

Fluoride in North African Groundwater: A Systematic Review of Occurrence, Hydrogeochemical Controls, Health Risks and Research Gaps

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Abstract:

Fluoride (F⁻) is a naturally occurring constituent of groundwater whose concentration and geochemical behaviour are controlled by mineral–water interactions, residence time, hydrochemical evolution, evaporation, and, locally, anthropogenic activities. In North Africa, groundwater is an essential source of drinking water, particularly in arid and semi-arid regions, where prolonged water–rock interaction and limited recharge may contribute to fluoride enrichment.

This systematic review synthesizes available evidence on fluoride occurrence in groundwater across Morocco, Algeria, Tunisia, Libya, and Egypt, with the literature considered and updated through December 2024. The review focuses on reported fluoride concentrations, hydrogeochemical controls, potential drinking-water exposure, spatial assessment approaches, management strategies, and research gaps. The review was guided by the PRISMA 2020 framework. A total of 12 documented groundwater study settings derived from 11 primary publications were considered in the qualitative synthesis. Reported fluoride concentrations range from below the World Health Organization guideline value of 1.5 mg/L to 22 mg/L in the Oued Rmel aquifer, Tunisia, and 10.50 mg/L in the Al-Jfara District, Libya.

The reviewed evidence indicates that fluoride enrichment is mainly associated with the dissolution of fluoride-bearing minerals, calcium availability and fluorite saturation, carbonate equilibria, ion exchange, evaporation, and prolonged groundwater residence time. The relative importance of these processes varies among aquifers and hydrogeological settings. GIS and geostatistical approaches provide useful tools for identifying spatial patterns and supporting groundwater-quality assessment, although their reliability depends strongly on sampling density, spatial representativeness, model selection, and validation.

Several reviewed groundwater settings contain fluoride concentrations above the WHO guideline value, indicating potential drinking-water exposure concerns. However, groundwater fluoride concentration alone does not establish population-level health effects, which depend on water consumption, exposure duration, age, body weight, and other dietary and environmental fluoride sources. Major research gaps include limited long-term monitoring, uneven spatial coverage, inconsistent hydrochemical datasets, insufficient mineralogical characterization, and the need for standardized exposure and spatial-risk assessment. Future research should integrate hydrochemistry, mineralogy, hydrogeology, GIS-based spatial analysis, temporal monitoring, and exposure assessment to support evidence-based groundwater management and fluoride mitigation in North Africa.

Keywords: fluoride; groundwater; North Africa; hydrogeochemistry; water quality; GIS; health risk; defluoridation; groundwater management.

I. Introduction

Fluoride is a naturally occurring component of groundwater and is widely distributed in geological materials. At appropriate concentrations, fluoride can contribute to dental health; however, prolonged exposure to elevated concentrations may result in dental fluorosis and, at higher sustained exposure levels, skeletal fluorosis (Shaji et al., 2024; World Health Organization [WHO], 2017).

Fluoride in groundwater originates primarily from the dissolution and weathering of fluoride-bearing minerals, including fluorite (CaF_2), fluorapatite and other phosphate minerals, micas, and amphiboles (Shaji et al., 2024). Its concentration in groundwater is controlled by a combination of mineral–water interaction, calcium availability, mineral saturation state, carbonate equilibria, ion exchange, pH, alkalinity, evaporation, and groundwater residence time.

North Africa includes extensive arid and semi-arid regions where groundwater represents an important source of water for drinking, domestic activities, and irrigation. Major regional aquifer systems, such as the Continental Intercalaire and Complex Terminal, are characterized in several areas by long groundwater flow paths, variable recharge conditions, and prolonged water–rock interaction. Local aquifer systems in Morocco, Tunisia, Libya, and Egypt may also display substantial spatial and hydrochemical variability.

Elevated fluoride concentrations have been documented in several North African groundwater systems, with some investigated areas reporting concentrations above the World Health Organization guideline value of 1.5 mg/L (Ameur et al., 2019; Benaissa et al., 2024; Edmunds et al., 2003; Elmabrok, 2023; Hassan et al., 2004; Karroum et al., 2017; Kechiched et al., 2020; Khalil et al., 2015; Lebrahimi et al., 2017; Nezli et al., 2009; Sweesi et al., 2022; WHO, 2017). However, the magnitude and controlling mechanisms of fluoride enrichment vary considerably between aquifers.

