Pol. J. Environ. Stud. Vol. XX, No. X (XXXX), 1-11
DOI: *10.15244/pjoes/214924* ONLINE PUBLICATION DATE: 2026-03-04

Original Research

Elemental Composition of *Xanthosoma sagittifolium* in the Amazon: Nutritional Value and Potential as an Environmental Bioindicator in the Context of Amazonian Edaphic Variability

Ronaldo Vitoriano Bastos[1], Maria Teresa Gomes Lopes[1], Jennifer Souza Tomaz[1]*, Caroline de Souza Bezerra[1], Carla Karoline Gomes Dutra Borges[1], Ricardo Lívio Santos Marques[1], Ricardo Lopes[2], Mágno Sávio Ferreira Valente[3], Anderson Mathias Pereira[1], Santiago Linorio Ferreyra Ramos[4]

[1]Faculdade de Ciências Agrárias, Universidade Federal do Amazonas, Av. Rodrigo Otávio, 3000, Manaus 69060-000, AM, Brasil
[2]Embrapa Amazônia Ocidental, rod. AM 10, Km 29, s/n, CP 319, Manaus 69010-970, AM, Brasil
[3]Instituto Federal do Amazonas, Av. da Onça-Pintada, S/N-Galo da Serra, Presidente Figueiredo 69735-000, AM, Brasil
[4]Instituto de Ciências Exatas e Tecnologia, Universidade Federal do Amazonas, rua Nossa Senhora do Rosário, 3863, Itacoatiara 69103-128, AM, Brasil

Received: 07 October 2025
Accepted: 30 November 2025

Abstract

Xanthosoma sagittifolium (taioba) is an unconventional food plant of nutritional and socio-environmental relevance. This study evaluated its elemental composition in five municipalities of Amazonas (Manaus, Itacoatiara, Novo Airão, Humaitá, and Tabatinga) to analyze its nutritional potential and use as an environmental bioindicator in the context of Amazonian edaphic variability. Rhizospheric soil and leaf samples were analyzed by total reflection X-ray fluorescence (TXRF). The results showed geochemical heterogeneity between the localities: soils of Tabatinga and Humaitá presented high concentrations of aluminum and iron, while the leaves revealed higher levels of phosphorus, potassium, calcium, and sulfur, especially in floodplain environments and seasonally flooded soils. The analysis of main components (PCA) showed clear separation between municipalities, confirming the edaphic influence on the mineral composition of the species. Positive correlations between nutrients (P, S, Si, K) and trace elements (Cr, Yb) indicated physiological adaptive mechanisms of absorption. The findings reinforce the dual role of taioba as both a food resource with high nutritional value and as a bio-indicator sensitive to environmental quality. However, the presence of traces of potentially toxic

*e-mail: jennifer.tomaz@ufam.edu.br
Tel.: +55-92-99258-7269

elements highlights the need for continuous monitoring to ensure the safety of human consumption and to broaden understanding of taioba in Amazonian ecosystems.

Keywords: food safety, TXRF spectrometry, heavy metals, environmental quality, phenotypic variability

Introduction

Chemical elements play important roles in environmental dynamics and in maintaining ecosystem quality. Although some are essential to plant metabolism, their presence in high concentrations can result in phytotoxicity, inducing physiological stress, bioaccumulation processes, and ecotoxicological imbalances [1, 2]. Elements such as aluminium (Al), manganese (Mn), iron (Fe), chromium (Cr), nickel (Ni), copper (Cu), zinc (Zn), and strontium (Sr) are necessary for certain metabolic functions in plants and organisms, but they may become toxic at elevated concentrations. Metals such as cadmium (Cd) and lead (Pb) are harmful even at low concentrations, since they do not perform metabolic functions and can cause oxidative stress, DNA damage, and reduced photosynthesis [2, 3].

