels

Prolonged exposure to elevated fluoride levels can result in diverse health consequences in humans, contingent on the source and duration of exposure. Fluoride is commonly present in water, dental products, and certain foods. Although moderate fluoride levels are generally deemed safe and even advantageous for dental health, an overabundance of intake can give rise to adverse effects. Here are some of the current repercussions linked to elevated fluoride levels:

Dental and skeletal issues

Long-term and excessive consumption of fluoride can give rise to dental and skeletal fluorosis. Dental issues such as enamel fluorosis may manifest, leading to discoloration or pitting of the teeth. In addition, skeletal fluorosis can impact the bones, causing discomfort and restricting mobility.

Health concern

Ongoing research and discussions continue to explore the potential health implications of elevated fluoride levels, with some studies suggesting associations with various issues, including neurological problems.

Water quality regulations

Numerous nations and areas have implemented regulations on water quality that set maximum allowable levels for fluoride in drinking water to safeguard public health (WHO, 2004). When these benchmarks are surpassed, it becomes imperative to undertake water treatment or engage in processes.

Bone health issues

Elevated levels of fluoride may be associated with a higher likelihood of experiencing bone fractures and joint pain. Excessive fluoride can impact bone density and mineralization, potentially resulting in skeletal abnormalities.

Neurological effects

Several studies propose a potential association between elevated fluoride exposure and unfavourable neurological outcomes (Grandjean, 2019; Valdez-Jiménez et al., 2011). Nevertheless, the evidence remains inconclusive, and additional research is required to definitively establish a clear link.

Endocrine disruption

There is apprehension regarding fluoride's potential to interfere with the endocrine system (Johnston and Strobel, 2020), potentially impacting the balance of hormones and influencing various hormonal processes, including thyroid function.

Kidney damage

Extended exposure to elevated fluoride levels may be a factor in causing damage to the kidneys (Dharmaratne, 2019). The kidneys are responsible for expelling fluoride from the body, and an excessive intake can surpass their ability, potentially resulting in harm.

Cardiovascular effects

Certain studies propose a potential connection between elevated fluoride levels and cardiovascular issues (Ayoob and Gupta, 2006), including a heightened likelihood of heart disease. Nevertheless, further research is required to confirm a conclusive link.

Gastrointestinal distress

Exposure to extremely elevated fluoride levels for a short duration can result in gastrointestinal discomfort (Susheela et al., 1993; Whitford and Pashley, 1984), such as feelings of nausea, vomiting, and abdominal pain.

Future consequences of high fluoride levels

The removal of fluoride from drinking water could result in various future consequences. For decades, fluoride has been intentionally added to water sources to enhance dental health by preventing tooth decay (Ahmadi, 2012). The absence of fluoride may contribute to a surge in dental cavities and associated oral health issues, especially among vulnerable populations. Over time, this could lead to heightened dental treatment expenses and potentially strain healthcare systems. Moreover, communities might confront social and economic difficulties due to the increased burden of dental problems. To address these potential consequences, it is crucial to implement public health campaigns and alternative measures to safeguard the ongoing oral well-being of the population. Therefore, the removal of fluoride from drinking water could lead to various potential consequences, with outcomes contingent on several factors, which are presented below:

Advancements in water treatment

Continual research and technological progress have the potential to result in more streamlined and economically viable approaches.

Increased awareness

With a growing awareness of the connection between water quality and its effects on health, there is a heightened focus on averting excessive fluoride exposure and adopting suitable water treatment measures.

Policy and regulation changes

Changes anticipated in future water quality standards and regulations could impact both the methods and the degree to which processes are implemented.

Integration of green technologies

In the future, we can anticipate a growing trend towards incorporating eco-friendly and sustainable technologies in water treatment, with a focus on minimizing the environmental impact of processes.

Impact on vulnerable populations

Removing fluoride may disproportionately affect children, individuals with low income, and those lacking regular access to dental care, making them more susceptible to the resulting consequences (Ayoob and Gupta, 2006).

Shift in dental health policies

Authorities in the realm of health and government may find it necessary to reassess and potentially modify dental health policies to tackle the heightened susceptibility to tooth decay.

Research and monitoring

There could be a heightened emphasis on researching and monitoring oral health trends to evaluate the consequences of fluoride removal and explore alternative strategies for maintaining dental health.