A regional synthesis is therefore needed to bring together the available evidence on fluoride occurrence, hydrogeochemical controls, potential drinking-water exposure, spatial assessment, management approaches, and remaining research needs.

The objectives of this review are to:

1. Document reported groundwater fluoride concentrations in Morocco, Algeria, Tunisia, Libya, and Egypt;
2. Synthesize the principal hydrogeochemical processes controlling fluoride occurrence;
3. Examine the implications of elevated groundwater fluoride for potential drinking-water exposure;
4. Review the use of GIS and spatial modelling for fluoride assessment; and
5. Identify major research gaps and management priorities.

II. Materials and methods

A. Review Framework and Study Scope

The review was guided by the PRISMA 2020 framework for systematic reviews (Page et al., 2021).

The geographical scope included Morocco, Algeria, Tunisia, Libya, and Egypt. The literature review considered available evidence on groundwater fluoride in these countries, with the literature search and synthesis updated through December 2024. Earlier studies were retained when they provided essential baseline information, historical evidence, or foundational hydrogeochemical data relevant to the regional assessment. Studies published after December 2024 were not included in the present synthesis.

Studies were considered relevant when they provided groundwater fluoride concentrations and/or information on the hydrogeochemical processes controlling fluoride occurrence. The review focused on groundwater quality, hydrogeochemical controls, potential drinking-water exposure, spatial assessment, and groundwater management.

Studies dealing primarily with fluoride removal or treatment were considered separately and were not counted as primary groundwater-occurrence settings.

The final qualitative synthesis comprises 12 documented groundwater study settings derived from 11 primary publications. One publication reports two distinct Egyptian settings, namely Marsa Matrouh and Arish.

B. Data Extraction

For each relevant study, the following information was extracted where reliably available:

- Location and country;
- Aquifer or hydrogeological setting;
- Publication year;
- Reported fluoride concentration;
- Number of groundwater samples or wells;
- Major hydrogeochemical interpretations; and
- Spatial assessment or modelling approaches where applicable.

Reported concentration ranges and sample numbers were retained as provided by the source when reliably established. Where a value could not be reliably established from the verified information available for the present synthesis, it was recorded as **NR (not reported or not reliably established)**.

Publication year was distinguished from sampling year whenever this information was available.

C. Data Synthesis

Because the reviewed studies differ substantially in sampling design, aquifer characteristics, geographical coverage, analytical methods, sampling periods, and reported variables, a quantitative meta-analysis was not considered appropriate.

The synthesis therefore follows a qualitative and comparative approach. Reported concentrations are discussed in relation to the WHO guideline value of 1.5 mg/L for drinking water (WHO, 2017). Exceedance of this guideline is interpreted as an indication of potential drinking-water concern and not as direct evidence of population-level fluorosis.

D. Hydrogeochemical Interpretation

The interpretation focused on the principal processes reported or discussed in the reviewed studies, including:

- Dissolution of fluoride-bearing minerals;
- Fluorite saturation and calcium availability;
- Carbonate equilibria;
- Ion exchange;
- Evaporation;
- Groundwater residence time and flow evolution; and
- Potential anthropogenic influences.

GIS and geostatistical approaches were considered according to the specific methodology used in each study rather than being quantitatively pooled.

III. Results and discussion

A. Fluoride Occurrence by Country

A.1. Morocco

Three groundwater settings were identified.

In the Khouribga–Oued Zem area of the Ouled Abdoun Basin, fluoride concentrations ranged from **0.08 to 1.93 mg/L** in **90 groundwater samples** (Lebrahimi et al., 2017).

In the Bahira Plain, groundwater fluoride occurrence was investigated in relation to the geochemical processes controlling groundwater quality (Karroum et al., 2017). The fluoride concentration range and sample number are **NR** where they could not be reliably established from the verified information available for the present synthesis.

In the Bakoya Massif, Benaissa et al. (2024) reported fluoride concentrations ranging from **0.01 to 2.60 mg/L** based on **30 groundwater samples**. This 2024 study represents the most recent Moroccan contribution included in the present synthesis.

A.2. Algeria

In the Hassi Messaoud area, within the Complex Terminal aquifer, fluoride concentrations ranged from **1.60 to 2.90 mg/L**, with a reported mean of approximately **2.1 ± 0.4 mg/L** (Kechiched et al., 2020). The study also assessed the spatial distribution of fluoride using indicator kriging. The sample size is **NR**.

