Emerging Risks for Children: Chemical Speciation of Metals in Urban Soils as an Environmental Diagnostic Tool

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Abstract
Children and the elderly are the most vulnerable to health problems, due to possible direct contact with contaminated soil and the inhalation of exhaust fumes. Also, quantifying chemical species of metals in soil is essential for estimating the bioavailability of the metals in the environment. The "Capibaribe Melhor" Project launched by the City Hall of Recife – PE – Brazil includes two large parks, Santana and Caiara. The Project involves environmental education actions, construction of a pier, and squares, with the aim of revamping the Capibaribe River, the city's main body of water, drawing the attention of the local population to the need to preserve the Capibaribe River and, at the same time, offering areas for entertainment and recreation. Parks usually attract the neighboring inhabitants, but their soils contain varying amounts of toxic trace metals such as As, Cd, Cu, Cr, Fe, Hg, Pb, Ni, Sn, Zn, Mn, Si, Pb and Sc, mainly because of atmospheric pollution from vehicles' exhausting pipes. This study aims to determine the metal distribution in geochemical phases of soil in parks and presents the total concentrations of chemical elements in soils collected in parks, obtained by Energy Dispersion X-Ray Fluorescence (EDXRF). The more toxics metals found in this study were: Al, Zn, Cu, and Pb, while the major chemical elements analyzed were Fe, K, Ca, and Si. Sequential extraction showed the presence of major metals (Mn and Fe) and minor ones (Zn and Cu), mainly in the oxidizable phase followed by the leachable or pseudo-residual phase. Only Mn is also highlighted in the leachable fraction. The results emphasize the importance of determining the chemical form of heavy metals in soil in parks to assess the availability and long-term environmental consequences of soil contamination and the effects of these new chemical pollutants that cause so-called noncommunicable diseases (NCDs).

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INTRODUCTION

Soil contamination by hazardous chemical elements constitutes a significant contemporary environmental problem, since surface runoff can transport these contaminants to water resources and food grown in agricultural areas, posing risks to human health. The main sources include industrial waste, pesticides, chemical fertilizers (Alamgir *et al.*, 2015; Souza *et al.*, 2022) and air pollution from vehicle emissions. Although some trace metals are essential for the development of organic structures and the assimilation of nutrients, high concentrations become toxic, motivating authorities to monitor their levels in public areas as a basis for remediation and requalification actions, such as in Caiara and Santana parks.

In the middle to low-income countries, the prevention of environmental pollution has been recognized as a strategy to improve child health and reduce the burden of non-communicable chronic diseases (NCDs), and its integration into disease control programs is recommended. The main routes of exposure to chemical contaminants are oral > dermal > inhalation, with children showing greater vulnerability compared to adults (Liang *et al.*, 2021).

In 2016, chemical pollution of air, water, and soil was responsible for approximately 940.000 deaths worldwide, two-thirds of which were in children under five years of age, mainly due to respiratory and gastrointestinal diseases, according to the Lancet Commission on Pollution and Health. In addition, pollution is associated with an increase in NCDs, such as asthma, cancer, low birth weight, and neurodevelopmental disorders. However, the real impact of chemical pollution on the global burden of pediatric diseases remains underestimated due to the limited characterization of exposure patterns and the toxicity of many contaminants (Fabiańska *et al.*, 2019).

The accumulation of metals in the soil occurs according to the following mechanisms: a) adsorption onto fine particles; b) precipitation as mineral compounds; c) co-precipitation with iron and manganese oxides; d) complexation with organic matter and incorporation into primary minerals (Sharamel, 2000; Lima *et al.*, 2014). In this context, the fractionation method proposed by Tessier *et al.*, (1979) has become widely used to assess the geochemical distribution of these elements.

The quantification of the chemical species of metals is essential to estimate their environmental bioavailability, since analysis based only on total concentration ignores significant differences between chemical forms and their ecological impacts. Speciation studies are therefore fundamental, as changes in environmental conditions (as pH and organic matter content), can modify the mobility and toxicity of metals to plants and animals (Ting *et al.*, 2021). Thus, this study aims to determine the concentrations of chemical elements in children's areas of the analyzed parks and investigate their bioavailability.

METHODS

Area´s Characterization

The parks studied are in Brazil, in the state of Pernambuco, in the city of Recife. Santana Park (Figure 1) was built in 1985, with an original area of 26,000 m², it has been extended to 63,000 m² and caters for about 70,000 inhabitants, mostly from high income neighbourhoods. The park's design forecasts the creation of an area where environmental education will be the focus, with the idea of establishing the park as a public space for contemplation and recreational and cultural leisure will also benefit part of Recife's West Side by renovating the Caiara Park (Figure 2).

This, last park, is in the Iputinga neighbourhood, populated mainly by lower-middle-class families, and has been renovated to provide the inhabitants in the vicinity, with a recreation area, to improve the quality of life of some 115,000 people. As expected, its inhabitants are keen on preserving their environment, and they welcomed the new park, as a place where children can play, and the elderly may exercise conveniently.

Figure 1 – Santana Park

Source: The authors (2024).

Figure 2 – Caiara Park

Source: The authors (2024).

