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Sustainable Management of Fluoride in Drinking Water and Public Health Protection in Southern Libya: A Study Based on Representative Samples

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الإدارة المستدامة للفلورايد في مياه الشرب وحماية الصحة العامة في جنوب ليبيا: دراسة تعتمد على عينات ممثلة

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Abstract

The fluoride levels in water in a number of locations (Ashkidah, Tamazawa, Zawiya, Achabiyat, Al Tarkibat, Abu Hurghada, Al Afiah, Dabdab, Tmassah, Zwila, and Awbari) in some regions of southern Libya, were evaluated by the authors. There is a weak negative correlation between pH and fluoride, indicating that other factors have a substantial impact on the content of fluoride in the water samples. High alkalinity frequently promotes the dissolution and release of fluoride from minerals, although other processes, such as binding with calcium or geological variables, might counteract this, leading to a weak overall relationship. The cluster analysis classified the samples into three clusters: (1) Low-fluoride cluster (F<1 mg/l); (2) Optimal fluoride cluster (1mg/l ≤F ≤1.5mg/l); and (3) High fluoride cluster (F>1.5 mg/l). The Libyan standard's and WHO guideline and the metal index indicated that the water was safe for drinking, except for one sample in the Zawiya area. Moreover, the water can be used for short-term irrigation.

Keywords: Fluoride, pH Indicators, Groundwater Quality, Public Health Protection, Sustainable Defluoridation, Southern Libya.

الملخص

تم تقييم مستويات الفلوريد في المياه في عدد من المواقع (أشكيدة، تمازاوة، الزاوية، الشعبيات، التركيبات، أبو غردقة، العافية، دبدب، تمسّه، زويلة وأوباري) في بعض مناطق جنوب ليبيا. أظهرت النتائج وجود ارتباط سلبي ضعيف بين الرقم الهيدروجيني (pH) وتركيز الفلوريد، مما يشير إلى أن هناك عوامل أخرى ذات تأثير كبير على محتوى الفلوريد في عينات المياه. وغالبًا ما تعزز القلوية المرتفعة ذوبان الفلوريد وانطلاقه من المعادن، إلا أن عمليات أخرى، مثل الارتباط بالكالسيوم أو العوامل الجيولوجية، قد تعاكس هذا التأثير، مما يؤدي إلى ضعف العلاقة الإجمالية بين المتغيرين.

كما أظهرت التحاليل تصنيف العينات إلى ثلاث فئات: (1) فئة منخفضة الفلوريد (F < 1 ملغم/لتر)، (2) الفئة المثلى للفلوريد (1 ≥ ≤ F 1.5 ملغم/لتر)، و(3) فئة مرتفعة الفلوريد (F > 1.5 ملغم/لتر). وأشارت المواصفة القياسية الليبية وإرشادات منظمة الصحة العالمية إلى أن المياه صالحة للشرب، باستثناء عينة واحدة في منطقة الزاوية. كما يمكن استخدام هذه المياه لأغراض الري على المدى القصير.

الكلمات المفتاحية: الفلوريد، مؤشرات الرقم الهيدروجيني (pH)، جودة المياه الجوفية، الصحة العامة، الإزالة المستدامة للفلوريد، جنوب ليبيا.

1. Introduction

Fluoride is a naturally occurring element that is present in many water sources. It has two roles in human health: at optimal concentrations, it prevents dental caries, but at elevated levels above recommended thresholds, it increases the risk of fluorosis and other negative effects (World Health Organization, 2024). Localized assessment is crucial for sustainable public health planning because groundwater, particularly in arid and semi-arid regions like North Africa, frequently displays wide variability in fluoride content due to geological and hydrogeochemical conditions (Ullah et al., 2023). Groundwater extracted from wells and artificial rivers, as well as desalinated supplies, are the sources of drinking water in Libya. Variations in fluoride concentrations have been shown to reflect differences in exposure among urban populations (Swisialgdar et al., 2022). The complexity of managing fluoride sustainably is highlighted by studies of Libyan coastal cities that revealed groundwater can either exceed or fall below international guidelines, with implications for both dental health and skeletal fluorosis risk (Swisialgdar et al., 2022). However, while technologies like reverse osmosis (RO) filtration can significantly lower fluoride levels, they may also remove advantageous minerals, so post-treatment public health effects must be carefully assessed (Sharif et al., 2025). In order to balance the benefits and risks, the World Health Organization (WHO) recommends that fluoride levels in drinking water not exceed 1.5 mg/L. However, measured levels in many global groundwater systems frequently exceed this threshold, necessitating targeted interventions (World Health Organization, 2024). Human health risk assessments in areas like the Main Ethiopian Rift show that high fluoride intake may have non-carcinogenic health effects on a sizable portion of the local population, especially children (Gebreegziabher et al., 2025; Ullah et al., 2023). In order to prevent fluorosis and other long-term effects, these results highlight the necessity of sustainable control mechanisms that combine community health initiatives with water quality monitoring. Adopting suitable, economical fluoride removal strategies that fit local infrastructure and financial circumstances, such as adsorption techniques and community-level treatment systems, is another aspect of sustainable control (Ibrahim et al., 2024). Low-cost materials for fluoride mitigation have been investigated in developing regions to address inequities in access to safe water, but their implementation necessitates careful evaluation of their efficacy, sustainability, and scalability (Low cost materials, 2024). Additionally, since infants and children frequently show the highest susceptibility to fluoride-induced toxicity, systematic health risk assessments are essential for identifying vulnerable demographic groups and guiding policy decisions that protect them (Ullah et al., 2023). Therefore, managing fluoride sustainably in southern Libyan settings requires a combination of strict water quality monitoring, the deployment of context-specific treatment technologies, and ongoing public health assessment. The creation of regulatory frameworks and guidelines that are specific to Libya's various hydrogeological zones and represent both national and WHO standards for safe drinking water is equally crucial. Campaigns for public awareness and education can improve community involvement and promote actions that reduce the dangers of excessive fluoride exposure and improve dental health outcomes. Desalination projects using RO technology in Libya may result in water with fluoride levels significantly below ideal, posing an additional public health risk that must be addressed by supplementation or, when necessary, alternative fluoridation techniques. On the other hand, communities may be exposed to supra-optimal fluoride concentrations associated with skeletal fluorosis, dental mottling, and other systemic effects if they rely on unmonitored groundwater. A balanced water safety plan based on empirical data on local fluoride distribution patterns is necessary to address these dual risks of excess and deficiency. In some parts of Africa, fluoride risk zones have been mapped using geographic information systems (GIS) and predictive modeling, providing useful tools for focusing interventions in high-risk areas. Additionally, by estimating hazard indices linked to different fluoride concentrations in community water sources, health risk modeling helps prioritize treatment options. In order to prevent interventions from unintentionally creating other water quality issues or disparities, sustainable fluoride management should be in line with more general water governance and public health integration. For example, removal technologies that deplete water of both fluoride and necessary minerals require compensatory measures like dietary supplementation or remineralization. In order to co-develop solutions that are both technically feasible and culturally acceptable, it is essential to engage local stakeholders, such as water authorities, public health officials, and impacted communities. Monitoring the long-term health effects of fluoride exposure requires ongoing research, particularly in understudied areas like southern Libya. Longitudinal studies can shed light on the long-term consequences of fluctuating fluoride levels and the efficacy of control strategies. Comparative research in comparable arid and semi-arid areas can highlight scalable strategies suitable for Libyan cities and further inform best practices. In this sense, the foundation of an all-encompassing approach to sustainable fluoride control is the integration of environmental science, hydrogeology, public health, and policy analysis. In order to navigate the trade-offs between dental health benefits and potential systemic health risks, as well as to customize interventions that safeguard community health over time, such interdisciplinary approaches are required. By focusing on a representative sample from selected areas of southern Libya (Fig. 1), where groundwater fluoride dynamics and their public health implications are still poorly understood, this study aims to contribute to the existing body of knowledge. The study will give local authorities and health planners evidence-based recommendations by integrating risk assessment frameworks with water quality analysis. The strategy used here acknowledges the distinct socioeconomic and environmental context of Libyan southern cities while reflecting global best practices. In the end, equitable and successful public health protection depends on sustainable fluoride control in drinking water, which necessitates ongoing monitoring, flexible management, and community involvement to produce long-term advantages.