In the Ouargla Basin, fluoride concentrations in Complex Terminal groundwater ranged from **1.00 to 2.00 mg/L** based on **19 samples** (Nezli et al., 2009).

The regional Continental Intercalaire aquifer system extending across southern Algeria and Tunisia was also considered. Reported fluoride concentrations were approximately **0.50–1.00 mg/L**, based on approximately **50 samples** (Edmunds et al., 2003).

A.3. Tunisia

In the Oued Rmel aquifer in north-eastern Tunisia, fluoride concentrations ranged from **4.00 to 22.00 mg/L** in **23 groundwater samples** (Ameur et al., 2019). This represents the highest reported concentration identified among the groundwater settings included in the present synthesis.

A.4. Libya

In the Al-Jfara District, fluoride concentrations ranged from **0.02 to 10.50 mg/L** in **21 groundwater wells** (Sweesi et al., 2022).

In the Western Jifarah Plain, concentrations ranged from **0.05 to 3.27 mg/L**, with a reported mean of **1.58 mg/L**, based on **30 wells** (Elmabrok, 2023).

A.5. Egypt

For groundwater south of the Ismailia Canal, **33 wells** were investigated, including **28 Quaternary wells and five Miocene wells** (Khalil et al., 2015). The fluoride concentration range is **NR** because the corresponding value was not retained without reliable verification.

The Egyptian assessment by Hassan et al. (2004) reported mean fluoride concentrations of **0.761 mg/L** for Marsa Matrouh and **0.926 mg/L** for Arish. The sample sizes for these two settings are **NR**.

B. Comparative Synthesis

The reviewed evidence demonstrates pronounced heterogeneity in groundwater fluoride concentrations across North Africa. Several investigated settings reported concentrations exceeding the WHO guideline value of 1.5 mg/L, including parts of Morocco, Algeria, Tunisia, and Libya.

The highest reported concentration was **22 mg/L** in the Oued Rmel aquifer in Tunisia (Ameur et al., 2019), followed by **10.50 mg/L** in the Al-Jfara District of Libya (Sweesi et al., 2022). Elevated concentrations were also reported in Hassi Messaoud, Western Jifarah, Bakoya, and other investigated groundwater systems (Ameur et al., 2019; Benaissa et al., 2024; Elmabrok, 2023; Kechiched et al., 2020; Nezli et al., 2009; Sweesi et al., 2022).

The observed variability should not be interpreted as a direct comparison of national groundwater quality. The studies differ substantially in sampling density, aquifer type, groundwater depth, sampling period, analytical approaches, hydrogeological context, and study objectives.

Consequently, the reported concentrations represent **investigated groundwater settings rather than nationally representative fluoride distributions**.

C. Hydrogeochemical Controls on Fluoride Occurrence

C.1. Mineral–Water Interaction and Fluoride-Bearing Minerals

The principal natural source of fluoride in groundwater is the interaction between water and fluoride-bearing minerals. Fluorite, fluorapatite and other phosphate minerals, micas, and amphiboles may contribute fluoride through weathering and dissolution (Shaji et al., 2024).

In the Ouled Abdoun Basin, the occurrence of fluoride is associated with phosphate-rich geological formations and groundwater interaction with the surrounding geological environment (Lebrahimi et al., 2017).

In the Bahira Plain, fluoride enrichment has been related to water–rock interaction, evaporation, mineral equilibria, low calcium concentrations, and fluorite-related processes (Karroum et al., 2017).

In the Bakoya Massif, the spatial distribution of groundwater chemistry indicates substantial heterogeneity, with natural hydrogeochemical processes and possible anthropogenic influences considered in the interpretation (Benaissa et al., 2024).

C.2. Calcium Availability and Fluorite Saturation

Calcium concentration plays an important role in controlling dissolved fluoride through fluorite saturation.

Under conditions of fluorite undersaturation, dissolution may contribute to increasing dissolved fluoride. Conversely, increasing calcium availability can favour fluorite saturation and limit further fluoride enrichment.

The relationship between elevated fluoride and relatively low calcium concentrations is particularly relevant in the Bahira Plain, where calcium availability and mineral equilibria contribute to the observed groundwater chemistry (Karroum et al., 2017).

