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Mapping residual water fluoride levels and geological patterns in a rural semi-arid area of Brazil

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Some areas of Brazil have natural sources of fluoride in their water supply. Identifying these areas is an important measure to guide oral health measures when implementing safe fluoride applications, either alone or in combination. The study aims to map residual water fluoride levels and geological patterns in a rural semi-arid area of Brazil. Therefore, water samples were taken from 24 rural areas in the municipality of Poço de José de Moura, located in the tropical semi-arid areas of the country. The samples were analyzed in triplicate with a special fluoride electrode and a shallow water buffer, namely the legendary fortified water (secretive). The residual fluoride values in the samples ranged from 0.04 ± 0.00 mgF/mL in São Geraldo to 6.81 ± 2.81 mgF/mL in Monteiro. Therefore, residual fluoride was found in all groundwater samples analyzed in this study, with several sites exceeding the WHO guideline characterization of a potential risk of dental fluorosis in children and high levels of fluoride that may be related to geological formation factors.

Keywords Geological Phenomena, Fluoride, Fluoridation, Water

Fluorine is a highly electronegative ion and is widely scattered in the environment, so that it is able to form rapid bonds with positively charged elements. Fluorine, a naturally occurring element, is easily dissolved in water, soil and air[1].

Fluoridation of municipal drinking water is considered by the Centers for Disease Control and Prevention to be one of the greatest public health achievements of the twentieth century, responsible for a reduction in tooth decay and a significant contribution to improved oral health[2]. In the United States, optimal water fluoridation reduces dental decay by about 20–40 percent. In England, water fluoridation has been shown to reduce dental caries by 44 percent in children from around 5 years of age[2,3].

Water and beverages made from water are the main source of systemic fluoride intake; fluoridated water accounts for approximately 75 percent of dietary fluoride intake of the population[4]. Different methods of intake of fluoride are discussed, including local and systemic use of fluoride. Of all the methods available, fluoridation of municipal drinking water is the cheapest and safest way to provide fluoride[5].

Systematic reviews concluded that this collective intervention is effective in reducing caries in children, both primary and permanent dental, and that the only side-effect is an increased risk of dental fluorosis[6,7].

However, in arid and semi-arid areas, rural and poor communities collect water through aquifers or cisterns[8] and use it for farming and drinking[9]. The high fluoride content in the water is due to geological conditions in which soil containing fluoride contaminates groundwater with high levels of fluoride[10,11] and consumption of groundwater containing high levels of fluoride (1.5 mg/ml) can result in a variety of health problems, including dental and skeletal fluorosis[12].

Many factors can affect fluoride concentrations in drinking water, such as mineral degradation in rocks, precipitation and water and air temperature[13]. The largest fluoride reservoir is considered to be a natural source from rocks and minerals containing fluoride in their composition[14]. It is mobile at high temperatures and is light and unstable. Most of the fluorine is found in acidic igneous rock, mineralized veins and sedimentary formations where biogeochemical reactions have occurred; it is also present in primary minerals such as biotite

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and amphibole, substituting for hydroxyl in mineral structures, as OH^{-}[15]. Of the minerals forming rock, of which fluoride is a major component, only fluorite and, to a lesser extent, topaz are relatively common.

Due to the risk to human health from fluoride exposure via groundwater in a semi-arid area with fluoride endemic groundwater as the main source of drinking water and irrigation in the absence of alternative sources of water. Given the lack of information on the risks for human health associated with drinking groundwater. This study on groundwater in rural areas in a semi-arid area of a northeastern Brazilian city focused on the evaluation of fluoride concentrations in groundwater, the assessment of its drinking water quality by comparison to World Health Organization (WHO) drinking water quality standards (WHO, 2017), and the relationship of fluoride in groundwater to geological and hydro-chemical literature.

Methods

Study area

Poço de José de Moura is a fluoride endemic area of 100,971 km[10] and an IDHM 0,574, located approximately 540 km from João Pessoa, capital of Paraíba, in northeastern part of Brazil[16] (Fig. 1). The city is on average about 280 m above the sea level. The predominant vegetation is caatinga, which is typical for the semi-arid northeast of the country. The climate is classified as semi-arid by the Köppen climate classification. The climate is characterized by high temperatures throughout the year and a pronounced dry season. Precipitation is relatively low, which is typical for semi-arid areas. Average annual rainfall is around 700 mm, with most of it falling between February and May, and little or no precipitation occurring during the dry season, which may last for several months (INPC, 2024).