The geomorphology of Recife, where Santana Park and Caiara Park are located, is that of a coastal/alluvial plain with predominantly flat relief, close to sea level, influenced by the Capibaribe River and its tributaries such as the Cavouco Stream. The Cavouco Stream and the surrounding area of Caiara Park have historically suffered from water contamination, mainly due to the discharge of clandestine domestic sewage. The lack of a comprehensive basic sanitation system in the region contributes to the water quality being classified as poor. Park users also report the presence of unpleasant odors in some areas. A notable revitalization initiative was the installation of a filtering garden system. This system uses plants that, together with the soil and microorganisms, help remove pollutants from the stream water. The region also suffers from the presence of garbage and the large number of irregular settlements in the area.

The same occurs in Santana Park, where the main environmental pollution problem near the park is the pollution of the adjacent Capibaribe River, mainly due to the lack of adequate sanitation and the irregular disposal of waste. The improper disposal of garbage and debris on public roads or in the river has been a problem in the area and in other regions of Recife. To combat this, an Eco-station was inaugurated near the parks, allowing for the correct disposal of furniture, electronic waste, construction debris, and recyclable materials.

Sample Collection

Soil samples were collected totalization 16 samples in Caiara Park and 20 samples around Santana Park in four different points in each park, with a plastic spoon, according to Tables 1 and 2 and Figure 3. The samples were dried, crushed in a mortar, sieved in thin series of sieves (63 - 500 mm/μm), and packed in plastic bottles, until the analysis that were carried out in our Laboratory on Centro Regional de Ciências Nucleares.

Table 1 - Geographical coordinate points of Santana Park

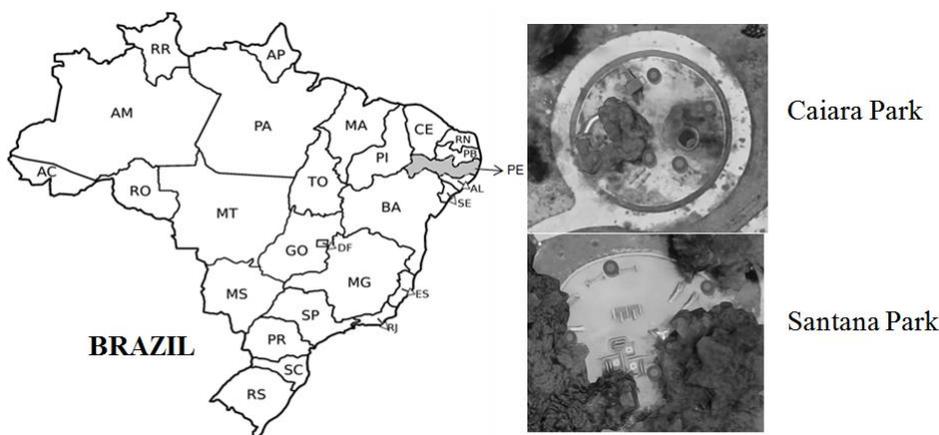| Sample Point	Latitude (S)	Longitude (W)
1	8°02'29.6"	34°55'04.4"
2	8°02'29.7"	34°55'04.1"
3	8°02'29.0"	34°55'04.1"
4	8°02'29.1"	34°55'03,6"

Source: The authors (2025).

Table 2 - Geographical coordinate points of Caiara Park

Sample Point	Latitude (S)	Longitude (W)
1	8°02'22.2"	34°55'39.8"
2	8°02'22.6"	34°55'39.7"
3	8°02'22.6"	34°55'40.0"
4	8°02'22.2"	34°55'39.9"

Source: The authors (2025).

Figure 3 - Sampling points

Source: Adapted by Google Maps (2022).

Determination of Organic Matter and Carbonate

The determination of organic matter and carbonate in the samples was carried out in an exhaust hood using H_2O_2 PA (Figure 4) and 10% hydrochloric acid, respectively.

Figure 4 - Determination of Organic Matter

Source: The authors (2024).

Determination of trace metals by EDXRF

The applicability of EDXRF (Energy dispersive X-ray fluorescence) was demonstrated for tropical soils from the State of Pernambuco, Brazil, characterizing terrigenous chemical elements, nutrients, and pollutants. It is a potential analytical technique for quantifying diverse chemical elements in geological material without chemical treatment (Fernández *et al.*, 2017).

The determination of trace metals was

performed by EDXRF that uses an X-ray beam to promote excitation of the electrons of the trace metals in the samples been the chemical elements were identified and quantified; after the EDX-720 (equipment from Shimadzu) had been calibrated from the energy and resolution calibration standards, A-750 and SUS and samples had been transferred to polyethylene capsules specific for EDXRF analysis and sealed with polypropylene films for analysis (Figure 5).