C.3. Alkalinity, pH, and Hydrochemical Evolution

pH influences mineral dissolution, aqueous speciation, and interactions between dissolved constituents and mineral surfaces. Neutral to alkaline conditions may favour fluoride mobility in some

hydrogeochemical environments, but pH alone cannot explain the occurrence of high fluoride concentrations.

Alkalinity and carbonate equilibria can indirectly influence fluoride by modifying calcium availability and mineral saturation.

The Continental Intercalaire system illustrates the importance of long groundwater flow paths and prolonged water–rock interaction in shaping groundwater chemistry (Edmunds et al., 2003).

C.4. Sodium, Bicarbonate, and Ion Exchange

Elevated fluoride is frequently associated with sodium-rich groundwater. Cation exchange between calcium and sodium can reduce dissolved calcium concentrations, potentially favouring fluoride persistence in solution.

Bicarbonate also contributes to hydrochemical evolution through its effects on carbonate equilibria and calcium availability. Calcite precipitation, for example, may reduce dissolved calcium and consequently influence fluorite saturation.

C.5. Evaporation in Arid and Semi-Arid Environments

Evaporation can increase dissolved fluoride concentrations by concentrating solutes, particularly in arid and semi-arid environments.

This process has been considered in the interpretation of fluoride enrichment in the Bahira Plain (Karroum et al., 2017) and Hassi Messaoud (Kechiched et al., 2020).

Evaporation should, however, be regarded primarily as a **concentrating mechanism rather than an independent fluoride source**.

C.6. Groundwater Residence Time and Flow Evolution

Long groundwater residence times increase the opportunity for water–rock interaction and hydrochemical evolution.

The Continental Intercalaire aquifer provides an important example of groundwater evolution associated with regional flow and prolonged interaction with geological formations (Edmunds et al., 2003).

Residence time is nevertheless not a universal predictor of fluoride concentration because its effect depends on mineralogy, calcium availability, recharge conditions, and the overall hydrochemical evolution of groundwater.

C.7. Anthropogenic Influences and Land Use

Agricultural activities, fertilizer application, mining, industrial activities, groundwater abstraction, and changes in recharge conditions may modify groundwater chemistry.

Anthropogenic influence has been considered alongside natural hydrogeochemical processes in the interpretation of groundwater quality in the Bakoya Massif (Benaissa et al., 2024) and Western Jifarah Plain (Elmabrok, 2023).

However, attribution of elevated fluoride to anthropogenic sources requires supporting evidence. The presence of human activities in a groundwater basin does not, by itself, demonstrate an anthropogenic origin of fluoride.

C.8. Integrated Conceptual Model

The reviewed evidence supports an integrated conceptual framework:

Fluoride-bearing minerals → fluoride release → calcium availability and fluorite saturation → carbonate equilibria and ion exchange → evaporation and concentration → groundwater residence time and flow evolution → spatial and hydrogeological variability.

The relative contribution of each process is aquifer-specific.

Future investigations should combine fluoride concentrations with major ions, pH, electrical conductivity, mineral saturation indices, groundwater age where available, lithological information, and spatial hydrogeological data.

IV. Discussion

A. Potential Health Risks Associated with Groundwater Fluoride

A.1. Dental and Skeletal Effects

Chronic exposure to elevated fluoride concentrations through drinking water may contribute to dental fluorosis, while prolonged exposure to higher fluoride levels may result in skeletal fluorosis (Shaji et al., 2024; WHO, 2017).

Several groundwater settings reviewed in this study reported concentrations above the WHO guideline value of 1.5 mg/L (Ameur et al., 2019; Benaissa et al., 2024; Elmabrok, 2023; Kechiched et al., 2020; Lebrahimi et al., 2017; Nezli et al., 2009; Sweesi et al., 2022). These observations indicate potential drinking-water exposure concerns.

However, groundwater concentration alone does not demonstrate the occurrence of fluorosis within a population. Health effects depend on cumulative fluoride intake and exposure duration.

A.2. Vulnerable Populations and Exposure Variability

Children may be particularly relevant in exposure assessments because fluoride intake depends on body weight, water consumption, dietary intake, and exposure duration.

A meaningful health-risk assessment therefore requires information on actual water consumption, age, body weight, duration of exposure, and other sources of fluoride.

