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Fluoride concentration in groundwater and relationship with the sodium (Na+), potassium (K+), (Ca_2+) and magnesium (Mg_2+)

Fluoride concentration in groundwater

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Abstract

Groundwater is the largest freshwater reserve on the planet, and its quality plays a fundamental role in human well-being and economic development. However, it sometimes contains potentially harmful compounds, such as fluoride in high concentrations, which has led to the implementation of quality standards to ensure

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water potability. This study evaluates the concentrations of fluoride in groundwater from the state of Paraguarí, Paraguay, and studies the joint occurrence of fluoride with elements such as calcium, magnesium, sodium, and potassium. Forty-one water samples were collected from boreholes at different locations in the state of Paraguarí. The results showed that 7% of the samples exceeded the maximum concentration limit allowed by the Paraguayan Standard and the World Health Organization, this means concentrations were above 2 mg/L; this was observed mainly in the district of Caapucú. These findings indicate that 93% of the wells meet potability standards. Additionally, fluoride was found to correlate with the sodium content in groundwater. The results suggest the need for continuous monitoring and implementation of effective fluoride reduction technologies, especially in areas with elevated concentrations.

Keywords: Groundwater, Fluoride, Spatial distribution,

1.Introduction

Groundwater is an essential resource for socioeconomic progress, providing approximately 50% of the world's drinking water and accounting for 98% of the unfrozen freshwater [1]. Despite its importance, its quality can be compromised by the presence of naturally occurring inorganic compounds, which, depending on the geomorphology of the region, can be potentially harmful for human consumption [2-3-4].

Fluoride is one of the most common natural contaminants in drinking water. In low concentrations, this ion is frequently added to drinking water to prevent dental

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caries, but in high concentrations, it can cause dental and skeletal fluorosis, affecting public health [5-6-7].

In 1981, it was discovered that fluoride forms very strong hydrogen bonds with amide functional groups in proteins [8]. Proteins are long-chain peptide polymers and their macromolecular structure is governed by hydrogen bonds formed between the N-H group of one amide fragment and the carbonyl group of another fragment on a parallel chain. So these amide hydrogen bonds are responsible for protein folding; when fluoride interferes with these hydrogen bonds, i.e. breaks them down, the characteristic protein configuration is altered and some specific protein properties might be lost. For instance, enzymes with a distorted spatial structure are sometimes considered as deactivated enzymes.

The double-stranded structure of the DNA is also stabilized hydrogen bonds involving amide groups. Any disruption of the hydrogen bonding of DNA by fluoride would certainly cause damage to the cell.

The effects of fluoride on the nervous system and endocrine glands of mammals, including the pineal gland have been extensively studied [9-10]. Concerns have risen that fluoride exposure leads to neuronal damage, such as Parkinson’s disease, Alzheimer’s disease, and a reduced intelligence quotient. Several studies have shown that fluoride exposure leads to oxidative stress and lipid peroxidation in the brain. Moreover, the production of enzymes responsible for the production of energy in mitochondria can be inhibited. As a consequence, memory, and learning ability in animals and humans have been observed to be negatively affected [9-10-11-12-13-14-15-16-17].

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Fluoride occurs naturally in air, soil, water, and plants. The fluoride concentration in groundwater depends on geological and climatic factors, such as the presence of minerals like fluorspar, cryolite, micas, and clay minerals [3-18-19-20].

In addition, its relationship with other elements such as calcium, magnesium, sodium, and potassium is crucial to understanding its dynamics. It has been shown that high fluoride concentrations often correlate with high sodium and low calcium levels, while the presence of calcium and magnesium can mitigate the toxic effects of fluoride [21-22].

In the state of Paraguarí, Paraguay, access to groundwater is vital for rural communities. However, until now there are no systematic studies that evaluate fluoride concentrations in this region, which raises health concerns, given that some areas of the country are known for elevated concentrations of this ion in groundwater [23-24-25]. This knowledge gap needs to be targeted through research that identifies fluoride levels and their potential risks to the population.