Figure 5 – Determination of trace metals by EDXRF
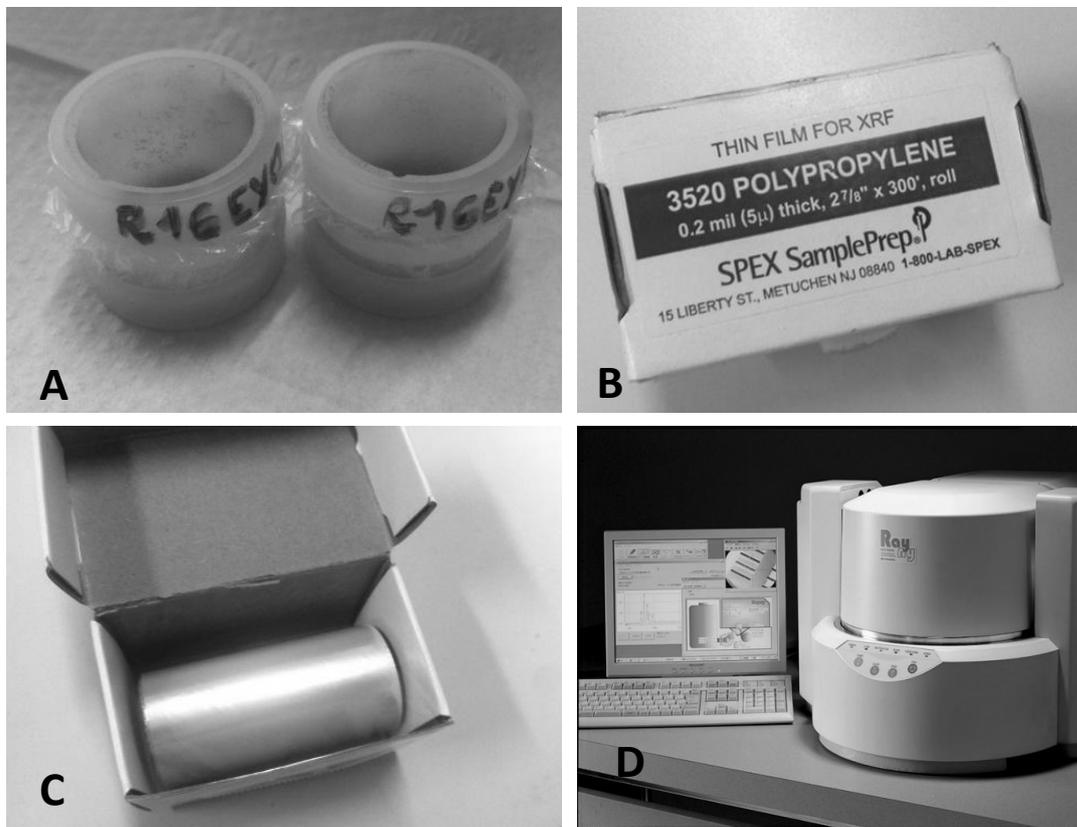
Source: The authors (2024).

The determination of trace elements in the samples was performed by from analytical curves obtained by reference materials (Fernández *et al.*, 2017). For the quality control of the analytical procedure, SRM 2711 certified reference material was analysed together with the samples (Table 3).

Table 3 - Chemical elements' concentrations observed in SRM 2711 standard

METALS	SRM 2711 mensured	SRM 2711 certificated values	En
Si	294332 ± 4	304400 ± 1900	-0,94
Al	62284 ± 5	65300 ± 900	-0,93
Fe	28088 ± 2	28900 ± 600	-0,96
K	23470 ± 3	24500 ± 800	-0,95
Ca	27618 ± 4	28800 ± 800	-0,92
Ti	3008 ± 61	3060 ± 230	-0,18
Mn	570 ± 23	638 ± 28	-0,50
Sr	261 ± 6	245,3 ± 0,7	0,87
Zn	396 ± 12	350,4 ± 4,8	0,95
Cu	121 ± 21	114 ± 2	0,26
Pb	1059 ± 15	1162 ± 31	-0,64
Ga	15 ± 14	15 ± 3	-0,04

Source: The authors (2025).

For the validation of the analytical procedure, the number En was used (Table 3). The number En allows comparing the value obtained with the certificate value, considering the expanded uncertainties of both values allowed to achieve the 95% confidence level, the appropriate range for the results. The number En should be between [-1 and 1], as recommended by ISO 13528/2005.

Determination of Bioavailability (metal distribution in the geochemical phases)

To verify the bioavailability of metals for plants and animals, were took 1g of each sample collected in both parks and it was separated for sequential extraction (Lima *et al.*, 2014, Table 4). Each of the extraction agents described in Table 4 corresponds to one of the geochemical phases, currently considered, respectively, and is responsible for mobilizing the metals present in each phase according to the following mechanisms: a) $MgCl_2$ (causes a change in salinity); b) acetic acid (causes a change in pH, carbonates); c) hydroxylamine hydrochloride (allows the release of metals linked to iron and manganese oxy-hydroxides); d) hydrogen peroxide and ammonium acetate promotes the degradation of organic matter, followed by leaching, respectively; e) aqua regia and hydrochloric acid (allows the release of metals associated with primary and secondary minerals) (Lima *et al.*, 2014).

