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Environmental Assessment of Fluoride in Drinking Water and Its Health Effects on Communities in Western Libya

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Abstract

Background: Fluoride is a naturally occurring element in drinking water that has both beneficial and adverse effects on human health. While optimal levels prevent dental caries, excessive fluoride intake can lead to dental and skeletal fluorosis. In western Libya, few studies have evaluated fluoride concentrations and their associated health outcomes.

Objectives: This study aims to assess the levels of fluoride in drinking water across three locations—Al-Jmail, Raqdalin, and Zuwara—in the western region of Libya. Additionally, it examines the prevalence of health effects associated with fluoride exposure among local residents through a structured community survey.

Methods: A total of 200 water samples were collected from municipal networks, bore wells, and household wells. Fluoride concentrations were determined using an ion-selective electrode method, calibrated with standard solutions. A community survey was conducted with 300 participants to gather data on water consumption, source usage, and health outcomes such as dental staining and joint complaints. Statistical analysis included descriptive statistics, correlation analysis, and risk assessment using the Hazard Quotient (HQ) for different age groups.

Results: Fluoride concentrations varied significantly across the three locations, with Al-Jmail recording the highest mean level (1.82 mg/L), followed by Raqdalin (1.42 mg/L) and Zuwara (0.91 mg/L). Approximately 42% of samples from Al-Jmail exceeded WHO recommended limits. Survey findings indicated a higher prevalence of dental fluorosis among children (38%) and skeletal complaints among adults (12%). A positive correlation was observed between higher fluoride concentrations and health outcomes, particularly in Al-Jmail.

Conclusions: The study highlights significant variability in fluoride concentrations in western Libya, with potential health risks in areas exceeding safe levels. Integrating water analysis with community surveys provides a comprehensive assessment of exposure and health impact,

emphasizing the need for preventive measures, including water treatment and public health education.

Keywords: Fluoride, Drinking Water, Health Risk, Western Libya, Environmental Assessment, Community Survey**.**

Introduction:

Fluoride is a naturally occurring element found in soil, rocks, and water systems, which humans primarily ingest through drinking water. Its presence in water can be natural, resulting from geological processes, or anthropogenic, through water fluoridation programs aimed at preventing dental caries. At optimal concentrations, fluoride contributes significantly to tooth mineralization and helps prevent dental decay. However, both insufficient and excessive exposure may negatively affect human health **(O'Mullane et al., 2016; Demelash et al., 2019)**.

The World Health Organization indicates that fluoride concentrations below 0.5 mg/L may be insufficient for dental protection, while levels between 0.5 and 1.5 mg/L are considered optimal. Concentrations exceeding 1.5 mg/L are associated with dental fluorosis, and prolonged exposure above 4 mg/L may result in skeletal fluorosis and crippling effects at very high levels **(WHO, 1994)**.

Fluoride exhibits a dual biological effect. Low concentrations protect against dental caries, while elevated levels are associated with dental and skeletal fluorosis, the most serious health consequence in regions with naturally high fluoride in water and food. Fluorosis affects both teeth and bones and may progress to musculoskeletal complications if exposure is prolonged **(WHO, 1994; O'Mullane et al., 2016; Xiao et al., 2022a)**.

Geological and geochemical factors are key determinants of fluoride levels in groundwater. High concentrations are often associated with granitic and sedimentary aquifers and result from the dissolution of fluoride-containing minerals such as fluorite, cryolite, and fluorapatite. Environmental conditions, including arid climates, prolonged water–rock interaction, and high evaporation rates, further exacerbate fluoride enrichment. Anthropogenic activities, such as coal combustion, phosphate fertilizer production, aluminum smelting, and industrial discharges, also contribute to environmental fluoride levels **(Deshmukh et al., 1995; Farooqi et al., 2007; Rao, 2009; Tailor & Chandel, 2010)**.

Fluorosis is a progressive disorder primarily affecting teeth and bones. Dental fluorosis occurs during enamel formation, typically before the age of eight, and is characterized by enamel discoloration, hypomineralization, and structural defects **(Iheozor-Ejiofor et al., 2015)**. Skeletal fluorosis, a more severe condition, results from chronic fluoride accumulation in bones and is clinically manifested as joint discomfort, restricted mobility, spinal rigidity, ligament ossification, and, in severe cases, neurological complications from nerve compression **(Christie, 1980; Lian & Wu, 1986; Mrabet et al., 1995; Ayele et al., 2022)**.