The World Health Organization (WHO) establishes a recommended maximum limit of 1.50 mg/L for fluoride in drinking water, a value also adopted by the Paraguayan Water Quality Standard NP 24 001 80. Several studies have shown that the presence of fluoride in concentrations above this limit is associated with the occurrence of fluorosis and other health problems, especially in mountainous and arid regions, where water mineralization is more significant [4-26-27-28].

In this scenario, the present study focuses on the state of Paraguarí, where, although symptoms of fluorosis have been observed in some areas, standardized studies on groundwater quality have not yet been carried out. Consequently, this

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research aims to evaluate the fluoride concentrations in different groundwater samples of this region. In addition, we try to correlate fluoride concentrations with the presence of other ions such as calcium, magnesium, sodium, and potassium.

2. Methodology

2.1 Geographic location of the state of Paraguarí

The region studied is located in the southwest of the eastern region of Paraguay (Fig 1), limited to the state of Paraguarí. This state is geographically surrounded in the north by the states of Cordillera and Caaguazú, in the south by the state of Misiones, in the east by the states of Guairá and Caazapá, and in the west by the states of Central and Ñeembucú. Paraguarí has a total area of 8,705 km² and a population of 8,719 inhabitants. The region's climate is moderate-humid, with all-year-round rainfall and hot summers. The average annual temperature and rainfall are 22.2 °C and 1,384 mm, respectively. The rainiest periods are March-April and October-November.

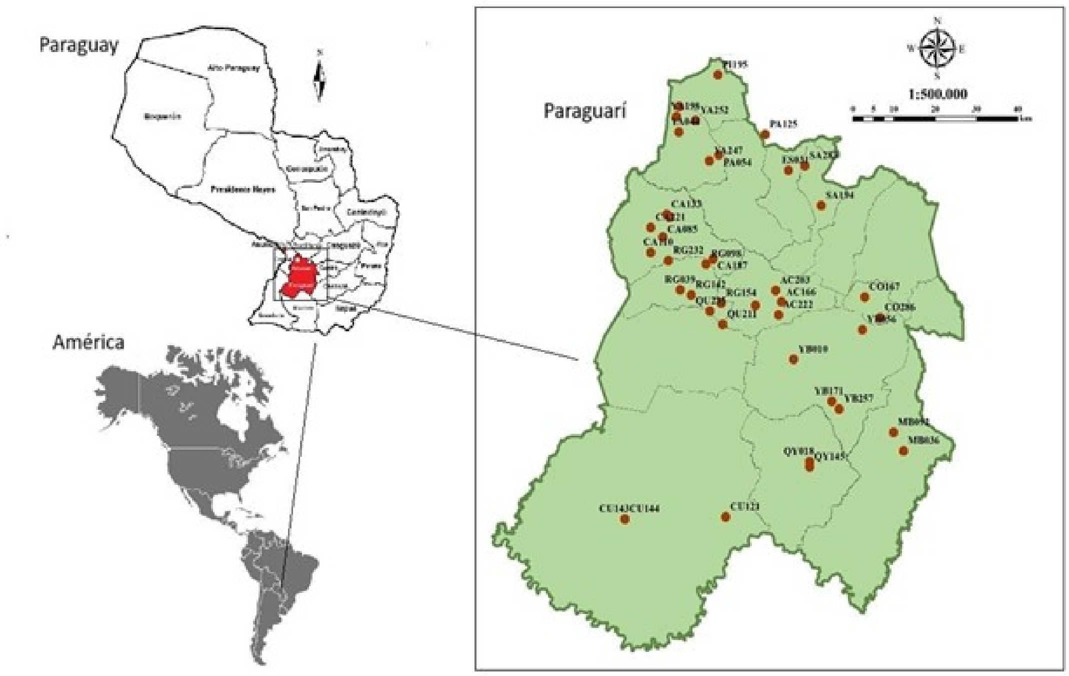

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Fig 1. Location of the sampling points in the state of Paraguarí.