Table 4 - Sequential extraction scheme for metal speciation used in the present study

Step	Fraction	Reagent	Shaking Time and Temperature
1	Exchangeable	20 mL of 1M $MgCl_2$	16 h at room temperature
2	leachable	20 mL of 0.11 M acetic acid	16 h at room temperature
3	Reducible	20 mL of 0.1 M hydroxylamine hydrochloride in 25% acetic acid	16 h at room temperature
4	Oxidizable	3 mL HCl and 5 mL H_2O_2 add 20 mL1 M ammonium acetate	100 °C 16 h at room temperature
5	Residual	Aqua regia 20 mL + HCl (5%)	100 °C 16 h at room temperature

Source: The authors (2025).

Figure 6 - Determination of Bioavailability

Source: The authors (2025).

After sequential extraction (Figure 6), then metal concentrations (Fe, Mn, Zn and Cu) were determined with a fast sequential atomic absorption spectrometer (VARIAN). The results present a total value ± uncertainty.

Either sequential extraction methodology used in this work was validated by using a certified reference material for sediments (Table 5).

Table 5 - Results of the certified reference material BCR-701 analysis

Elements	Cu (mg/kg)		Ni (mg/kg)	
Phase	This work	Acceptable value	This work	Acceptable value
leachable	47.8 ± 1,4	47.6 a 51	14.5 ± 3.0	14.5 a 16.3
reducible	121.4 ± 3	121 a 127	25.4 ± 3.1	25.3 a 27.9
oxidizable	52.7 ± 7.3	51.2 a 59.2	14.4 ± 3.9	14.4 a 16.2

Source: The authors (2025).

RESULTS AND DISCUSSION

Results for determination of trace metals by EDXRF

This method allows for a general overview of the chemical elements present in the samples, characterizing the local soil. Majority and minority (Figures 7 and 8) elements analysis by EDX-RF in Santana Park's soil and Caiara Park´s soil is shown. And were represented numerically in Table 6 and 7 respectively.

Table 6 - Chemical elements' concentrations, Santana Park

Metals	Mean Concentrations ± Combined Uncertainty				
	P1	P2	P3	P4	Average Value
Si	293694 ± 4	322392 ± 3	265452 ± 4	311314 ± 3	298213
Al	83857 ± 4	128952 ± 3	72787 ± 5	79459 ± 4	91264
Fe	16728 ± 3	14521 ± 4	46244 ± 1	16296 ± 3	23447
K	9512 ± 7	8699 ± 8	5464 ± 12	12596 ± 6	9068
Ti	5863 ± 5	5186 ± 5	5895 ± 5	5144 ± 5	5522
Ca	2613 ± 36	2810 ± 33	1837 ± 51	3498 ± 27	2690
Mn	175 ± 80	180 ± 75	154 ± 89	221 ± 64	183
Sr	139 ± 14	125 ± 16	125 ± 16	173 ± 12	144
Cu	56 ± 47	49 ± 52	52 ± 51	49 ± 52	52
Zn	42 ± 75	58 ± 55	43 ± 71	46 ± 68	47
Pb	37 ± 190	44 ± 161	66 ± 118	24 ± 281	42
Ga	11 ± 25	10 ± 25	12 ± 23	10 ± 23	11

Source: The authors (2025).

Figure 7 - Majority elements in Santana Park´s soil
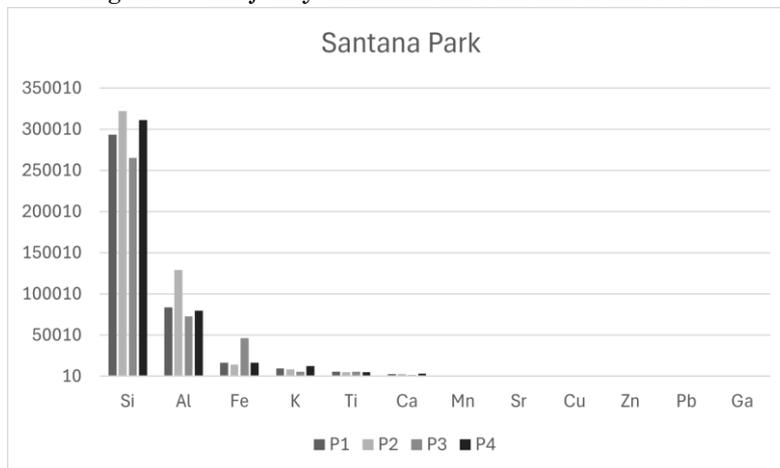
Source: The authors (2025).

Table 7 - Chemical elements' concentrations, Caiara Park

| Metals | Mean Concentrations ± Combined Uncertainty | | | | |
	P1	P2	P3	P4	Mean
Si	269041 ± 4	234258 ± 5	262133 ± 4	292141 ± 4	264393
Al	89319 ± 4	178852 ± 2	123993 ± 3	100631 ± 3	123199
Fe	30833 ± 2	48131 ± 2	31938 ± 2	21588 ± 3	33122
K	24836 ± 3	13294 ± 5	19538 ± 4	14792 ± 5	18115
Ca	11088 ± 9	6701 ± 14	10466 ± 9	5597 ± 17	8463
Ti	5372 ± 4	7638 ± 4	5895 ± 4	4315 ± 5	5805
Mn	581 ± 26	303 ± 44	398 ± 35	285 ± 45	392
Sr	259 ± 8	141 ± 12	254 ± 8	196 ± 9	213
Zn	90 ± 35	64 ± 43	91 ± 35	66 ± 44	78
Cu	53 ± 44	ND	ND	57 ± 40	55
Pb	26 ± 226	26 ± 191	28 ± 200	29 ± 199	27
Ga	10 ± 18	10 ± 17	10 ± 19	9 ± 21	10

Source: The authors (2025).