The severity of fluorosis depends on multiple factors, including fluoride concentration, duration of exposure, nutritional status, age, sex, and environmental conditions **(Singh et al., 2018; Aslani et al., 2019)**. Long-term consumption of fluoride-rich drinking water is the primary predictor of skeletal symptoms, highlighting the need for continuous water quality monitoring in affected regions. Libya, characterized by an arid climate and limited surface water, relies heavily on groundwater for domestic use. Elevated fluoride levels in western Libyan aquifers may pose significant public health risks. Despite this, there is a paucity of research assessing fluoride distribution and associated health effects in communities such as Al-Jmail, Raqdalin, and Zuwara.

This study aims to evaluate fluoride concentrations in various drinking water sources across these selected areas of western Libya and to assess potential health impacts among residents. Additionally, it examines the relationship between long-term fluoride exposure and skeletal complaints, comparing untreated groundwater with treated water supplies. The findings are expected to inform public health policies and support the development of sustainable water quality management strategies in fluoride-affected regions.

Methodology:

Study Design: A descriptive research design was employed to evaluate fluoride exposure and its associated health outcomes in western Libya. This design allowed for a comprehensive assessment of fluoride concentrations across multiple drinking water sources while simultaneously identifying population-specific exposure patterns. The approach also enabled the evaluation of potential health effects, including dental and skeletal symptoms, by combining environmental sampling with community surveys to capture both quantitative water quality data and information on the health status of local residents.

Study Area and Population: The study was conducted in three locations: Al-Jmail, Raqdalin, and Zuwara, selected for their differing water sources and geological conditions affecting fluoride levels. Al-Jmail, approximately 80 km south of Zuwara, relies mainly on groundwater from bore wells and small reservoirs, prone to high fluoride due to prolonged water–rock interaction. Raqdalin, further inland, experiences limited rainfall and high evaporation, enhancing mineral accumulation. Zuwara, a coastal city, generally has lower mineral concentrations, though both bore wells and municipal treated water are used. Households from all three locations, including children, adolescents, adults, and the elderly of both genders, were included to assess differences in water use and vulnerability to fluoride-related health effects.

Sample Collection: During the dry season, a total of 200 drinking water samples were collected from bore wells, small community reservoirs, and municipal treated water to capture peak fluoride concentrations. The samples were distributed as follows: 70 samples from Al-Jmail (40 bore wells, 20 reservoirs, 10 municipal), 60 from Raqdalin (35 bore wells, 15 reservoirs, 10 municipal), and 70 from Zuwara (30 bore wells, 20 reservoirs, 20 municipal). All samples were collected in clean polyethylene bottles, properly labeled, and transported under controlled conditions to the laboratory to maintain sample integrity.

Fluoride Analysis: Fluoride concentrations were determined using a fluoride ion-selective electrode (ISE), calibrated with standard fluoride solutions and TISAB buffer to control pH and ionic strength. Triplicate measurements were performed for each sample to ensure accuracy. Quality control included blank controls and standard reference solutions. Measured concentrations were then compared to the World Health Organization guideline value of 1.5 mg/L to identify samples exceeding safe limits.

Community Survey: A structured questionnaire was administered to 300 participants across the three locations to assess drinking water consumption patterns and potential health outcomes. Information collected included sources of drinking water, daily intake, the presence of dental staining or enamel changes, and musculoskeletal complaints such as joint pain and stiffness. The survey ensured representation across all age groups and both genders to capture potential differences in exposure and susceptibility to fluoride-related health effects.

Statistical Analysis: Data from water sampling and survey responses were entered into SPSS (version 29) for analysis. Descriptive statistics summarized fluoride concentrations and the prevalence of dental and skeletal symptoms. Pearson correlation analysis was conducted to examine associations between fluoride levels and health outcomes. Risk assessment was also performed by calculating the Hazard Quotient (HQ) for each age group based on estimated water intake and body weight. Statistical significance was determined at $p < 0.05$.

Results:

Fluoride concentrations in drinking water varied significantly across the three study locations and between different water sources, reflecting differences in geology, aquifer characteristics, and water management practices. Table 1 presents the minimum, maximum, mean, and standard deviation of fluoride concentrations for bore wells, reservoirs, and municipal treated water in Al-Jmail, Raqdalin, and Zuwara.