A.3. Exposure and Risk Assessment

For studies where the necessary exposure parameters are available, chronic daily intake can be estimated as:

$$CDI = (C \times IR \times EF \times ED) / (BW \times AT)$$

Where:

C = fluoride concentration in drinking water;
IR = ingestion rate;
EF = exposure frequency;
ED = exposure duration;
BW = body weight; and
AT = averaging time.

The hazard quotient can subsequently be expressed as:

$$\text{HQ} = \text{CDI} / \text{RfD}$$

Where RfD represents the applicable reference dose.

No pooled regional HQ was calculated because the required exposure parameters and methodological assumptions were not sufficiently standardized across the reviewed studies.

B. GIS and Spatial Assessment of Groundwater Fluoride

GIS provides a valuable framework for integrating groundwater chemistry with geological, hydrogeological, topographical, and land-use information.

Several reviewed studies applied spatial approaches to investigate fluoride distribution. Indicator kriging was used to assess the spatial distribution of fluoride in the Hassi Messaoud Complex Terminal aquifer (Kechiched et al., 2020). GIS-based hydrochemical assessment was applied in the Bakoya Massif (Benaissa et al., 2024), while spatial and hydrochemical analyses were used in the Oued Rmel aquifer (Ameur et al., 2019).

Spatial interpolation can help identify areas where fluoride concentrations may exceed drinking-water guidelines. However, interpolation reliability depends strongly on sampling density, spatial representativeness, geological continuity, model selection, and independent validation.

Future North African fluoride assessments could integrate GIS and geostatistics with geology, hydrogeology, groundwater depth, digital elevation models, major-ion chemistry, electrical conductivity, pH, land use, remote sensing, and groundwater flow characteristics.

Machine-learning or hybrid spatial approaches may also provide useful predictive tools, but only when supported by adequate training data, independent validation, uncertainty assessment, and hydrogeological interpretation.

A standardized regional groundwater fluoride database would substantially improve future spatial assessments.

C. Remediation and Groundwater Management

Where groundwater fluoride concentrations exceed drinking-water guidelines, management strategies should consider both treatment and source-management options.

Potential defluoridation technologies include adsorption, precipitation/coagulation, membrane processes, ion exchange, and combinations of these approaches.

Adsorption using activated alumina and activated carbon has been investigated for fluoride removal from drinking water (Lebrahimi et al., 2020). Such laboratory-scale studies demonstrate treatment potential but should not automatically be interpreted as evidence of field-scale feasibility.

Membrane processes such as reverse osmosis and nanofiltration can provide effective fluoride removal but may involve higher energy requirements, concentrate-management issues, and infrastructure costs.

Blending groundwater with a lower-fluoride water source may represent another management option where suitable water sources are available.

The choice of intervention should consider initial fluoride concentration, groundwater chemistry, treatment efficiency, water demand, operational requirements, energy consumption, waste generation, cost, and long-term sustainability.

D. Research Gaps

D.1. Uneven Spatial Coverage

Available studies are concentrated in specific groundwater systems, while large areas of North Africa remain insufficiently characterized.

D.2. Limited Long-Term Monitoring

Many investigations represent individual sampling campaigns. Long-term monitoring is needed to distinguish persistent fluoride enrichment from temporal variability.

D.3. Incomplete Hydrochemical Datasets

Not all studies report the same major ions, physicochemical parameters, or saturation indices. Standardized reporting would improve regional comparison.

D.4. Insufficient Mineralogical Constraints

More detailed mineralogical and geochemical characterization is needed to distinguish the contribution of fluorite, phosphate minerals, silicates, and other fluoride-bearing phases.

D.5. Natural versus Anthropogenic Fluoride

In some areas, the relative contribution of natural processes and human activities remains uncertain. Source attribution requires integrated geological, hydrochemical, isotopic, and land-use evidence.

D.6. Standardization of Health-Risk Assessment

Future studies should use transparent and comparable exposure assumptions, including age-specific water intake, body weight, exposure duration, and dietary fluoride contributions.

D.7. GIS Uncertainty and Validation

Spatial prediction should systematically report sampling density, interpolation methodology, validation procedures, and uncertainty.

D.8. Integrated Groundwater Management

Future programmes should link fluoride monitoring with groundwater quantity, quality, abstraction, recharge, climate variability, and drinking-water management.

E. Limitations of the Review

The reviewed studies differ substantially in sampling design, spatial and temporal coverage, aquifer characteristics, analytical methods, sample size, and hydrochemical variables.