The rural area of Poço de Jose de Moura-PB has been chosen for this study because of its historical presence of residual fluoride naturally occurring in the water supply. The sampling plan for this study was based on rural clusters, on the basis of information provided by the municipality's department of public health.

The same methodology used by the Ministry of Health for the Oral Health National Survey (Brazil[17]) has been used. Rural villages were identified and selected on the basis of the primary Community Health Report, based on criteria such as the presence of family health centers, schools, churches or post offices. As a result, a data collection team, composed of two trained persons, visited households within 500 m of the family health unit or the cluster's focal point (church or school).

Data collection was carried out from 25 to 29 November 2024 at temperature of 32ºC in a uniform manner by the same person using clean Falcon 50 ml containers which had previously been washed with perchloric acid and deionized water.

Geological characteristics

The Poço de Jose de Moura area is mainly covered by the Rio do Peixe sedimentary basin, with the Jaguaretama complex forming the northern part, as illustrated in Fig. 2.

According to the CPRM[18], the basin of Rio do Peixe comprises the Antenor Navarro, Sousa and Rio do Peixe formations. They are generally a group of clayey sandstones with intercalated carbonate levels. This unit is partly covered by riverbed sand, alluvial deposits. The Antenor Navarro formation is deposited directly in the crystalline basement, and the Jaguaretama complex is located in the northern part of the municipality, and is generally represented by metamorphic igneous rock.

Fig. 1. General location of study area. Poço de José de Moura, located in the western part of Paraiba, northeastern part of Brazil, 540 km from the state capital, João Pessoa.

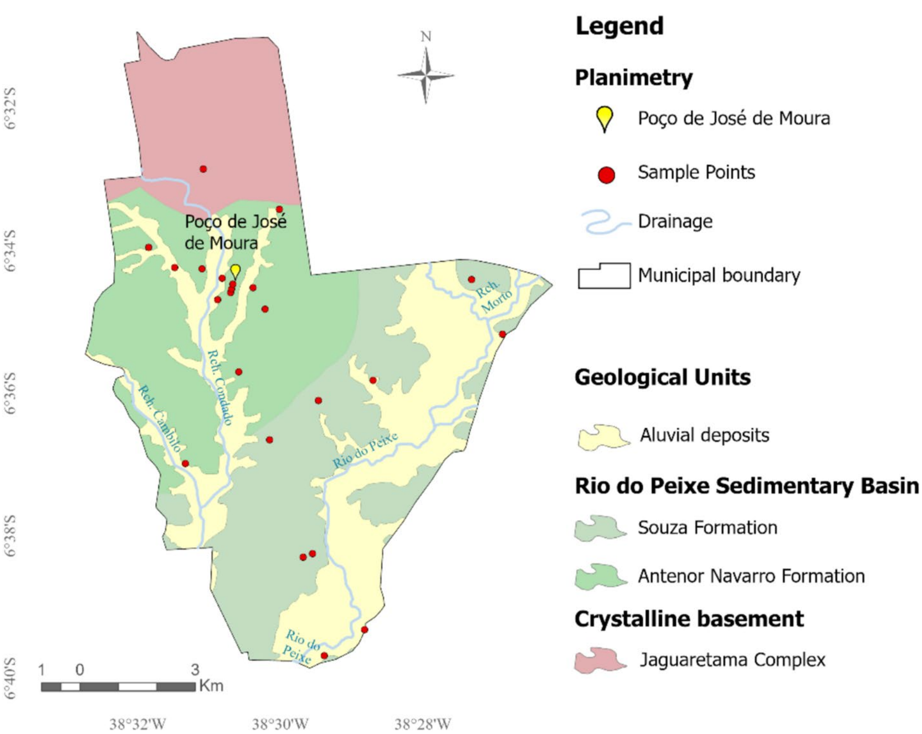

Fig. 2. The location of sampling points and the geological context of the city. Most of the municipality is part of the geological unit Rio do Peixe Sedimentary Basin, which here is characterized by the Sousa and Antenor Navarro formations, above the Jaguaretama complex, and is covered by alluvial deposits associated with the drainage.