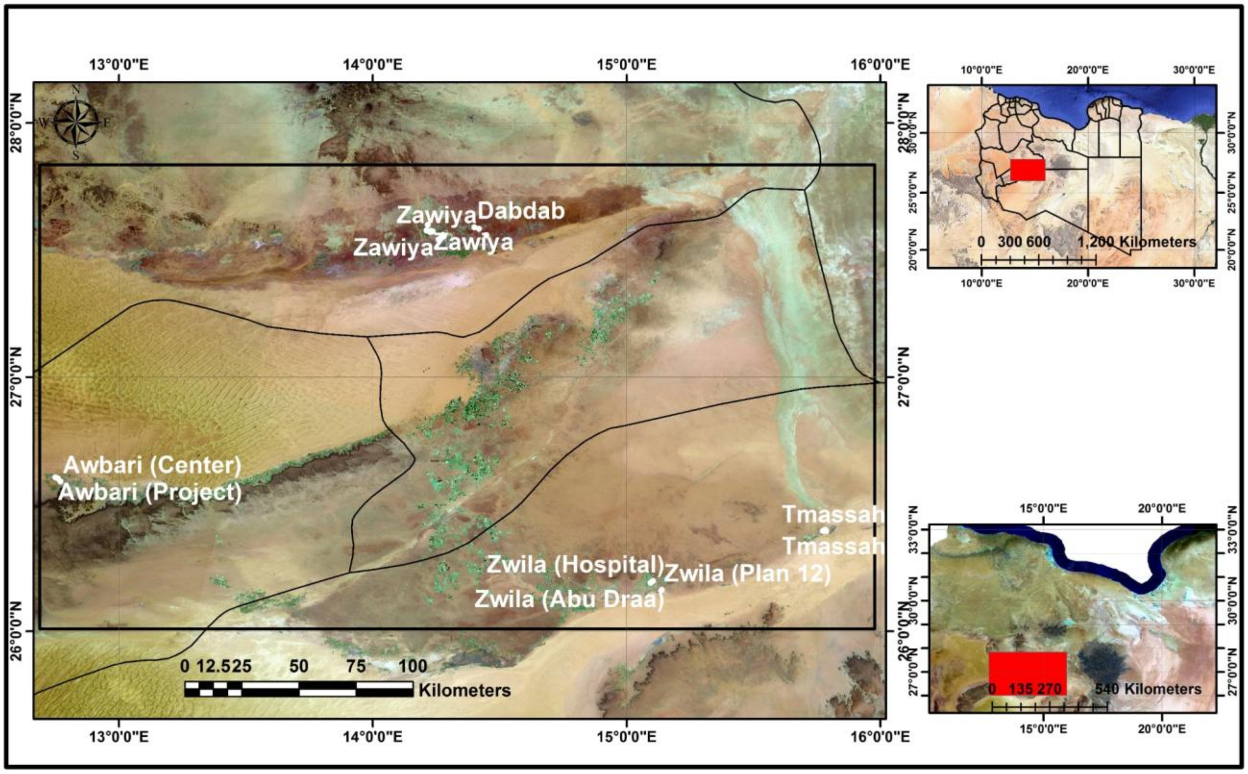

Fig. 1. Landsat image of southern Libya showing the location of the sampled stations.

2. PROBLEM STATEMENT

In many arid and semi-arid areas, especially in southern Libya, where groundwater is the main source of domestic water supply, access to safe drinking water continues to be a significant public health concern. Groundwater naturally contains fluoride due to geochemical interactions between water and fluoride-bearing minerals, which results in considerable spatial variability in fluoride concentrations. High concentrations of fluoride pose major risks, including skeletal and dental fluorosis, especially in children and long-term users, even though optimal fluoride levels are good for dental health.

There is a dearth of systematic information about fluoride levels in drinking water sources and their possible effects on public health in the cities of southern Libya. Sustainable fluoride control methods are not regularly used or assessed, and current water treatment procedures are frequently not adequately monitored. The effectiveness of current mitigation strategies and population exposure levels are uncertain due to the lack of an integrated assessment. A thorough investigation that measures fluoride levels, evaluates related health risks, and suggests sustainable control strategies suited to the socioeconomic and environmental circumstances of southern Libya is therefore desperately needed.