Figure 8 - Majority elements in Caiara Park's soil
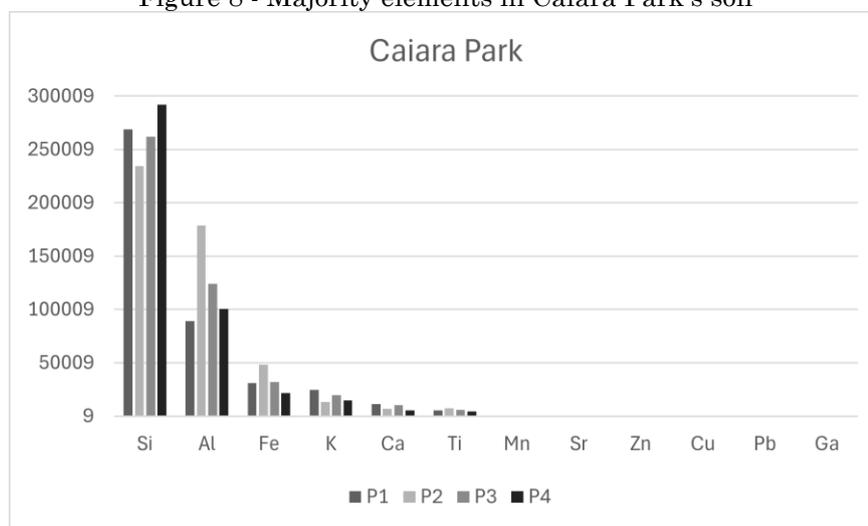
Source: The authors (2025).

The values presented in Tables 6 and 7 are the results of elemental analyses carried out at Santana and Caiara Parks. At Caiara Park could be seen that: Si > Al > Fe > K > Ca > Ti > Mn > Sr > Zn > Cu >Pb> Ga. And at Santana Park: Si > Al > Fe > K > Ti > Ca > Mn > Sr > Cu > Zn > Pb > Ga. It was found that the presence of the more dangerous elements was Al, Zn, Cu and Pb, that tends to increase with the depth, while for major elements such as Fe, K, Ca and Si the influence of depth was not significant. The values for Fe in soil are up to 26000 mg/kg (Adriano, 1986). In the Santana park, this value is within the world average for soils, while in Caiara Park the average value found is above 33000 mg/kg. Ti may originate from ores used to produce alloys (Guilherme *et al.*, 2005).

Values expressed in Table 8 represent the guiding values for soils in Pernambuco (CPRH, 2014). The standards are to be taken as reference to element concentrations for contamination control and management of contaminated areas under investigation.

Table 8 - Guiding values for Pernambuco' soils

Element	Values (mg/kg)
Pb	13
Cu	5
Ni	9
Zn	35

Source: Adapted from the State Environmental Agency – CPRH (2014).

Table 8 was used to compare the obtained values with this kind of statal legislation. The mean value of the parks for Zn (Caiara = 78 mg/kg and Santana = 47 mg/kg) is higher than the guiding values for soils in PE suggested by CPRH (2014).

The mean value for Cu is 55 mg/kg in the investigated parks; this value is higher than value cited by the CPRH (2014). According to Adriano (1986), the value for Fe, in soils reach 26,000 mg/kg, in Santana Park this value is near to the world average for soils, although in Caiara Park the value found is over 33,000 mg/kg.

Pb values vary from 27 mg/kg, in Caiara Park, to 42 mg/kg, in Santana Park, these values are higher than the suggested value by the CPRH (2014), that was, only, 13 mg/kg. We concluded that Pb is considered as a contaminant element, despite the indicated value from Pb, around the world, is 29 mg/kg. Titanium probably originated from the alloys' production (Guilherme *et al.*, 2005).

Mn was near 183 mg/kg, in Santana Park, this value is lower than   300 mg/kg, while, in Caiara Park, Mn was near 392 mg/kg and both values are higher than the recommended by Thomas (1987) value for soils and cited by Souza (2020).

In surface soils were observed values between 240 and 480 mg/kg by (Lange, 2018), however, in the Santana and Caiara Parks these values were between 183 and 392 mg/kg.

As expected, Si and Al exhibited the highest content followed by, K, Ca and Mn, indicating their crustal origin (Watts *et al.*, 2017). Lange (2018) found values of manganese between 240 to 480 mg/kg, these values, are like the average value observed herein for the superficial soils ($\cong$ 356 mg/kg) (Kabata-Pendias; Pendias, 2001).

Pernambuco's urban soils were enriched in strontium (Sr) presenting maximum value near 400 mg/kg. Comparing our results with other studies in urban area soils (Lange, 2018), it is observed that there are many similarities. For example, Lange (2018) found 61 mg/kg for Cu versus 55 mg/kg for both Santana and Caiara Parks.