2.2 Sampling and parameters

The study included 41 wells officially enabled and in use for consumption, according to SENASA records, distributed in the Department of Paraguarí, in addition to the criteria, according to recommendations from experts from the Paraguayan Network of Studies of Fluoride Exposure and the Treatment of Fluorosis. of CEMIT, include wells with a minimum depth of 100 m [29] and wells that are in areas with people diagnosed with dental or bone fluorosis. The 41 sampled points were as detailed in the following table (Table 1).

Table 1. Sampling points for each district in the state of Paraguarí.

District	Number of sampling points	Codification
Acahay	4	AC
Caapucu	3	Cu
Carapegua	6	CA
Escobar	1	ES
La Colmena	2	CO
Mbuyapey	2	MB
Paraguarí	2	PA
Pirayu	2	PI
Quiindy	2	QU
Quyquyho	2	QY
San R. González	5	RG
Sapucai	2	SA
Yaguarón	4	YA
Ybycui	4	YB
Total	**41**	

All wells were deeper than 100m. Samples for fluoride determination were stored in 100 mL sterile polyethylene bottles, while those used for the analysis of the other ions were stored in 1L bottles. All bottles were previously washed with a 10% HNO3 (nitric acid) solution, following the laboratory's quality and biosafety protocols.

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The samples were sealed and properly stored before transport. All analyses were carried out at the Water Quality Laboratory of the Multidisciplinary Center for Technological Research.

The fluoride concentration in the groundwater samples was determined potentiometrically utilizing an ion-selective electrode, as indicated in the Standard Methods for the Examination of Water and Wastewater (SM-4500-F-C). An OAKTON ION 6+ potentiometer, previously calibrated, was employed. For samples with significant fluoride content, the elements calcium (Ca2+) and magnesium (Mg2+) were determined by EDTA titration (SM-3500-Ca B y SM-3500-Mg B, respectively), while sodium (Na+) and potassium (K+) concentrations were quantified by atomic absorption spectroscopy using an air-acetylene flame (SM-3111 B). A Schimadzu, AA-7000 (APHA-AWWA-WEF, 2017) unit was used.

2.3 Statistical analysis

The obtained fluoride concentrations were compared with the maximum permitted levels established by the Paraguayan Drinking Water Standard (NP 24 001 80). To evaluate a possible correlation between fluoride concentration and the concentrations of calcium, magnesium, sodium, and potassium, the Pearson correlation coefficient (r) was calculated using IBM SPSS Statistics software. Then, the spatial distribution of fluoride was determined using the Kriging geostatistical interpolation technique, implemented in ArcGIS 10.1. software.

3. Results and discussion

3.1 Evaluation of fluoride concentrations at different points

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Fluoride concentrations recorded in the groundwater samples ranged from 0.01 to 3.30 mg/L (Table 2). Most of the samples presented low fluoride concentrations, except Yere and Montiel Potrero, belonging to the Caapucú district. The pH values ranged between 5.26 and 7.29. García et al. (2023) [4] mention that an alkaline environment (7.6-8.6) with high bicarbonate concentration favors fluoride dissolution in groundwater. In contrast, Gutiérrez and Alarcón-Herrera (2021) [30] noted that at lower pH, fluoride speciation tends to show a higher proportion of F complex ions.

The World Health Organization states that dental fluorosis occurs more likely when fluoride concentrations in drinking water exceed 1.5 mg/L, while skeletal fluorosis tends to manifest at concentrations higher than 3 mg/L. Both conditions result from chronic exposure to elevated levels of fluoride.

Table 2. Fluoride concentrations and recorded parameters.