2.1 Research Questions

This study seeks to answer the following research questions:

- What are the fluoride concentrations in drinking water sources in selected areas of southern Libya?
- To what extent do the measured fluoride levels comply with World Health Organization (WHO) and national drinking water guidelines?
- What potential public health risks are associated with fluoride exposure among residents of the study area?
- What are the current practices used for drinking water supply and treatment in the selected areas and how effective are they in controlling fluoride levels?
- What sustainable strategies can be proposed to manage fluoride concentrations and enhance public health protection in southern Libyan cities?

3. Objectives of the Study

The main objective of this study is to evaluate the sustainability of fluoride control in drinking water and its implications for public health protection in southern Libyan cities.

The specific objectives are to:

- Measure fluoride concentrations in representative drinking water samples from selected areas of southern Libya.

- Compare the observed fluoride levels with international and national drinking water standards.
- Assess potential health risks associated with fluoride exposure among the local population.
- Examine existing water supply and treatment practices related to fluoride control in the study area.
- Propose sustainable and context-appropriate strategies for fluoride management to protect public health in southern Libyan cities.

4. Significance of the Study

This study is significant from environmental, public health, and policy perspectives. Scientifically, it contributes to the limited body of knowledge on fluoride distribution and exposure risks in southern Libya, a region that remains under-represented in water quality research. From a public health standpoint, the findings will help identify potential health risks associated with fluoride in drinking water and support evidence-based interventions to reduce adverse outcomes, particularly among vulnerable groups.

Practically, the study gives water utilities, health planners, and local governments trustworthy information to support decision-making and enhance drinking water management. Similar arid areas dealing with fluoride-related issues can use the suggested sustainable control methods as a model. Additionally, the findings might help create water safety plans and regulations that are in line with WHO guidelines, improving long-term environmental sustainability and public health protection in southern Libyan cities.

5. Literature Review

5.1 Fluoride in Drinking Water: Sources, Chemistry, and Health Implications

Fluoride is a naturally occurring ion in the environment that mainly finds its way into drinking water through interactions with soil and rock matrices as well as the geochemical weathering and dissolution of fluoride-bearing minerals like fluorite and apatite. In arid and semi-arid areas where groundwater serves as the primary source of drinking water, this process is especially important (International Groundwater Resources Assessment Centre, 2024). Long-term contact between water and these minerals under circumstances that encourage fluoride ion mobilization frequently results in high fluoride concentrations in groundwater (Kimambo et al., 2019). Fluoride is chemically present in water as F^-, which makes it extremely soluble and persistent in aquifers, occasionally leading to concentrations above advised safety thresholds (World Health Organization, n.d.). Because they encourage enamel remineralization and prevent demineralization, low to moderate fluoride levels—typically between 0.5 and 1.5 mg/L—have been linked to protective effects against dental caries (Fluoride occurrence and prevalence of fluorosis study, 2022). On the other hand, consuming more fluoride from water than the WHO's recommended level of 1.5 mg/L can have negative health effects, such as skeletal and dental fluorosis (World Health Organization, n.d.). Dental fluorosis manifests as discoloration or mottling of tooth enamel, while skeletal fluorosis can result in joint pain, stiffness, and bone deformities (Kimambo et al., 2019). The main factors controlling fluoride enrichment in groundwater include aquifer mineralogy, residence time, pH, temperature, and interactions with other ions (International Groundwater Resources Assessment Centre, 2024). Both too much and too little fluoride can be harmful to one's health; too much fluoride can cause long-term skeletal issues, while too little fluoride can make one more prone to dental decay (Fluoride occurrence and prevalence of fluorosis study, 2022). Children and other populations that depend on high-fluoride groundwater are especially susceptible to these health effects, according to epidemiological studies (Kimambo et al., 2019). To reduce these risks and balance the positive and negative effects of fluoride, regular monitoring and risk assessment of fluoride levels in drinking water are crucial (World Health Organization, n.d). Integrating chemical analysis of groundwater with public health evaluations provides a comprehensive framework for understanding fluoride exposure and informing sustainable water management practices (Health risk assessment of fluoride exposure, 2023). In order to ensure the dental benefits of fluoride as well as the prevention of fluorosis, WHO also suggests community-specific interventions when natural fluoride levels surpass ideal concentrations (World Health Organization, n.d). Designing effective mitigation strategies requires an understanding of the sources, chemical behavior, and dose-dependent health effects of fluoride, particularly in areas like southern Libya, where groundwater composition varies significantly (International Groundwater Resources Assessment Centre, 2024). Hydrogeologists, environmental scientists, and public health authorities must work together to manage fluoride sustainably in order to preserve the advantages of optimal fluoride exposure while safeguarding community health (Health risk assessment of fluoride exposure, 2023).

5.2 Global and Local Standards for Fluoride in Drinking Water

Fluoride drinking water standards, which are set at both the national and international levels, are a fundamental component of public health policy that aims to balance the advantages of preventing dental caries with the dangers of overexposure. The World Health Organization (WHO, 2006) states that the recommended level of fluoride in drinking water is 1.5 mg/L, above which there is a substantial increase in the risk of dental fluorosis and other possible negative health consequences, especially for populations that depend on untreated groundwater. Although WHO's guidelines are not legally binding, nations can use them as a guide when creating or updating their own national drinking water quality laws (WHO, 2006). National authorities frequently modify this international recommendation to fit local circumstances; for instance, the establishment of standards is influenced by variables like dietary fluoride sources, water intake rates, and climate (WHO, 2006). Fluoride is subject to both primary and secondary standards in many developed nations. The primary level is intended to protect health, while the secondary level addresses cosmetic or aesthetic effects like dental mottling (U.S. EPA, 2006). In order to prevent skeletal fluorosis in communities that depend on public water systems, the U.S. Environmental Protection Agency (EPA) currently sets an enforceable maximum contaminant level (MCL) of 4 mg/L for fluoride, with a secondary standard of 2 mg/L to minimize cosmetic effects (U.S. EPA, 2006). In the meantime, to optimize dental health benefits and lower the prevalence of dental fluorosis, the U.S. Public Health Service suggests an ideal fluoride concentration of roughly 0.7 mg/L in community water systems (Public Health Service, 2015). Although some regions modify limits based on particular health risk assessments and exposure patterns specific to their populations, many other nations either adopt similar frameworks or adhere to WHO guidelines (Health Canada, 2023). The differential between the WHO guideline and national enforceable limits highlights the complexity in standard setting, where international guidance informs but does not mandate local regulation. In order to account for overall dietary exposures, some nations also regulate the amount of fluoride in bottled water and other sources of potable water. These regulations are frequently in line with or stricter than WHO recommendations. For example, authorities in charge of water safety plans incorporate fluoride limit values into more comprehensive public health strategies that take into consideration all sources of drinking water, not just groundwater (WHO, 2006). National standards are crucial in initiating defluoridation interventions or alternative sourcing to safeguard public health in areas with naturally high fluoride concentrations, such as arid regions that rely on groundwater. Strong monitoring and enforcement procedures backed by frameworks for water quality surveillance are necessary for these standards to be effective. Without adherence to scientifically grounded guideline values, populations may remain at risk of either insufficient fluoride exposure, leading to higher dental caries rates, or excessive intake with consequent fluorosis. Therefore, in addition to setting suitable fluoride limits, sustainable water quality management calls for thorough implementation strategies that take into account local disease burdens, consumption patterns, and environmental factors. Public health safeguards are kept in line with the most recent scientific findings through the regular updating of standards based on new data and technological developments in water treatment. Ultimately, global and local standards for fluoride in drinking water reflect an interplay between health protection priorities, environmental realities, and socio-economic contexts that shape water governance practices worldwide.