Therefore, reported fluoride ranges should not be interpreted as representative of entire countries or regional aquifers unless supported by appropriate sampling designs.

The synthesis is based on published and accessible information that could be reliably verified. Where numerical information could not be reliably established, **NR** was used rather than estimating or reconstructing values.

The reviewed studies cover different publication periods. Older studies were retained where they provided important baseline or foundational information, while the literature synthesis was updated through December 2024.

A pooled regional health-risk assessment was not performed because exposure assumptions and reported parameters were insufficiently standardized.

No country-level ranking of fluoride occurrence was attempted because differences in sampling density, hydrogeological settings, and study design prevent a robust national comparison.

Table 1. Reported groundwater fluoride concentrations in selected North African study settings

Country / Region	Study Setting	Reference	Publication Year	Reported F ⁻ Concentration (mg/L)	Sample Size
Morocco	Khouribga–Oued Zem / Ouled Abdoun Basin	Lebrahimi et al., 2017	2017	0.08–1.93	90
Morocco	Bahira Plain	Karroum et al., 2017	2017	NR	NR
Morocco	Bakoya Massif	Benaissa et al., 2024	2024	0.01–2.60	30
Algeria	Hassi Messaoud, Complex Terminal aquifer	Kechiched et al., 2020	2020	1.60–2.90 (mean 2.1 ± 0.4)	NR
Algeria	Ouargla Basin, Complex Terminal aquifer	Nezli et al., 2009	2009	1.00–2.00	19
Algeria–Tunisia	Continental Intercalaire aquifer	Edmunds et al., 2003	2003	0.50–1.00	~50
Tunisia	Oued Rmel aquifer, Zaghuan	Ameur et al., 2019	2019	4.00–22.00	23
Libya	Al-Jfara District	Sweesi et al., 2022	2022	0.02–10.50	21
Libya	Western Jifarah Plain	Elmabrok, 2023	2023	0.05–3.27 (mean 1.58)	30
Egypt	South of Ismailia Canal	Khalil et al., 2015	2015	NR	33
Egypt	Marsa Matrouh	Hassan et al., 2004	2004	0.761 (mean)	NR
Egypt	Arish	Hassan et al., 2004	2004	0.926 (mean)	NR

NR: not reported or not reliably established.

V. Conclusion

This systematic review demonstrates that fluoride is an important and heterogeneous groundwater-quality issue across several investigated areas of North Africa. Reported concentrations vary substantially among aquifer systems, ranging from values below the WHO drinking-water guideline to **22 mg/L in the Oued Rmel aquifer, Tunisia**, and **10.50 mg/L in the Al-Jfara District, Libya**.

The reviewed evidence indicates that fluoride enrichment generally results from interacting hydrogeochemical processes, including fluoride-bearing mineral dissolution, calcium availability, fluorite saturation, carbonate equilibria, ion exchange, evaporation, and prolonged groundwater residence time. The relative contribution of these processes varies according to geological and hydrogeological conditions.

Several investigated groundwater settings contain fluoride concentrations above the WHO guideline value of 1.5 mg/L, indicating potential drinking-water exposure concerns.

Nevertheless, groundwater concentrations alone cannot establish population-level health effects, which depend on actual exposure, duration, age, body weight, water consumption, and other fluoride sources.

GIS and geostatistical approaches provide useful tools for identifying spatial patterns and supporting groundwater-quality management, but their reliability depends on representative sampling, appropriate modelling, independent validation, and uncertainty assessment.

The literature updated through **December 2024** highlights the need for stronger long-term monitoring, improved spatial coverage, standardized hydrochemical datasets, detailed mineralogical investigations, and more consistent exposure assessment.

Future research should integrate hydrogeochemistry, mineralogy, hydrogeology, GIS-based modelling, temporal monitoring, and health-oriented exposure assessment. Such integrated approaches are essential for developing sustainable groundwater-management strategies, identifying vulnerable areas, and selecting appropriate interventions such as alternative water sources, blending, or defluoridation where elevated fluoride concentrations constitute a drinking-water concern.

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Conflicts of interest

The author declares no conflict of interest.

Compliance with ethical standards

This study is a systematic review of previously published scientific literature and did not involve human participants, animals, or the collection of new biological samples.

AI use declaration

AI tools were used to assist with the preparation and language editing of this manuscript.

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