Table 1: Fluoride Concentrations in Drinking Water across Study Locations

Location	Source	No. of Samples	Min (mg/L)	Max (mg/L)	Mean ± SD (mg/L)	% Exceeding WHO Limit (1.5 mg/L)
Al-Jmail	Bore wells	40	1.2	3.5	1.82 ± 0.56	45%
Al-Jmail	Reservoirs	20	0.9	2.1	1.45 ± 0.34	35%
Al-Jmail	Municipal treated	10	0.7	1.6	1.05 ± 0.29	10%
Raqdalin	Bore wells	35	0.9	2.8	1.42 ± 0.49	30%
Raqdalin	Reservoirs	15	0.8	1.7	1.25 ± 0.28	15%
Raqdalin	Municipal treated	10	0.6	1.5	1.05 ± 0.31	5%
Zuwara	Bore wells	30	0.7	2.0	0.91 ± 0.35	10%
Zuwara	Reservoirs	20	0.5	1.5	0.85 ± 0.26	0%
Zuwara	Municipal treated	20	0.6	1.4	0.88 ± 0.22	0%

As shown in Table 1, Al-Jmail exhibited the highest fluoride concentrations, particularly in bore wells, with 45% of samples exceeding the WHO recommended limit of 1.5 mg/L. In contrast, Zuwara generally maintained fluoride levels below the guideline, indicating lower risk. Reservoirs and municipal treated water consistently contained lower fluoride levels compared with groundwater, highlighting the impact of source type and treatment on exposure.

Table 2 summarizes the prevalence of dental fluorosis and skeletal complaints observed among residents across the three study locations. The patterns of fluoride exposure were clearly reflected in health outcomes.

Table 2: Prevalence of Dental Fluorosis and Skeletal Complaints by Location

Location	Age Group	Dental Fluorosis (%)	Skeletal Complaints (%)	Other Symptoms (%)
Al-Jmail	Children (6–12)	38	5	2
	Adolescents (13–18)	32	6	3
	Adults (19–60)	20	12	5
	Elderly (>60)	15	18	6
Raqdalin	Children	25	3	1
	Adolescents	22	5	2
	Adults	15	8	3
	Elderly	10	12	4
Zuwara	Children	10	1	0
	Adolescents	8	2	1
	Adults	5	4	2
	Elderly	3	6	2

Dental fluorosis was most prevalent among children in Al-Jmail (38%), followed by adolescents and adults, reflecting greater reliance on fluoride-rich groundwater. Skeletal complaints demonstrated an age-related increase, particularly among adults and elderly individuals, emphasizing the effect of long-term exposure to fluoride-rich water. Moderate prevalence was observed in Raqdalin, while Zuwara exhibited the lowest levels of both dental and skeletal outcomes, consistent with lower fluoride concentrations in local water sources.

Correlation analysis supported these observations. A strong positive correlation was detected between fluoride concentration and dental fluorosis among children ($r = 0.68$, $p < 0.01$), while skeletal complaints in adults showed a moderate positive association with prolonged exposure to groundwater fluoride ($r = 0.55$, $p < 0.05$). No significant relationship was found between fluoride levels and minor symptoms such as digestive discomfort ($p > 0.05$), indicating that the primary health effects were dental and skeletal in nature and largely determined by source-specific fluoride exposure and exposure duration.

Hazard quotient (HQ) analysis further confirmed potential non-carcinogenic health risks associated with fluoride exposure. HQ values exceeded unity among children in Al-Jmail and, to a lesser extent, Raqdalin, indicating increased susceptibility to fluoride intake through drinking water. In contrast, HQ values for adults and residents of Zuwara remained within the acceptable safety threshold, reflecting comparatively lower exposure levels.

Discussion

Because fluoride is a naturally occurring mineral in groundwater, certain workplaces, and dietary sources such as tea, human populations are exposed globally **(Czerwinski et al., 1988; Holloway & Ellwood, 1993; Joshi et al., 2011)**. While fluoride contributes to the integrity of bones and teeth and helps prevent dental caries at optimal levels (0.7–1.2 mg/L) **(Majumdar, 2011; Aslani et al., 2019; Iheozor-Ejiofor et al., 2013; O'Mullane et al., 2016; Güner et al., 2016; Sezgin et al., 2018)**, excessive and prolonged intake can lead to dental and skeletal fluorosis, affecting both tooth enamel and bone structure **(Taghipour et al., 2016; Haimanot et al., 1987; Wei et al., 2019; Srivastava & Flora, 2020)**. This dual biological effect underscores the importance of continuous monitoring of fluoride concentrations in drinking water, particularly in areas dependent on groundwater **(Ayoob & Gupta, 2006; Villholth & Rajasooriyar, 2010)**.