5.3 Technologies and Strategies for Sustainable Fluoride Control

Numerous methods of physical, chemical, and biological treatment are used in technologies and strategies for sustainable fluoride control in drinking water with the goal of bringing excessive fluoride levels down to acceptable levels. Adsorption techniques, which use materials like activated alumina or biochar to bind and remove fluoride ions from water through surface interactions, are among the most extensively researched methods (Tolkou et al., 2021). Research on low-cost adsorbents indicates that locally available materials can significantly reduce fluoride concentrations while maintaining sustainability and economic feasibility, making them suitable for rural and low-resource settings (Journal of Environmental

Management, 2024). Membrane-based processes, including reverse osmosis (RO) and nanofiltration, have been demonstrated to be effective at rejecting fluoride ions, with RO systems often achieving near-complete removal when operated under optimized conditions, though they require higher energy input and maintenance (PubMed Review, 2020). Electrocoagulation, which uses electrical current to create a coagulant that binds fluoride, has also been investigated as an effective defluoridation technique. In experimental studies, removal efficiencies of over 90% have been reported (Rabiha et al., 2022). By capturing fluoride through a variety of mechanisms, adsorption combined with coagulation or filtration improves treatment performance and increases removal efficiency. Bio-based materials like biochar, which can be made from agricultural waste and have a high surface area and affinity for fluoride, are the focus of emerging sustainable strategies. They provide a low-carbon and eco-friendly solution (Khan et al., 2025). Additionally, the combination of adaptive treatment design and water quality monitoring guarantees that the technologies selected are in line with the unique chemistry of the local groundwater, which can differ greatly in terms of pH, ionic strength, and competing anions that affect fluoride sorption dynamics (Tolkou et al., 2021). To balance cost, effectiveness, and ease of use, sustainable community-level systems may combine finer processes like adsorption or membrane filtration with pretreatment steps like sedimentation or coagulation. Advances in material science continue to yield novel adsorbents and composite media that improve fluoride uptake capacity and regeneration potential, which is critical for long-term system sustainability. Evidence also suggests that decentralized filtration units using porous media like zeolites can simultaneously address multiple contaminants, including fluoride, while operating with minimal infrastructure (Zhou et al., 2024). Despite the promise of advanced technologies, careful consideration of maintenance requirements, energy needs, and local technical capacity is essential for ensuring sustainable deployment. Community engagement and training are vital to support regular monitoring, media replacement, and evaluation of treatment performance over time. By guaranteeing greater access to safe drinking water, policies that encourage the use of affordable and sustainable fluoride control technologies can improve public health outcomes. Lastly, resilience in water treatment systems is enhanced by fusing conventional techniques with creative solutions, especially in areas like southern Libya with inconsistent water quality and scarce resources.

5.4 Public Health and Policy Perspectives on Fluoride Management

In order to maximize health benefits while minimizing risks, public health and policy perspectives on fluoride management in drinking water reflect a complex interaction between scientific evidence, regulatory guidelines, and community health objectives. The World Health Organization emphasizes that fluoride management requires integrated policy frameworks that combine drinking-water quality standards with surveillance, risk assessment, and public health planning to protect populations from both excessive and insufficient fluoride exposure (World Health Organization, 2024). In many countries, community water fluoridation is recognized as a public health intervention that reduces dental caries, a common and costly disease, by maintaining fluoride concentrations at levels that provide preventive benefits; this is supported by comprehensive policy statements issued by major health authorities such as the Centers for Disease Control and Prevention (CDC, 2024) which describe fluoridation as one of the most personal effective disease prevention measures of the twentieth century. CDC guidelines recommend optimal fluoride levels that maximize oral health benefits while reducing the risk of dental fluorosis, and emphasize the importance of sustained public health programming and monitoring to maintain these levels (CDC, 2024). Policy perspectives also address disparities in oral health outcomes, with fluoride management seen as a tool to reduce inequities among vulnerable groups, including low-income communities with limited access to dental care (CDC, 2024). However, public health policy must balance these benefits against emerging concerns and debates regarding potential adverse effects at higher exposures, leading to calls for regular review and adjustment of guidelines based on evolving evidence (Umer, 2023). Despite persistent support from the scientific and dental communities, controversial policy decisions in some jurisdictions, such as recent legislative bans on adding fluoride to public water supplies in parts of the United States, highlight the conflicts between public health recommendations and political or choice arguments (Associated Press, 2025). These developments underscore the necessity of evidence-based communication strategies to educate the public and policy makers about the limitations and demonstrated advantages of fluoride interventions within larger water safety plans. In order to ensure safe and sustainable water quality management, WHO's fluoride guidance emphasizes that policy frameworks should incorporate protocols for monitoring, treatment, and community education in addition to regulatory standards for maximum exposure (World Health Organization, 2024). Furthermore, public health policy integrates considerations of overall fluoride exposure from multiple sources — including toothpaste and dietary intake — to refine recommendations and minimize risk of overexposure, while maintaining preventive benefits against dental decay (U.S. Public Health Service, 2015). To achieve a balance between optimizing oral health protection and protecting broader health outcomes for diverse populations, public health and policy perspectives on fluoride management advocate for adaptive governance, ongoing research, coordinated monitoring systems, and stakeholder engagement. Such integrated perspectives are especially critical in regions with variable natural fluoride levels, where local authorities must design context-specific policy responses grounded in evidence and aligned with international guidelines.