Nº	District	Code Well	Prof. (m)	F mg/L-1	pH	Cond ms/cm
1	Acahay	AC114	160	0.01	6.14	42.3
2	Acahay	AC166	120	0.00	5.26	51.1
3	Acahay	AC203	100	0.01	5.8	9.92
4	Acahay	AC222	150	0.01	6.39	78.4
5	Caapucu	CU121	102	3.20	6.74	331
6	Caapucu	CU143	126	3.30	7.29	594
7	Caapucu	CU144	121	2.50	6.03	43.7
8	Carapegua	CA085	132	0.00	6.18	30.3
9	Carapegua	CA110	126	0.02	5.67	41.7
10	Carapegua	CA133	150	0.01	5.97	34.7
11	Carapegua	CA187	122	0.01	5.79	47.7
12	Carapegua	CA191	150	0.01	7.28	436
13	Carapegua	CA221	120	0.14	6.9	183.9
14	Escobar	ES031	152	0.00	5.64	48.2
15	La Colmena	CO167	150	0.01	6.18	131.6
16	La Colmena	CO286	104	0.04	6.2	52.6
17	Mbuyapey	MB036	124	0.00	5.82	46.7
18	Mbuyapey	MB092	150	0.01	5.85	49.5
19	Paraguari	PA054	150	0.01	6	37.8

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20	Paraguari	PA125	108	0.02	6.84	198.3
21	Pirayu	PI195	104	0.00	5.79	9.88
22	Pirayu	PI253	120	0.00	6.09	7.69
23	Quiindy	QU211	150	0.00	5.83	51.1
24	Quiindy	QU235	117	0.00	5.78	81.5
25	Quyquyho	QY018	153	0.18	5.7	10.17
26	Quyquyho	QY145	112	0.52	5.85	9.42
27	San R. Gonzalez	RG039	105	0.00	6.19	111.6
28	San R. Gonzalez	RG098	110	0.04	5.87	29.6
29	San R. Gonzalez	RG142	105	0.00	6.14	36.7
30	San R. Gonzalez	RG154	105	0.00	6.81	62.9
31	San R. Gonzalez	RG232	150	0.68	6.4	35.3
32	Sapucai	SA194	132	0.00	6.83	154.3
33	Sapucai	SA283	169.5	0.01	5.84	43.6
34	Yaguaron	YA044	105	0.00	5.78	134.7
35	Yaguaron	YA198	138	0.01	5.89	64.4
36	Yaguaron	YA247	120	0.00	6.52	163.3
37	Yaguaron	YA252	146	0.00	5.68	53.4
38	Ybycui	YB010	105	0.00	6.02	117.1
39	Ybycui	YB056	100	0.01	6.01	31.2
40	Ybycui	YB171	125	0.00	5.89	43
41	Ybycui	YB257	121	0.00	5.48	53.6

Considering the maximum allowable concentration of fluoride (1.5 mg/L) according to the Paraguayan Drinking Water Standard (NP 24 001 80), 93% of the sampled wells (38 samples) meet national and international standards. However, 7% of the samples (3 wells) exceed this limit, with concentrations higher than 2 mg/L. Figure 2 shows the fluoride concentrations obtained, where wells CU121, CU143 and CU144 stand out, which greatly exceeded the permitted limit. Well CU143 recorded the highest concentration, with 3.30 mg/L.

These results are consistent with those obtained by the Ministry of Environment and Sustainable Development [6] (MADES, 2012) in the region "Cuenca Hídrica del arroyo San Lorenzo", where 95.38% of the samples presented concentrations between 0 and 0.5 mg/L. Similarly, Diez Pérez et al. (2019) [26]

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reported that 8% of the samples in the district of Loreto, Department of Concepción, exceeded the allowable limit. However, the results differ from those reported by DIGESA in Borja [25], located in the state of Guairá, where fluoride concentrations ranged from 0 to 21.8 mg/L, significantly exceeding the concentrations observed in this study. It is important to note that these results coincide with the observations of Núñez (2018) [25], who noted the presence of natural fluoride concentrations equal to or higher than 1.5 mg/L in the departments of Alto Paraná, Concepción, San Pedro, and Paraguarí.