Metal contamination in soil results from natural processes, such as weathering and erosion, as well as anthropogenic activities, including mining, vehicular emissions, urban runoff, and agricultural and industrial practices. Some metals, such as Al, Cd, Cr, Cu, Fe, Mn, Ni, Pb, Zn, and Co, are often detected due to atmospheric deposition, use of sewage sludge, fertilizers, pesticides, and improper waste disposal. Because they are resistant and non-biodegradable, they remain in the environment, acting as continuous sources of contamination [1-4]. Its effects on plants vary according to their bioavailability, which is influenced by the type of metal, soil pH, organic matter, climatic conditions, chemical composition, and plant species [3].

Once incorporated into the soil, these elements can be absorbed by plants through the root system, accumulating in different organs, such as leaves, stems, and other edible structures, a process known as phytoextraction. Alternatively, phytostabilization mechanisms can retain them in the soil, thereby limiting their mobility but not eliminating the associated environmental risk. These processes affect both plant growth and human health, since they facilitate the entry of contaminants into the food chain [5]. Under certain conditions, bioaccumulation makes plants useful as bio-indicators of environmental pollution, although excessive accumulation compromises physiological functions such as photosynthesis, chlorophyll synthesis, and nutrient absorption [2, 3, 6].

The response of plants to the presence of metals varies according to species and tolerance mechanisms. While some accumulate the elements in the roots, restricting their translocation (exclusion strategy), others transport and store metals in leaves and stems (accumulation strategy), characteristics that make them relevant in biomonitoring and phytoremediation strategies [1, 3]. The species *Xanthosoma sagittifolium* (L.) Schott, popularly known as “taioba”, presents itself as promising for environmental studies, because, in addition to having a wide distribution in rural and urban areas, it is prominent in traditional and agricultural communities. Its high growth rate and ability to accumulate metals in foliar and edible tissues allow it to be used with both environmental quality monitoring and human health risk assessments in conjunction with the consumption of contaminated food [7, 8].

Xanthosoma sagittifolium is a perennial herbaceous plant of the Araceae family, robust and widely adapted, which can reach up to 2 m in height, with broad leaves and underground tubers traditionally used for feeding. Native to Central and South America, it is widely distributed in tropical and subtropical regions, having been naturalized in Brazil, where it is mainly cultivated by small farmers [9-11]. It is considered one of the six most important root and tuber crops in the world, playing an essential role in the subsistence of rural and urban communities, especially in periods of food insecurity. Their corms, kernels, and leaves are consumed in several ways, among them, cooked, fried, baked, or processed into flour; they constitute an important source of carbohydrates, fiber, vitamins (C and E), and minerals [9, 10, 12].

In addition to nutritional and socioeconomic relevance, taioba attracts scientific interest for its ability to accumulate heavy metals in edible tissues, a characteristic that qualifies it as a bioindicator and phytoextractor, but also represents a risk to human health. Associated with widespread distribution and cultivation by small producers, along with cultural and food relevance, this characteristic reinforces the need to investigate its absorption capacity and translocation of chemical elements in contaminated soils [2, 7, 8]. Sensitive and multi-elemental techniques are indispensable, and total reflection X-ray fluorescence spectrometry (TXRF) stands out, requiring minimal sample preparation, having low operating costs, and being able to simultaneously detect various chemical elements, including heavy metals and trace elements [13]. The TXRF technique allows quantification at very low concentrations, with high levels of sensitivity, accuracy, and reproducibility, in addition to reducing the consumption of chemical reagents and environmental impact, and enabling direct analysis in soil, leaves, roots, and grains [14-16].

Recent studies show technical versatility, such as its application in monitoring potentially toxic elements (PTEs) and nutrients in urban park plants [17], and in nutrient analysis in soils and plants with simplified calibration [18]. Other research reports the use of TXR considering metals such as Cr, Ni, Cu, Zn, and Pb [14-16, 19]. Thus, the TXRF technique is considered an essential tool for environmental, agricultural, and public health studies, allowing both the assessment of heavy metal contamination and the identification of nutrients relevant to biofortification and food safety. Despite these advances, few studies have addressed Amazonian edible aroids using TXRF, particularly integrating soil-leaf correlations [20].