6. Materials and Methods

This study was conducted to determine fluoride concentrations in domestic well water used for drinking purposes in different areas of southern Libya. A total of 23 groundwater samples were collected from private household wells distributed across various residential locations within the study area. Water samples were collected in clean, pre-washed polyethylene bottles to avoid contamination. Prior to sampling, each bottle was rinsed three times with the well water. The samples were transported to the laboratory under appropriate conditions and analyzed as soon as possible after collection. All water samples were analyzed at the laboratories of the Libyan Center for Biotechnology Research. The pH of all samples was measured using a pH-Meter (JENWAY 3510) as shown in Figure 1, in accordance with standard analytical procedures.

Prior to measurement, the instrument was calibrated using standard buffer solutions with pH values of 4, 7, and 10. Calibration was considered complete when the instrument readings corresponded precisely to the pH values of the buffer solutions.

Before analysis, it was ensured that all samples were at an appropriate temperature. It is well established that the pH value decreases by approximately 0.45 units when the temperature exceeds 25 °C, indicating increased acidity. Such a decrease in pH results in more acidic water, which may have significant adverse effects on the health. The concentration of fluoride in the water samples was measured using a Palintest Photometer 7500, UV–Visible spectrophotometer, as shown in Figure 2, following the standard colorimetric method recommended by the manufacturer. This method is based on the reaction of fluoride ions with specific reagents to produce a colored complex, the intensity of which is directly proportional to the fluoride concentration in the sample. Fluoride concentration was determined by performing three replicate measurements for each sample. The mean value of the three replicates was calculated and reported as the final fluoride concentration to ensure accuracy and reproducibility of the results. Before analysis, the spectrophotometer was calibrated using standard fluoride solutions to ensure accuracy and reliability of the measurements. All measurements were performed according to the operating instructions of the Palintest Photometer 7500 instrument, and the fluoride concentrations were expressed in mg/l. To ensure the precision and accuracy of the results, blank samples and standard solutions were analyzed periodically during the measurement process. All samples were analyzed under the same laboratory conditions.

7. Results and Discussion

The pH and F values in the studied samples are shown in Table 1. The F levels vary clearly (0.29–4.9 mg/l), while there is no significant difference in the pH values (6.57-7.5). The spatial distribution of F in southern Libya is depicted in Fig. 2.

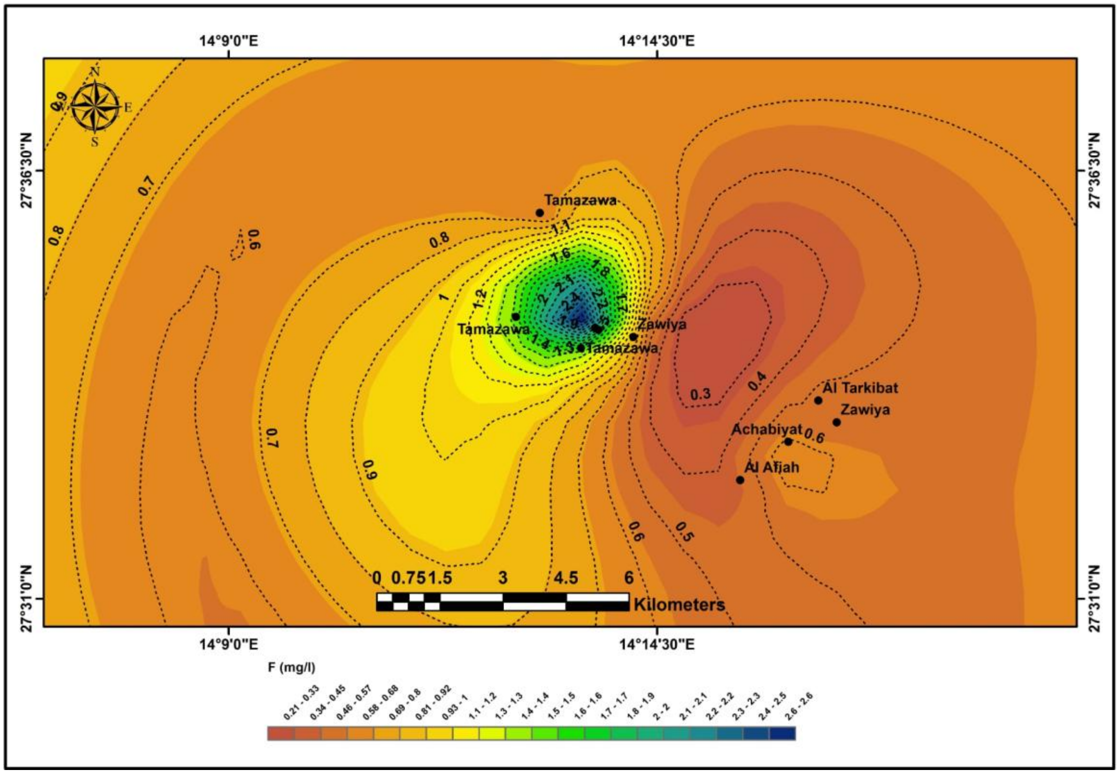

Fig. 2: Spatial distribution of fluoride in some regions of southern Libya

Table 1: Values of pH and fluoride in some regions of southern Libya

Area	Sample No.	pH	F (mg/l)
Ashkidah	w1	6.96	0.81
Tamazawa	w2	7	0.59
Zawiya	w3	6.85	0.51
Tamazawa	w4	6.83	1.37
Achabiyat	w5	6.92	0.67
Al Tarkibat	w6	6.85	0.5
Zawiya	w7	6.89	1.19
Zawiya	w8	6.57	4.9
Zawiya	w9	7.11	0.29
Abu Hurghada	w10	6.83	0.57
Al Afiah	w11	7.03	0.46
Al Tarkibat	w12	7.02	0.51
Tamazawa	w13	7.12	0.62
Dabdab	w14	6.78	0.67
Tmassah	w15	7.12	1.12
Zwila (Abu Draa)	w16	7.1	1.4
Zwila (Plan 12)	w17	7.23	1.08
Zwila (Hospital)	w18	7.3	1.1
Tmassah	w19	7.14	1.25
Tmassah	w20	6.86	0.92
Awbari (Project)	w21	7.02	0.59
Awbari (Al Mustache)	w22	7.2	0.73
Awbari (Center)	w23	7.5	0.54

7.1. Statistical Treatment

7.1.1. Correlation Coefficient

There is a weak negative correlation between pH and fluoride ($r = -0.43$). Because the presence and quantity of F are influenced by intricate geological processes and water chemistry that are not usually directly related to pH, particularly in natural water, there is frequently a weak or negligible correlation between pH and F in water. Higher pH, however, may make F more soluble.