In the case of Pb, the values were between 19.7 and 50 mg/kg in the samples analyzed by Lange (2018), whereas in Santana and Caiara parks results between 27 and 42 mg/kg were found. The same applies to Zn: 22.7 to 89 mg/kg (Lange, 2018) vs. 47 to 78 mg/kg. The presence of Pb, Zn and Cu can be attributed to incorrectly discarded car batteries and lamps in the environment (Wu *et al.*, 2013).

It was found that total metals concentrations are directly related to traffic density in particular sites of the urban environment and a style of vehicle driving. The highest emission of airborne was found at a crossroad and city center sites where traffic is the densest and vehicles stops and starts are frequent (Fabiańska *et al.*, 2019).

Caiara Park is located on Avenida Maurício de Nassau, where there is a high volume of motor vehicle traffic. Although phosphates were not determined in the samples, it is known that higher emissions of organic phosphates are generally found at intersections and in locations where traffic is denser and vehicle stops and starts are more frequent. Residential areas are less exposed to phosphate emissions. These phosphate concentrations show exponential correlations with each other, and human exposure to these compounds increases exponentially with increasing traffic density (Fabiańska *et al.*, 2019).

Determination of Organic Matter and Carbonate

The values for organic matter in Caiara Park ranged from 0.56 to 1.19%. The values for organic matter in Santana Park ranged from 0.48 to 0.81%. The carbonate values for Caiara Park ranged from 0.39 to 0.88%. The carbonate results for Santana Park ranged from 0.25 to 0.36%. Studies involving lake sediments also showed organic matter values of 0.6–4.8%.

According to Aguiar *et al.*, (2007), the values found for organic matter ranged from 0.05–0.39%. Research conducted in Ibirapuera Park (São Paulo) indicates that organic matter content is around 70%, values quite different from those found in parks in the city of Recife.

Sediment samples collected in western Ceará, for organic matter, ranged from 4.55 to 95.0%, corroborating other studies that report values of 0.2 – 95%. The values found in Santana and Caiara parks are well below the cited values.

The correlation between carbonate and elements was calculated using the "statistics" program. We identified that Ga, Fe, and Ca have a positive correlation in the presence of carbonate, as these are chemically bioavailable; they also show a positive correlation with carbonates in the presence of organic matter.

Si and Pb, on the other hand, showed an inversely proportional relationship in the presence of carbonates, making them less bioavailable to animals and plants. When correlating organic matter with elements, a positive response was found for Ga, Ca, and Mn. Si and Pb, however, showed an inverse proportionality to organic matter.

After determining Organic Matter and Carbonate, and this correlation was performed (that we could see in Table 9, these results) and element to element correlation are shown in Table 10. This correlation of metals with organic matter and carbonates and, also of the elements among themselves, showed good results when compared with the bioavailability of these elements in the soils studied (which will be discussed at the next session).

Table 9 - Correlation of organic matter with the elements and of carbon with the elements

	Positive Correlation	Negative Correlation
Carbonate	Fe, Ca and Ga	Si and Pb
Organic Matter	Mn, Ca and Ga	Si and Pb

Source: The authors (2025).

Table 10 - Correlation between Chemical elements

Elements	Positive Correlation	Negative Correlation
Si	Pb	Fe, Ti, Al and Ga
Fe	Al, Ti	Si and Pb
K	Ca, Mn, Sr and Zn	Al
Ti	Fe, Al, Ga	Si and Pb
Ca	Zn, K, Mn, Sr and Ga	-
Mn	K, Ca, Sr and Zn	-
Sr	K, Ca, Mn and Zn	Al and Fe
Zn	K, Ca Mn and Sr	-
Pb	Si	Fe, Ti and Ga
Ga	Fe, Ti and Ca	Si and Pb

Source: The authors (2025).

Results of bioavailability (metal distribution in the geochemical phases)

In general, for these soils analysed, the sequential extraction (soil bioavailability) showed the presence of major metals (Mn and Fe) and minor ones (Zn and Cu), it could be observed in Tables 11 to 18. They are in the oxidizable phase followed by the leachable or pseudo-residual phase.

These phases demonstrate lower bioavailability of metals in the environment, so the metals are not readily available. Only Mn is highlighted in the leachable fraction also, that is a fraction (or phase) very higher bioavailability Tables 11 and 12).

Table 11 - Manganese bioavailability values for Santana Park

Manganese (mg/kg ± standard deviation)				
Santana Park				
Sample Point	Exchangeable Phase 1	Leachable Phase 2	Reducible Phase 3	Oxidizable Phase 4	Pseudo-Residual Phase 5
P1	0.36 ± 0.01	12.05±1.52	9.65±4.72	3.55 ± 4.14	12.43 ± 6.01
P2	4.13 ± 3.95	13.84±3.14	5.10±2.91	24.24 ± 0.0	24.24±0.01
P3	2.60 ± 3.76	12.72±1.23	4.81±0.68	6.67 ± 1.68	12.78 ± 8.09
P4	7.91 ± 3.86	14.41±1.40	10.08±2.69	0.381 ± 0.38	7.48±1.05
Mean	3.75	13.25	7.41	8.71	14.23

pseudo-residual > leachable > oxidizable > reducible > exchangeable
Source: The authors (2025).