Rehman et al. (2022) [7] suggest that elevated fluoride concentrations may be associated with the presence of minerals such as clay, mica, dolomite, and limestone, hydrogeological features also observed in the region of this study.

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Fig 2. Fluoride concentrations registered according to the Paraguayan Standard NP 24 001 80.

3.2 Description of the spatial fluoride distribution

Figure 3 shows the spatial distribution of fluoride in the state of Paraguarí estimated by the Kriging interpolation method. The areas with the lowest concentration are located in the northeast, while the highest concentrations are found in the southwest, suggesting a relatively uniform distribution over much of the area. The areas represented in light and dark blue tones correspond to areas with low fluoride concentrations, within the permitted limits. In contrast, the dark blue areas indicate concentrations that exceed the maximum allowable limit. These results are consistent with those reported by the Ministry of Environment and Sustainable Development (MADES, 2012) [6], which observed a uniform distribution of fluoride in the "Cuenca Hídrica del Arroyo San Lorenzo", without the presence of elevated concentrations. Similarly, Durán et al. (2017) [31] documented a heterogeneous geographic distribution of fluorides in the province of Tucumán, Argentina, differentiating between areas with deficit, excess, and concentrations within the recommended values.

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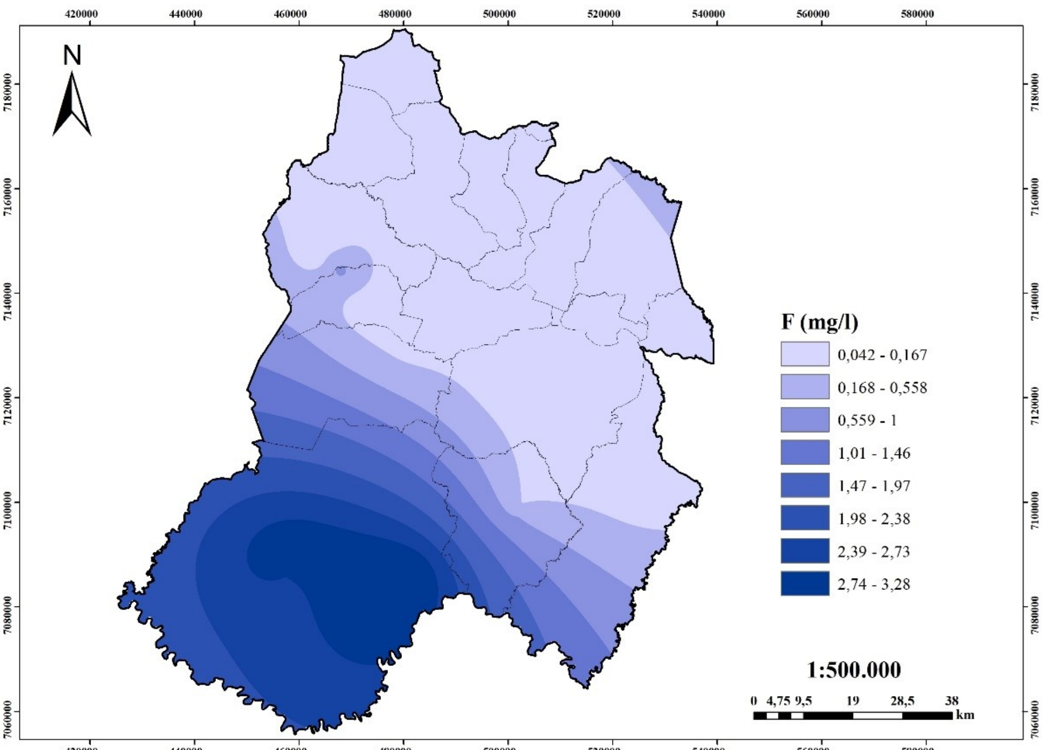

Fig 3. Spatial distribution of fluoride Department of Paraguarí.