7.1.2. Cluster Analysis

Using cluster analysis, the examined samples can be separated into three clusters (Fig. 3):

Cluster 1: This cluster consisted of samples w1, w2, w3, w5, w6, w9, w10, w11, w12, w13, w14, w20, w21, w22, and w23. It can be called a low-fluoride cluster ($F<1$ mg/l).

Cluster 2: This cluster included samples w4, w7, w15, w16, w17, w18, and w19. Optimal fluoride cluster is the appropriate name for this cluster (1mg/l ≤F ≤1.5mg/l).

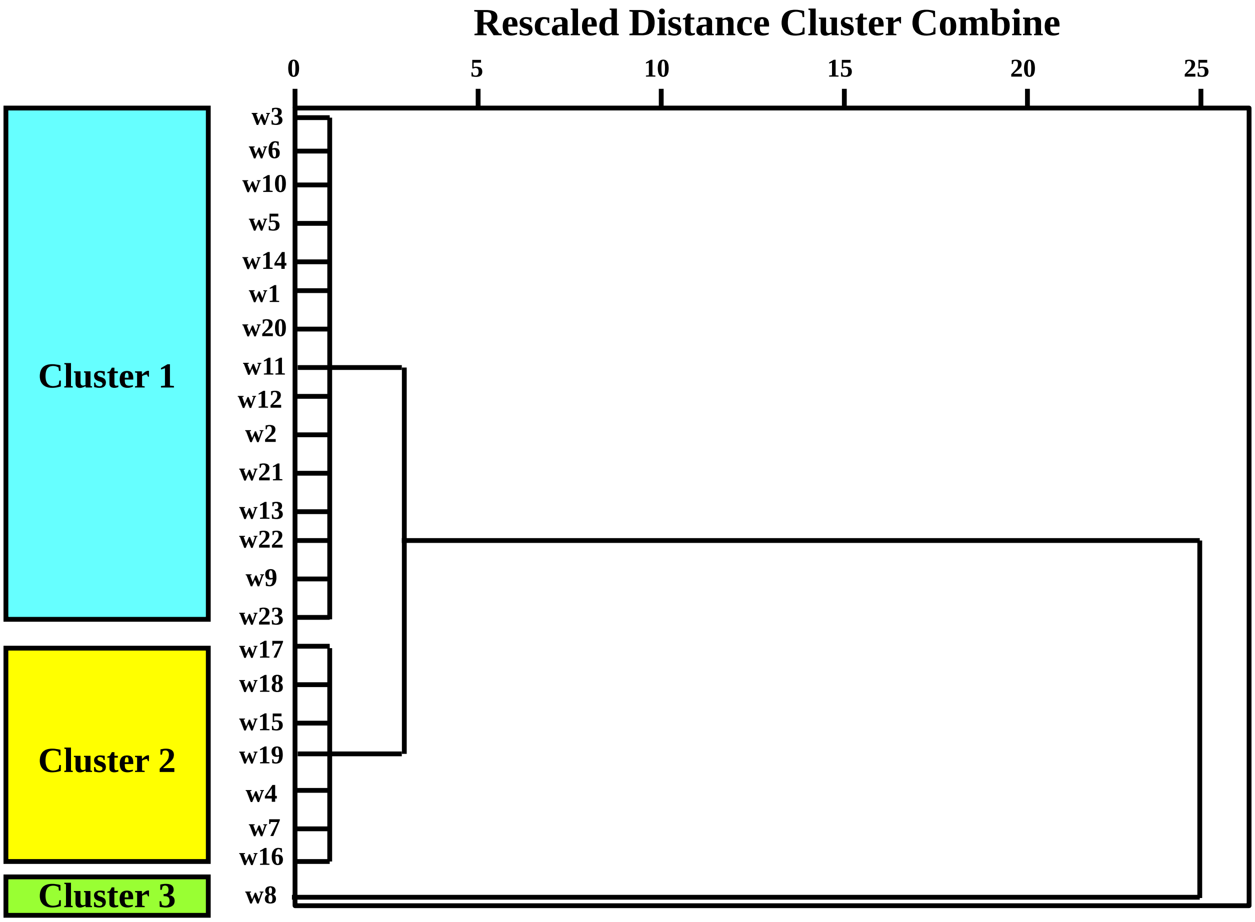

Fig. 3: Dendrogram from cluster analysis (Ward method) of the studied samples.

7.2. Drinking Water Quality

The potability of the water samples was evaluated using the Libyan standard's and WHO guidelines of pH (6.5-8.5 mg/l) and F (1.5 mg/l), and the metal index (MI). The MI is calculated by dividing the metal value in the sample by the WHO guideline (Caerio et al., 2005). Figs. 4 and 5 show that the pH and F values are below or within the permissible limits, with the exception of sample w8 (Zawiya) where the F value is three times the guidelines. The MI supports this assumption because sample w8 is in the moderately affected field, while the remaining samples fall into the very pure and pure fields (Fig. 6). Unfortunately, numerous areas of Libya, like Wadi Irawan, Tikiumit, Hasi Anjiwal, Wadi Bu Ash Shaykh, Essabria, and Al Ajaylat, have significant fluoride concentrations (Table 2 and Fig.7).