Groundwater sampling

The municipality is made up of 24 rural areas, each of which has been sampled for groundwater for drinking purposes as shown in Table 1 and Fig. 2. After sampling each container of samples was clearly marked with permanent ink and the details of each sample recorded.

After sampling, the samples were transported to the laboratory of oral biology at the Federal University of Paraiba, Joao Pessoa, Paraiba, Brazil, under low temperature and sun protection. Google Maps GPS has been used to determine the sampling site's latitude and longitude.

Data analysis

The water analysis was carried out with a fluoride-specific ion electrode (Orion Model 96–09, Orion Research, Cambridge, MA, USA) connected to an ion analyzer (Orion EA-740, Thermo Scientific Inc., Waltham, USA) and a fluoride-specific ion analyser (Orion Model 96–09, Orion Research, Cambridge, MA, USA) connected to the ion analyzer.

The samples were buffered with the same volume of total ionisation buffer II (TISAB II) (1:1) and the calibration was carried out with standard solutions at fluoride concentrations of 0.25 to 2.00 ppm F and 50 per cent TISAB II. Millivoltage potentials (mV) have been converted into mg per L by linear regression using standard curves with $r2 > 0.99$ correlation coefficients. The measured microvoltage values, in triplicate for each standard, were converted into Fluoride (mg/F and L) concentration values in Windows Excel and recorded.

The data were tabulated in the light of the Brazilian Regulation No 518 of 2004, using calculated mean and standard deviations and analyzed from the point of view of descriptive statistics. The data have been classified in accordance with the Technical Consensus Paper on the classification of public water supplies by fluoride content. published by the Collaborative Centre of the Ministry of Health in the field of oral health surveillance[19]. On this basis, samples are classified as suitable when fluoride concentrations are within the prescribed range of 0.55 to 0.84 ppmF, which is most likely to be beneficial in preventing caries and in preventing dental fluorosis.

Results

Residual fluoride levels were observed at all sites, ranging from 0.04 ± 0.00 mgF/L at the São Geraldo to 6.56 ± 2.81 mgF/L at the Monteiro (Table 2).

According to the CECOL criterion, fluoride concentrations were within the MRLs (0.55 to 0.84 ppmF) in 25.0 percent of samples, while 33.3 percent were above the MRLs.

On the basis of the data in Tables 1 and 2, the map in Fig. 3 was drawn up showing the sampling points for the well water throughout the whole of the municipality of Poço de José de Moura. The concentrations of fluoride found are represented by red circles. Spatialization of fluorine in groundwater showed a saturation in

	Rural áreas	Latitude and Longitude
1	Torrões	6°35′49"S 38°28′42"W
2	Pau D´arco	6°35′42"S 38°30′35"W
3	Lagoa Vermelha	6°38′15"S 38°29′33"W
4	Nambi	6°34′49"S 38°30′13"W
5	Outro Lado	6°34′15"S 38°31′06"W
6	Silva	6°32′51"S 38°31′05"W
7	Pedro da Costa	6°34′23"S 38°30′49"W
8	Cambito	6°36′59"S 38°31′20"W
9	Jenipapeiro	6°35′58"S 38°33′56"W
10	São Geraldo	6°34′31"S 38°30′23"W
11	Carretão	6°36′39"S 38°30′09"W
12	Altamira	6°34′14"S 38°31′29"W
13	São Francisco	6°33′25"S 38°30′01"W
14	Carnaubinha	6°34′35"S 38°30′42"W
15	Barreiros	6°33′57"S 38°31′51"W
16	Vaquejador	6°39′19"S 38°28′49"W
17	Monteiro	6°34′32"S 38°30′41"W
18	Alto dos Seixos	6°39′41"S 38°29′23"W
19	Cabaços	6°35′10"S 38°26′53"W
20	Bezerro Amarrado	6°38′18"S 38°29′41"W
21	Caiçara	6°34′28"S 38°30′40"W
22	Recanto de Caiçara	6°36′06"S 38°29′28"W
23	Casas Velhas	6°34′41"S 38°30′53"W
24	Alto dos Gomes	6°34′24"S 38°27′19"W

Table 1. Sample location and geographic coordinates of rural areas of Poço de José de Moura, Brazil.

the sedimentary rocks, with enrichment in the northern part of the municipality, near the crystalline basement (Fig. 2) and the town center of the municipality.