3.3 Correlation of fluoride with calcium, magnesium, sodium, and potassium.

Figures 4 and 5 show graphically possible correlations between fluoride and other compounds (Ca, Mg, K, Na) in the groundwater. Only samples with significant fluoride concentration were considered (5 wells). Numerical values of the measured concentrations are given in Table 3.

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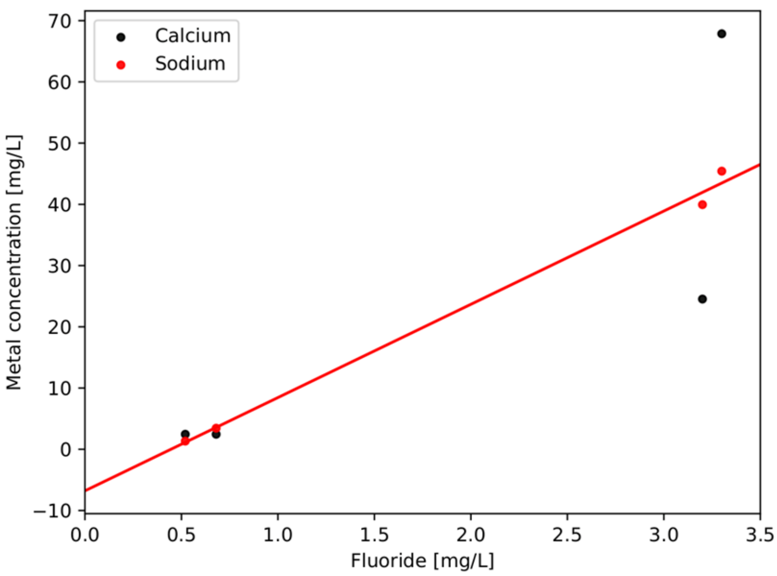

Fig 4. Graphical detection of correlations between fluoride and sodium or fluoride and calcium. The red line is a linear fit of the sodium concentration versus fluoride concentration.

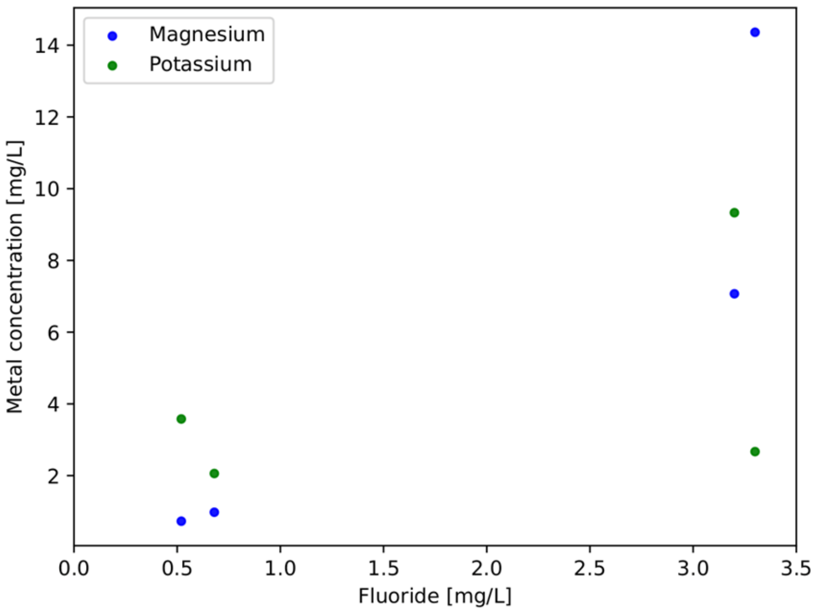

Fig 5. Graphical detection of correlations between fluoride and magnesium or fluoride and potassium.