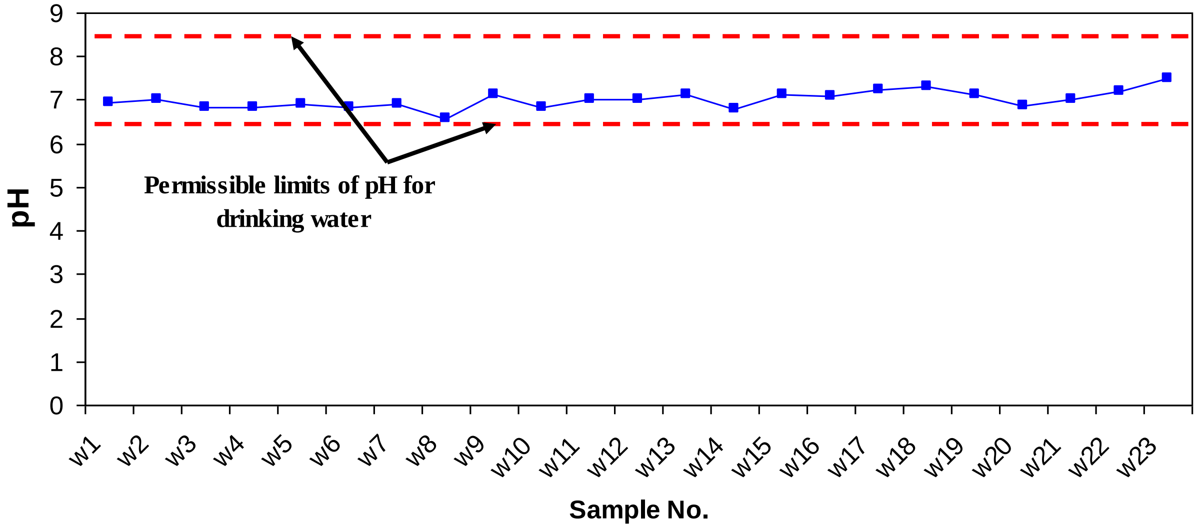

Fig. 4: Binary plot showing comparison between the pH values in the studied water and the permissible limits of Libyan and WHO for drinking water.

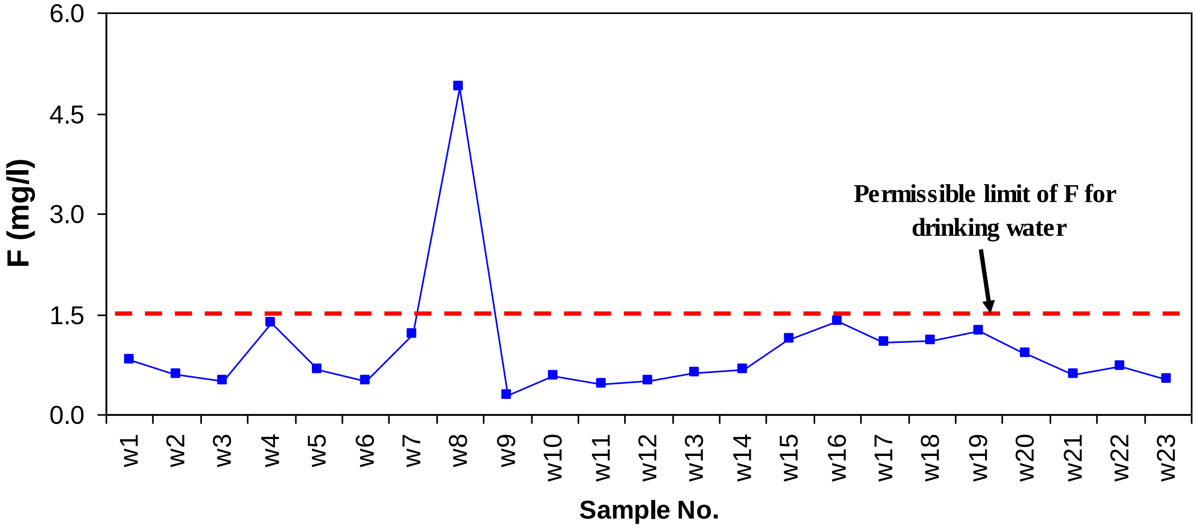

Fig. 5: Binary plot showing comparison between the fluoride values in the studied water and the permissible limit of Libyan and WHO for drinking water.

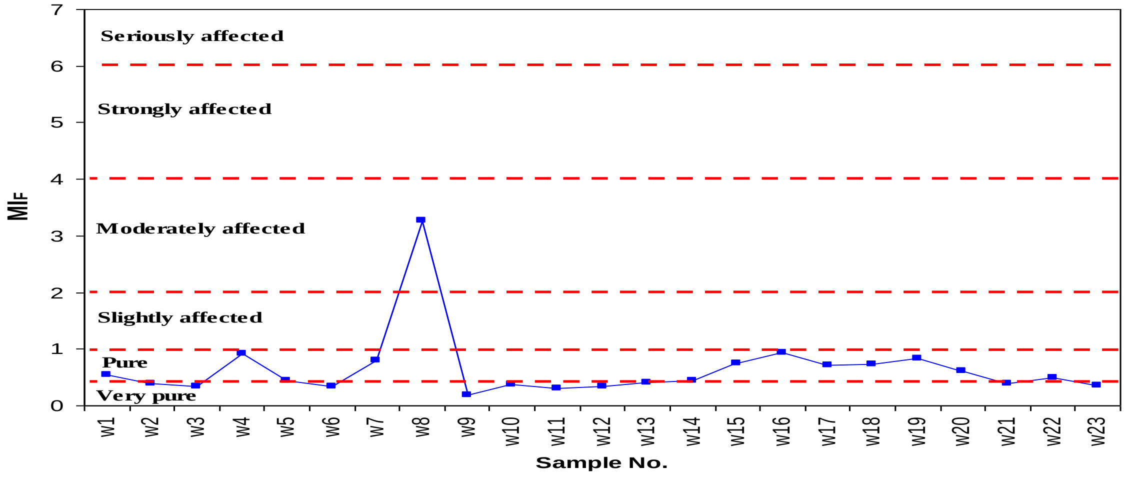

Fig. 6: Classification of the water samples based on the MI_F (fields after Caerio et al., 2005).

7.2. Irrigation Water Quality

Non-potable water is widely and successfully utilized for irrigation, as is well known. Irrigation suitability takes into account soil health, crop yield/quality, and environmental consequences to minimize soil degradation and promote plant development, providing sustainable agriculture, while direct human health is the goal of drinking water quality. Rowe and Abdel-Magid (1995) proposed acceptable limits for F in irrigation water. The acceptable limits for long-term and short-term basis are 1 and 15 mg/l, respectively. In general, the water in southern Libya is suitable for short-term irrigation (Fig. 8).