Discussion

This study represents the first known attempt to evaluate residual fluoride levels in groundwater and their potential implications for rural populations in the municipality of Poço de José de Moura, Brazil. The findings revealed a wide range of fluoride concentrations, with several sites surpassing the World Health Organization's recommended threshold of 1.5 mg/L for drinking water. These results underscore the potential risk of chronic fluoride exposure in vulnerable groups such as children.

Longitudinal variations in fluoride concentrations were not evaluated. Although seasonal fluctuations may influence fluoride levels, often increasing with water consumption in warmer months[20], previous studies conducted in the semi-arid region of Paraíba indicated that such variations are generally minimal[21,22].

Elevated fluoride levels in groundwater are a widespread concern, particularly in arid and semi-arid regions worldwide. More than 200 million people are estimated to be affected globally, with high-risk areas documented in Asia, Africa, and Latin America[7,22–27]. Consistent with these global patterns, prior studies in the Brazilian semi-arid region, such as those in Catolé do Rocha[28] and São João do Rio do Peixe[29], also identified fluoride concentrations well above safe limits.

In the present study, samples from Pedro da Costa, Barreiros, and Monteiro showed particularly high fluoride concentrations, classifying these locations as fluorosis-prone areas. This aligns with findings from other Brazilian communities where water contributed up to 62% of total fluoride intake in children[30]. Similar risks have been observed in rural China[14], India[31], and Tunisia[32], reinforcing the need for local health surveillance in fluoride-endemic regions.

The presence of fluoride in groundwater is closely linked to geological features, particularly the mineralogical composition of aquifer-bearing formations. In this study area, most wells are located within the Rio do Peixe Sedimentary Basin, particularly in the Antenor Navarro and Sousa Formations. These formations contain rock types, such as sandstones, claystones, and carbonates, that are known to host fluoride-bearing minerals[14,18,33–35].

Fluoride in these rocks is primarily associated with clay minerals and micas, which can undergo weathering and release fluoride into groundwater. The Jaguaretama Complex, located in the northern portion of the municipality, includes metamorphic rocks such as biotite-bearing orthogneisses and amphibolites, which also contribute to the geogenic fluoride load in groundwater (CPRM[18]).

In addition to lithological factors, climatic and hydrochemical conditions also play a significant role. The semi-arid climate promotes evaporation, which enhances mineral dissolution and leads to the precipitation of calcium as $CaCO_3$, thereby decreasing calcium availability. This, in turn, reduces the formation of CaF_2 (fluorite), increasing fluoride concentration in solution[14,36].

	Rural area	Concentration of F (mg/L)	± dp
1	Torrões	0.83	0.02
2	Pau D´arco	0.29	0.01
3	Lagoa Vermelha	**1.49**	0.09
4	Nambi	0.15	0.00
5	Outro Lado	0.15	0.01
6	Silva	0.24	0.00
7	Pedro da Costa	**3.92**	0.90
8	Cambito	**1.46**	0.01
9	Jenipapeiro	0.25	0.00
10	São Geraldo	0.04	0.00
11	Carretão	0.80	0.04
12	Altamira	0.63	0.02
13	São Francisco	0.19	0.00
14	Carnaubinha	0.59	0.03
15	Barreiros	**4.18**	1.21
16	Vaquejador	0.80	0.02
17	Monteiro	**6.56**	2.81
18	Alto dos Seixos	0.46	0.03
19	Cabaços	**1.14**	0.03
20	Bezerro Amarrado	0.13	0.01
21	Caiçara	0.85	0.03
22	Recanto de Caiçara	**1.49**	0.16
23	Casas Velhas	0.22	0.01
24	Alto dos Gomes	0.21	0.01

Table 2. Distribution of collection points according to population estimate and residual fluoride concentration. Poço de José de Moura-PB, Brazil. Significant values are in bold.