Table 12 - Manganese bioavailability values for Caiara Park

| | Manganese (mg/kg ± standard deviation) | | | | |
| | Caiara Park | | | | |
Sample Point	Exchangeable Phase 1	Leachable Phase 2	Reducible Phase 3	Oxidizable Phase 4	Pseudo-Residual Phase 5
P1	2.91 ± 0.155	15.5 ± 2.07	13.90 ± 1.53	9.38 ± 6.75	10.98 ± 3.82
P2	0.26 ± 0.14	13.12 ±1.71	9.17 ± 1.90	46.87 ± 11.13	17.51 ± 0.41
P3	19.85 ± 18.11	14.88 ±2.47	20.41 ± 6.46	46.95 ± 13.90	15.01 ± 4.54
P4	31.28 ± 13.58	13.58 ±2.40	7.88 ± 1.92	16.64 ± 0.71	8.40 ± 1.19
Mean	13.57	14.27	12.84	29.96	12.97

oxidizable> leachable > exchangeable> pseudo-residual > reducible

Source: The authors (2025).

Fe's bioavailability is not observed for both parks, because the samples are mainly found in less bioavailable phases (Tables 13 and 14).

Table 13 - Iron bioavailability values for Caiara Park

| | Iron (mg/kg ± standard deviation) | | | |
| | Caiara Park | | | |
Sample Point	Leachable Phase 2	Reducible Phase 3	Oxidizable Phase 4	Pseudo-Residual Phase 5
P1	51.64±15.38	1,066.98±174.72	3,744.10±94.16	1,416.64±66.24
P2	80.14±4.09	613.87±121.00	1,850.66±70.05	1067.64±68.44
P3	64.15±42.79	884.21±308.50	935.04±100.01	2,639.02±319.73
P4	61.67±19.91	584.42±179.11	5,921.68±270.33	827.73±229.99
Mean	644	787.37	3,112.87	1,487.76

oxidizable > pseudo-residual > reducible > leachable > exchangeable

Source: The authors (2025).

Table 14 - Iron bioavailability values for Santana Park

| | Iron (mg/kg ± standard deviation) | | | |
| | Santana Park | | | |
Sample Point	Leachable Phase 2	Reducible Phase Phase 3	Oxidizable Phase Phase 4	Pseudo-Residual Phase 5
P1	15.16±6.86	336.9±92.87	1,777.40±262.39	2,938.21±378.26
P2	39.18±6.66	473.59±172.52	2,555±278.25	930.25±220.01
P3	44.34±5.19	424.42±65.81	3,217.69±4.23	901.53±160.05
P4	23.23±2.40	389.66±151.72	2,843.20±155	830.23±170.05
Mean	30.48	406.14	2,598.32	1,400.10

oxidizable > pseudo-residual > reducible > leachable > exchangeable

Source: The authors (2025).

The results indicate that Fe (15-600 mg/kg) and Mn (0.2-47 mg/kg) are the most abundant metals in these soil samples, including all parks; in addition, they are mainly concentrated in the oxidizable phase.

On the other hand, copper is relatively immobile, primarily in the pseudo-residual and oxidizable fraction in all collected samples for both parks (Table 15 and 16). This metal is in high proportion, linked to the excellent stability of organic compounds of cooper, about other metals (Guoa *et al.,* 2010). Guoa *et al.,* (2010) also suggests the element that has the most stable copper form with humic materials in the soil.

Lima *et al.,* (2014) also demonstrated that cooper binds, preferentially, to organic matter in soils, have been found in the oxidizable phase. However, it can be mobilized under oxidizing conditions, due to organic matter degradation.

Table 15 - Zinc bioavailability values for Caiara Park

Zinc (mg/kg ± standard deviation)
Caiara Park

Sample Point	Exchangeable Phase 1	Leachable Phase 2	Reducible Phase 3	Oxidizable Phase 4	Pseudo-Residual Phase 5
P1	3.98±0.014	4.49±3.53	7.32 ± 0.00	19.53 ± 2.70	5.83 ± 0.56
P2	6.36±0.0014	4.34±2.71	6.14 ± 1.20	62.65 ± 11.13	6.52 ± 0.08
P3	3.62±0.56	11.29±1.50	7.09 ± 1.48	62.73 ± 13.90	7.27±0.28
P4	2.05±0.03	1.94±0.05	7.08 ± 2.72	32.42 ± 0.71	3.07, ± 0.61
Mean	4.00	5.20	6.90	44.33	5.72

oxidizable > reducible > pseudo-residual > leachable > exchangeable
Source: The authors (2025).

Table 16 - Zinc bioavailability values for Santana Park

Zinc (mg/kg ± standard deviation)
Santana Park

Sample Point	Exchangeable Phase 1	Leachable Phase 2	Reducible Phase 3	Oxidizable Phase 4	Pseudo-Residual Phase 5
P1	2.50 ± 0.45	3.56 ± 0.17	5.50 ± 0.75	7.18 ± 0.14	2.12 ± 0.65
P2	1.51 ± 0.67	5.64 ± 1.19	5.62 ± 0.44	14.33 ± 14.33	14.33 ± 0.50
P3	6.43 ± 3.85	3.24 ± 0.05	5.95 ± 0.72	17.04 ± 0.16	2.87 ± 0.45
P4	2.00 ± 0.50	3.09 ± 0.34	5.06 ± 0.41	12.74 ± 12.74	12.74 ± 0.60
Mean	3.11	3.88	5.53	12.82	8.02

oxidizable > pseudo-residual > reducible > leachable > exchangeable
Source: The authors (2025).