Table 2: The highest fluoride levels in several Libyan regions

Area	F	Reference
Anay	0.4	Galecic (1984)
Al Awaynat	0.78	Jakovljevic (1984)
Wadi Irawan	4.08	Komarnicki (1984)
Tikiumit	2	Protic (1984)
Wadi Tanezzuft	0.56	Radulovic (1984a)
Ghat	0.52	Radulovic (1984b)
Hasi Anjiwal	3.04	Roncevic (1984)
Zallah	1.6	Vesely (1985)
Wadi Bu Ash Shaykh	6.9	Jurak (1985)
Ain Tafarut	0.95	Shaltami et al. (2019)
Sidi Farag	1.22	Shaltami et al. (2021)
Essabria	2.05	Shebani and Dokhan (2022)
West Zawiya	1.03	Shebani and Dokhan (2022)
Surman	1.57	Shebani and Dokhan (2022)
Sabratah	1.41	Shebani and Dokhan (2022)
Al Ajaylat	2.03	Shebani and Dokhan (2022)
Bottled water	0.22	Shaltami and Algomati (2024)
Brak Al-Shati	4.9	Present study

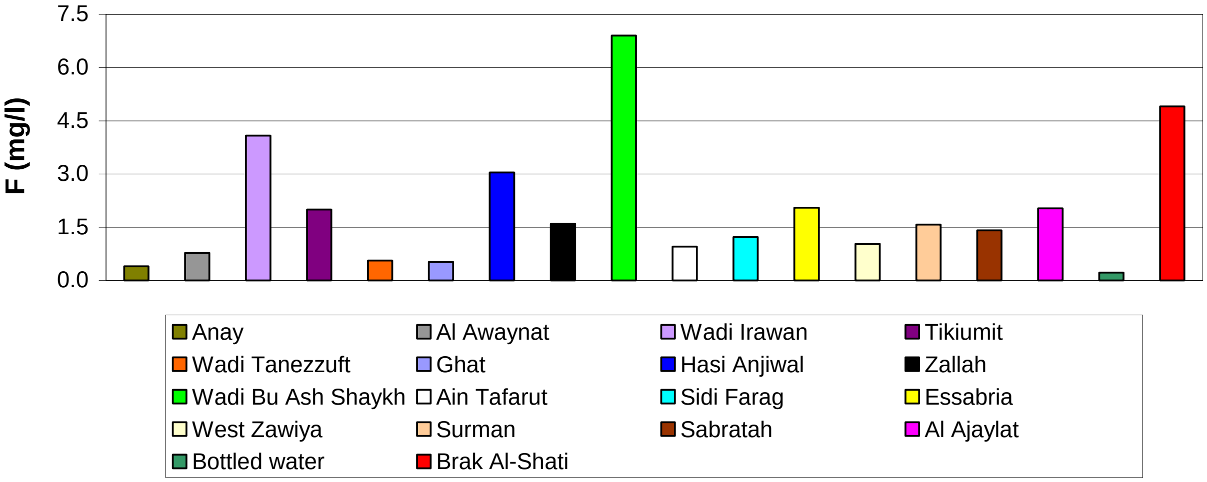

Fig. 7: Highest fluoride levels in several Libyan regions.

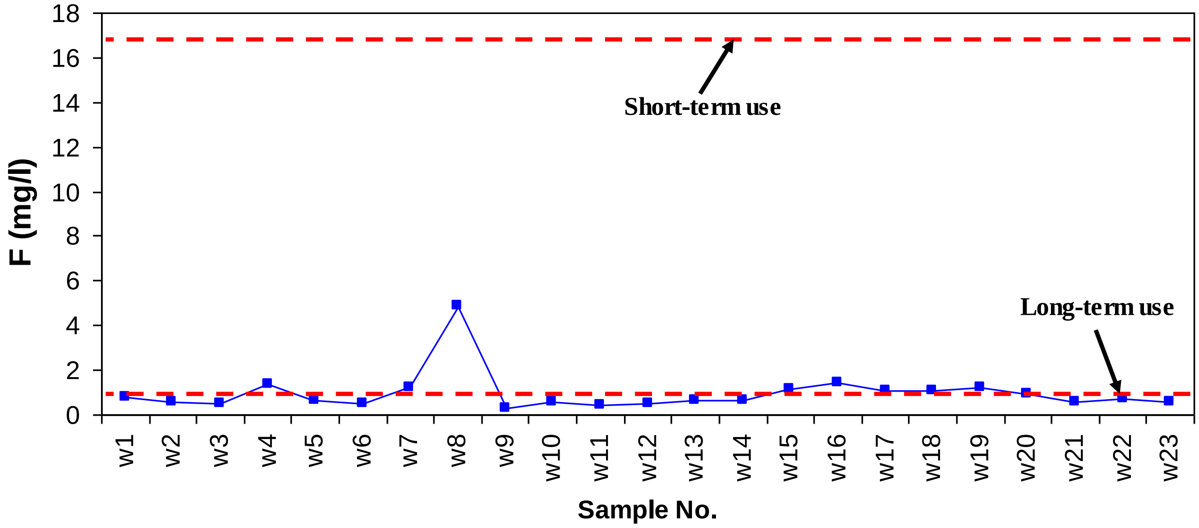

Fig. 8: Binary plot showing comparison between the fluoride values in the studied water and the allowable limits for irrigation water (fields after Rowe and Abdel-Magid, 1995).

8. Conclusions

This study assessed fluoride content in water samples collected from several areas in southern Libya. The main findings of the study are summarized as follows:

(1) The fluoride content in water samples is unaffected by pH.

(2) Based on fluoride values, the samples can be divided into three clusters: (a) Low-fluoride cluster; (b) Optimal fluoride cluster; and (c) High fluoride cluster.

(3) Although a single sample from the Zawiya area exceeded limits, the water generally matched WHO requirements and had acceptable metal index readings.

(4) Short-term irrigation can be done with the water.

9. Recommendations

Dental caries and the long-term risk of osteoporosis are associated with low fluoride concentrations in drinking water, whereas excessive fluoride levels may lead to dental and skeletal fluorosis.

To prevent dental caries and support optimal oral health, fluoride concentrations should be maintained within the recommended range. This can be achieved through fluoridation in areas with naturally low levels or defluoridation where concentrations are high.

Effective management strategies include continuous water quality monitoring, blending of water sources, and providing alternative safe water supplies when necessary. In addition, the use of fluoride-containing dental products (such as toothpaste or mouth rinses) may help maintain oral health where water fluoride levels are suboptimal.

Furthermore, management of high fluoride levels requires identification of natural or anthropogenic sources, regular monitoring, implementation of defluoridation techniques, and public awareness programs to reduce health risks.

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