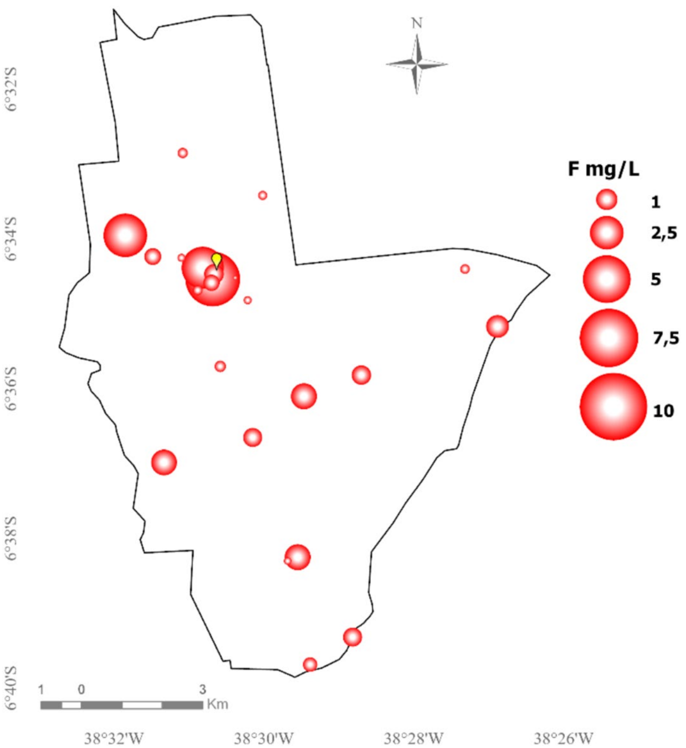

Fig. 3. Location of the sampling points with the respective fluoride concentrations in the water. The highest concentrations are close to the urban center. Figure 2 also shows the crystalline basement region to the north of the municipality, which contains rocks where higher levels of fluoride in minerals and rocks are expected.

Furthermore, the region's groundwater is characterized by a low Ca/Na ratio and high pH, both of which promote fluoride mobility. High pH conditions diminish fluoride adsorption onto mineral surfaces, while elevated bicarbonate and sodium levels enhance desorption of fluoride ions through hydroxyl exchange reactions[13,15].

Despite the geological and climatic plausibility of fluoride enrichment in groundwater, this study did not include essential water chemistry parameters such as pH, electrical conductivity (EC), or major ions (e.g., Ca^{2+}, Na^{+}, HCO_3^{-}). The absence of these measurements limits the ability to confirm hydrogeochemical mechanisms or perform multivariate analyses to establish causal relationships. These represent critical gaps and should be addressed in future investigations.

Additionally, the study did not assess human health risks using metrics such as Estimated Daily Intake (EDI) or Hazard Quotient (HQ), which are standard tools in fluoride risk analysis. Incorporating these assessments would allow for a more complete understanding of the potential impact on local populations, particularly young children who are more susceptible to dental fluorosis. Epidemiological studies are also needed to evaluate dental fluorosis and caries prevalence in the communities relying on these water sources.

While fluoride plays a critical role in preventing dental caries, excessive exposure can lead to adverse health effects, particularly during early childhood development[37]. Therefore, public health strategies in fluoride-endemic areas must balance caries prevention with fluorosis mitigation through regular monitoring, public awareness, and potential de fluoridation interventions.

Access to clean and safe water is a fundamental determinant of health[38]. Municipal authorities should prioritize water quality monitoring, especially in rural and vulnerable areas, and ensure that oral health professionals are informed about the risks posed by naturally occurring fluoride. Evidence-based actions are needed to guide community-level decision-making regarding water use, dental care practices, and preventive interventions.

Conclusions

Residual fluoride was detected in all groundwater samples analyzed in this study, with several sites exceeding the WHO guideline of 1.5 mg/L. These elevated concentrations, particularly in specific rural locations, pose a potential risk of dental fluorosis in children. The geological formations present in the study area, including fluoride-bearing sedimentary and metamorphic rocks, may contribute to natural fluoride enrichment in groundwater. Regular monitoring, community awareness, and preventive interventions are essential to ensure safe drinking water and reduce fluoride-related health risks in vulnerable semi-arid regions.

Data availability

The geographical coordinates (latitude and longitude) of each sampling site (Table 1) were obtained from Google Maps at the time of data collection. The water samples (Table 2) have been classified in accordance with the Technical Consensus Paper on the classification of public water supplies by fluoride content [5]. All raw data must be in the possession of the corresponding author and made available on reasonable request. Requests for information should be sent to Marcos Oliveira at marcosalexandrec@gmail.com.

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Author contributions

MO, CD, CL and FS wrote the main text. MO collected the water samples. MO, AAJ, and IS analyzed the water samples. MD and RS prepared all the figures for the article, and all authors reviewed the manuscript.

Declarations

Competing interests

The authors declare no competing interests.

Additional information

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