Impact on oral health disparities

Eliminating fluoride may have a greater impact on communities with limited dental care access, potentially exacerbating disparities in oral health (Mullane et al., 2016).

Public health costs

The expenses related to public health in addressing dental issues might increase due to the growing number of individuals seeking treatment for preventable dental problems.

Educational initiatives

It may be essential to implement public health campaigns and educational initiatives to increase awareness regarding alternative methods for maintaining optimal oral hygiene when water fluoridation is not available.

CONCLUSIONS

In conclusion, addressing the challenge of excess fluoride contamination in drinking water has become a significant undertaking, necessitating the of water through various techniques. The use of methods such as adsorption, precipitation, and membrane technologies has demonstrated promising outcomes in reducing fluoride levels, effectively tackling issues related to cost, accessibility, and environmental impact.

Currently, ongoing research and technological advancements are continuously improving these techniques, enhancing their efficiency and scalability. Given the multifaceted nature of fluoride contamination, a comprehensive approach integrating diverse methods is essential to cater to different geographical and socioeconomic contexts. In addition, sustainable and innovative solutions are crucial to combating the persistent problem of fluoride in water. Collaborative efforts involving researchers, policymakers, and communities will play a vital role in implementing these techniques on a broader scale. Moreover, emphasizing education and awareness programs can empower communities to proactively ensure the safety of their drinking water. As we navigate the evolving landscape of water treatment, adopting a holistic and adaptive approach will be essential to effectively address the dynamic challenges posed by fluoride contamination and protect the well-being of communities worldwide.

Further studies should prioritize the development of economically viable, energy-efficient, and environmentally sustainable methods. Advancements in membrane technology, such as advanced anti-fouling coatings and hybrid systems, have the potential to significantly improve performance. Investigation of inexpensive adsorbents, like charcoal and nanomaterials, can enhance availability in underdeveloped areas. Furthermore, it is necessary to conduct pilot-scale studies and life cycle assessments to analyze the environmental effects of these technologies. Prioritizing environmentally friendly and renewable methods, such as biosorption and electrocoagulation, has the potential to result in more sustainable solutions. Coordinated endeavors in multidisciplinary research will be essential for surmounting present constraints and tackling forthcoming obstacles. However, the practical implications of this study lie in its potential to develop low-cost, locally adaptable defluoridation techniques using readily available materials, such as clay, bone char, and plant-based adsorbents. These methods can be realistically implemented in rural and resource-limited communities through decentralized treatment units, community-scale filters, or household-level systems. By emphasizing affordability, simplicity, and material reusability, these approaches can provide sustainable, long-term solutions for fluoride mitigation, reducing health risks, and improving access to safe drinking water in fluoride-affected regions.

The study holds significant societal and community benefits by addressing the critical public health issue of excessive fluoride in drinking water. Elevated fluoride levels can cause severe health problems, including dental and skeletal fluorosis, which disproportionately affect vulnerable populations in rural and underdeveloped regions. By systematically evaluating existing defluoridation methods and identifying their limitations, this research provides a roadmap for developing more efficient, cost-effective, and environmentally sustainable water treatment solutions. The insights from this study can guide policymakers, water authorities, and local communities in implementing safer water practices, ultimately improving overall health outcomes, reducing healthcare burdens, and enhancing the quality of life for affected populations.

Future scope of the study

The growing concerns surrounding fluoride contamination in drinking water demand continuous innovation in treatment methods. Future research should prioritize the development of energy-efficient, low-cost, and eco-friendly technologies such as biosorption, electrocoagulation, and hybrid membrane systems. Emphasis should also be placed on novel adsorbent materials like nanomaterials, bio-based media, and metal-organic frameworks to enhance selectivity and removal efficiency. Integration of real-time monitoring, machine learning models, and pilot-scale trials could significantly optimize operational parameters and system design for large-scale deployment, especially in fluoride-endemic regions.

Limitations of the study

Despite notable progress, several limitations remain. Many conventional techniques face challenges related to high energy consumption, cost, limited regeneration capability, and potential sludge generation. Socio-cultural barriers, such as resistance to bone-char usage and the lack of community awareness, further hinder implementation in rural areas. Additionally, no single method proves universally effective due to variations in raw water composition and socioeconomic factors. Therefore, interdisciplinary collaboration and context-specific solutions are essential to ensure long-term access to safe and fluoride-free drinking water.

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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