Table 17 - Cooper bioavailability values for Caiara Park

Cooper (mg/kg ± standard deviation)
Caiara Park

Sample Point	Exchangeable Phase 1	Leachable Phase 2	Reducible Phase 3	Oxidizable Phase 4	Pseudo-Residual Phase 5
P1	0.31 ± 0.00	0.33 ± 0.15	0.88 ± 0.28	0.45 ± 3.46	1.79 ± 1.26
P2	0.57 ± 0.00	0.21 ± 0.13	1.60 ± 0.07	0.32 ± 5.85	1.90 ± 0.45
P3	0.43 ± 0.15	0.65 ± 0.81	0.908 ± 0.30	0.91 ± 0.85	1.57 ± 0.071
P4	0.25 ± 0.10	0.49 ± 0.07	0.750 ± 0.32	0.56 ± 0.59	2.62 ± 1.78
Mean	0.39	0.42	1.03	0.56	1.97

pseudo-residual > reducible > oxidizable > leachable > exchangeable
Source: The authors (2025).

Table 18 - Cooper bioavailability values for Santana Park

Cooper (mg/kg ± standard deviation)
Santana Park

Sample Point	Exchangeable Phase 1	Leachable Phase 2	Reducible Phase 3	Oxidizable Phase 4	Pseudo-Residual Phase 5
P1	0.27 ± 0.06	0.72 ± 0.66	0.47 ± 0.17	1.90 ± 0.93	1.45 ± 1.20
P2	0.42 ± 0.11	0.29 ± 0.21	0.36 ± 0.18	0.44±0.12	0.44 ± 0.11
P3	0.36 ± 0.05	0.17 ± 0.14	0.46 ± 0.05	85.53 ± 11.38	2.79 ± 2.25
P4	0.48 ± 0.05	0.34 ± 0.04	0.55 ± 0.14	5.00 ± 1.0	5.00 ± 1.50
Mean	0.38	0.38	0.46	23.22	2.42

oxidizable > pseudo-residual > reducible > leachable = exchangeable
Source: The authors (2025).

Tables 17 and 18 show the bioavailability of Cu in the soil of the parks, which is generally unavailable. However, the copper in the soil of Caiara Park is present in the reducible fraction, demonstrating high availability.

Xiangdong-li (2015) studying metals as Zn, Cu, Ni and Co, found all of them, mainly, in the residual phase. In this study, Zn, Cu and Fe are preferentially in the oxidizable phase, while Mn is mainly in leachable fraction (carbonate fraction), demonstrating high mobility and availability.

Considering the results for zinc and copper related to the PEL and TEL values, the sampled points do not show contamination.

FINAL CONSIDERATIONS

It can be concluded that the natural concentrations of the main chemical elements found in these areas of Santana Park and Caiara Park were identified; as well as some chemical elements resulting from anthropogenic activities.

The more toxics metals found in this study were: Al, Zn, Cu, and Pb, while the major chemical elements analyzed were Fe, K, Ca, and Si. Lead's values, in both Parks, were higher than the suggested value by CPRH in document from 2014, wherefore, Pb could be considered a contaminant. Because in tropical environments, the search for reference values is a continuous challenge for agriculture, vegetation, and estuarine soils; the quality assessment of tropical soils and sediments is still under discussion, although every effort has been made by governmental agencies to establish reference values. Silicon and Aluminum exhibited the highest content followed by, K, Ca and Mn, indicating their crustal origin.

It was interesting to notice that the values of the correlation of metals with organic matter and carbonates and, also of the elements among themselves, mainly the terrigenous elements (Al, Fe, Si, and Ti), showed consistent results when compared with the bioavailability of these elements in the soils of the studied parks.

The bioavailability results show that Fe an Mn present the highest concentrations among the metals studied. Besides, the sequential extraction method indicated that they are mainly present in the pseudo-residual phase; therefore, they are not available for plants and animals (including children and ancients). On the other hand, Mn, Fe, Zn and Cu are also mainly associated with the oxidizable phase. They are, therefore, relatively immobile, although they can be found associated with organic matter. Mn is present in the leachable phase being available for animals (including children and ancients) and plants. In summary, the results indicate that the area has been affected by human activity. The results stress the importance of determining the chemical form of heavy metals in soil in the parks as a way of assessing the availability and long-term environmental consequences of soil contamination, being as an environmental diagnostic tool.

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Vivianne Lúcia Bormann de Souza - administration, Supervision, Funding acquisition, Investigation, Methodology, Data curation and writing original draft. Sandra Dias Barbosa - Investigation, data curation and validation. Waldecy Ananias da Silva - Data curation and Validation. Suzana Oliveira Santos - original draft. Lorena Colliard de Farias Antas - original draft and review & editing. Crescêncio Andrade Silva Filho - review & editing.