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As can be seen from these figures, only sodium exists in a linear concentration dependence on the fluoride concentration. The red line in Figure 4 is a linear fit of these concentration data with the slope of 15,23 mg sodium / 1 mg fluoride. This can be expressed as millimol Na per millimol F-, dividing the mass values by the corresponding atomic masses, i.e., 15.24 mg / 22.99 g/mol = 0.66 mmol, and 1 mg /9.499 g/mol = 0.11 mmol. This means that for every fluoride anion in solution, there are 6 sodium cations present (0.66/0.11 = 6).

These results are comparable with the findings of Rehman et al. (2022) [7], who reported a moderate correlation between fluoride and Mg^{2+}, Ca^{2+}, and K^{+}. Podgorski and Berg (2022) [21] suggest that increased fluoride along with high Ca^{2+} and Mg^{2+} concentrations are likely related to evaporative conditions and increased salinity, reflected in parameters such as electrical conductivity (EC), total dissolved solids (TDS), and elevated Na^{+} and Cl- levels. Huepallara et al. (2021) [29] also observed a strong positive correlation between sodium and fluoride (r = 0.985). Kashyap et al. (2021) [20] mention that several studies have reported a strong positive correlation between F- and Na^{+} and K^{+}, whereas a negative correlation between F- and Ca^{2+} and Mg^{2+} ions has been documented.

However, the dissolution of fluoride-containing minerals should generate a positive correlation with Ca^{2+} and Mg^{2+}. This could be explained by the reverse ion exchange process, where Na^{+} present in an aquifer mineral is exchanged for Ca^{2+} and Mg^{2+} cations in groundwater. Ali et al. (2016) [22] studied global al water contamination by fluoride, multiple investigations are cited that evidence the correlation of fluoride with various ions. Jabal et al. (2014) and Rao (2009) [32-33]

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reported a positive correlation between F- and Na^{+}, Ca^{2+} , and Mg^{2+}, while studies by Liu et al. (2015) [34] documented negative correlations with Ca^{2+}, Mg^{2+} , and K^{+}.

Table 3. Cation values in wells with high, medium and low fluoride concentrations.

Code Well	F mg/L-1	Ca+2	Mg+2	Na+	K+
CU143	3.30	67.86	14.362	45.42	2.67
CU121	3.20	24.53	7.070	39.95	9.33
RG232	0.68	2.45	0.976	3.44	3.06
QY145	0.52	2.45	0.731	1.33	3.58
MB036	0.00	2.45	0.976	1.79	2.76
PI253	0.00	1.64	0.732	0.74	1.25

Table 4. Pearson correlation.

	F-	**Ca+2**	**Mg+2**	**Na+2**	**K+**
Coefficiet e correlation	1	.854*	.905*	.987**	.609
Sig. (bilateral)		0.030	0.013	0.000	0.199
N	6	6	6	6	6

*. The correlation is significant at the 0.05 level (two-sided)
**. The correlation is significant at the 0.01 level (two-sided)

4. Conclusions

This work emphasizes the importance of future studies to evaluate the dynamics of other related elements. This work emphasizes the importance of future studies to evaluate the dynamics of other related elements, such as calcium, magnesium, sodium, and potassium, which could be influencing the distribution and concentration of fluoride in the region.

This study on fluoride concentration in groundwater in the state of Paraguarí reveals that most of the analyzed samples present fluoride levels within the limits

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allowed by Paraguayan and WHO regulations. However, a small percentage of wells, mainly in the district of Caapucú, exceed these limits, posing a potential risk to public health, particularly concerning dental and skeletal fluorosis. Therefore, it is suggested that specific monitoring and treatment strategies, such as the application of efficient technologies for fluoride reduction in affected water sources, should be implemented to ensure the sustainability of drinking water sources and protect the health of local communities

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