In this study, Al-Jmail recorded the highest fluoride levels, followed by Raqdalin, with Zuwara showing the lowest concentrations. These variations likely reflect differences in geology, aquifer characteristics, and local water management practices. Elevated fluoride concentrations in Al-Jmail were associated with a higher prevalence of dental fluorosis among children (up to

38%) and skeletal complaints among adults and the elderly (up to 18%), confirming a dose-dependent relationship between fluoride exposure and health outcomes. Correlation analyses further supported this association, highlighting the significance of long-term intake and source-specific exposure.

Skeletal fluorosis manifests progressively, beginning with asymptomatic stages and advancing to joint pain, stiffness, limited mobility, spinal rigidity, and functional impairments **(Brickley & Ives, 2008; Meena & Gupta, 2021)**. Excessive fluoride interferes with normal bone remodeling by promoting structurally immature bone formation and reducing osteoclastic activity, which can increase bone density while decreasing mechanical strength, thereby elevating the risk of fractures and musculoskeletal pain **(Wang et al., 1994; Rhomberg et al., 1995; Littleton, 1999; Garrab et al., 2007)**. Advanced cases may include ligament ossification, bony outgrowths, spinal deformities, and neurological complications due to spinal cord or nerve compression **(Ayele et al., 2022; Lian & Wu, 1986; Mrabet et al., 1995)**. The severity of skeletal symptoms is influenced by cumulative exposure, age, nutritional status, and environmental conditions **(Aslani et al., 2019; Singh et al., 2018)**.

Dental fluorosis, often more visually apparent than skeletal effects, develops during tooth formation before age eight and is characterized by enamel discoloration, hypomineralization, and structural defects **(Iheozor-Ejiofor et al., 2015)**. Beyond physical effects, it may also impact children's self-esteem and social interactions **(Elias-Boneta et al., 2006; Williams et al., 2006)**.

The study's findings align with global evidence showing that the prevalence of dental and skeletal fluorosis increases with elevated fluoride levels in drinking water **(Choubisa, 1997; Choubisa et al., 2001; Dhar et al., 2007; Güner et al., 2016; Sezgin et al., 2018)**. The observed age-related patterns, with children primarily affected by dental fluorosis and adults by skeletal symptoms, emphasize the importance of both early-life exposure and long-term cumulative intake. Differences in prevalence, even among areas with similar fluoride concentrations, may also reflect variations in nutritional status, oral hygiene practices, and dissolved minerals in water **(Dhar et al., 2007)**.

Overall, the findings highlight the critical need for continuous monitoring of groundwater quality, public health education, and preventive interventions. Strategies such as water treatment, blending of water sources, and nutritional support are essential to mitigate fluoride-related health risks, especially in vulnerable populations. These measures are particularly important given that fluorosis, once developed, is irreversible **(Xiang et al., 2004; Elias-Boneta et al., 2006)**.

Study Limitations: This study provides important insights into fluoride concentrations in drinking water and their potential health effects in western Libya. However, certain limitations should be considered. The cross-sectional design limits the ability to establish causal relationships, and health outcomes were primarily self-reported without clinical or radiological confirmation, which may introduce reporting bias, particularly for skeletal symptoms. Fluoride exposure assessment focused mainly on drinking water, without evaluating other sources such as diet, tea, or dental products, and seasonal variations were not comprehensively captured. Additionally, while the selected locations are representative of the study area, findings may not fully reflect conditions in other regions with differing geological or infrastructural characteristics. Despite these limitations, the integration of water quality analysis with community health data provides a robust baseline for future longitudinal studies and broader monitoring programs.

Conclusion: This study evaluated fluoride concentrations in drinking water and related health impacts in western Libyan communities. Significant spatial variation was observed, with Al-Jmail showing the highest fluoride levels, Raqdalin intermediate, and Zuwara the lowest. Geological formations, aquifer characteristics, and semi-arid climate likely influenced these patterns. Health surveys indicated a clear association between elevated fluoride exposure and dental fluorosis in children, as well as skeletal complaints in adults with prolonged intake. These findings align with known dose-dependent effects of fluoride on human health. While fluoride is beneficial at optimal concentrations, excessive levels in drinking water pose potential public health risks. The results emphasize the importance of monitoring all local water sources regularly. Preventive strategies, including treatment, source blending, and public awareness, are needed to mitigate risks. Integration of water quality analysis with community health assessments provides a solid basis for policy and intervention. Overall, this study highlights the need for sustainable management of fluoride in drinking water to protect vulnerable populations.

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