Thus, this study aimed to evaluate the mineral composition of taioba (*Xanthosoma sagittifolium*) in different locations of the state of Amazonas, relating it to the nutritional potential of the species and its use as a bioindicator of soil contamination.

Materials and Methods

The study areas are in urban areas of Manaus, Itacoatiara, Novo Airão, Humaitá, and Tabatinga, in the state of Amazonas, Brazil. The localities present different levels of urbanization and were selected based on the occurrence of the species *Xanthosoma sagittifolium*.

The soils of Manaus (3°06’07” S, 60°01’30” W) are predominantly dystrophic, deep, very temperate, acidic, yellow Latosols with low natural fertility and high permeability [21]. Itacoatiara, located between the coordinates (3°08’00” S, 58°26’00” W), presents yellow oxisols and utisols, also of low fertility, with the occurrence of sandy areas near the Amazon River, subject to leaching [22].

In Novo Airão (2°37’28”S, 60°56’43”W), there is the predominance of quartzite entisols and oxisols, sandy soils with low nutrient retention capacity, associated with areas of dry land forest and igapó [23]. The soils of the locality of Humaitá (7°30’27”S, 63°01’15”W) are characterized by the incidence of Plintosols and Gleissolos, influenced by the proximity to the river Madeira, with periods of waterlogging, as well as Latosols in areas of dry land [23]. The soils of Tabatinga (4°14’32”S, 69°56’43”W) are characterized by the strong presence of gleissolos and entisols (fluvents), related to the floodplain of the river Solimões, marked by young, fertile soils, but seasonally watered [24].

Collection of Soil and Plant Material

Collections of adult leaves and rhizospheric soils of *X. sagittifolium* were carried out in July 2024, in backyard homes and vacant lots in urban centers of the study areas. 29 leaf samples of *X. sagittifolium* and 29 corresponding soil samples were randomly collected, totaling 58 samples in the study. For the collection of rhizosphere soils, the cleaning of undergrowth and soil collection was carried out at a depth of 0 to 20 cm around the selected plants. The processing of laboratory analyses followed the protocol described by Bezerra et al. [14], Gomes et al. [15], and Tomaz et al. [16].

Total Reflection X-ray Fluorescence Analysis (TXRF)

The preparation of rhizospheric samples of soil and leaves of *X. sagittifolium* was carried out in the laboratory of Genetics and Plant Breeding at the Federal University of Amazonas (LABGEMVEG-UFAM). Analysis using total reflection X-ray fluorescence spectrometry (TXRF) was conducted in the Technical-Scientific Laboratory of Chemical Analysis (SETEC), linked to the Regional Superintendence of the Federal Police in the State of Amazonas. The procedures for the analysis were based on the protocols outlined by Bezerra et al. [14], Gomes et al. [15], and Tomaz et al. [16]. Iridium (Ir) was used as an internal standard with known mass to ensure the accuracy and reproducibility of the analyses, functioning as a reference for the quantification of the elements present in the samples [25]. The acquisition time of the measurements was approximately 600 seconds, ensuring better definition of the obtained spectra. The samples were packaged in quartz supports, which also acted as reflectors during the analyses. From the standard, the sensitivities were calculated based on the spectral peak area of each element, according to the expression

$$S_i = (N_i \times C_{Ir})/(N_{Ir} \times C_i)$$

in which: N_i: liquid counts of the peak of a given element; N_{Ir}: liquid counts of the iridium peak; C_i: concentration of a particular element in the solution; C_{Ir}: concentration of the iridium element in the solution. The detection limits (DLs) for the analyzed elements ranged from 0.01 to 1.0 $mg{\cdot}kg^{-1}$, depending on the atomic number and matrix effects, which are consistent with values reported for TXRF analysis of plant and soil samples. Quality control was ensured by the inclusion of analytical blanks and duplicate samples in each batch. Replicate analyses showed relative standard deviations (RSD) below 5%, confirming the precision and reproducibility of the measurement.

Statistical Analysis

The results were subjected to tests for the detection and exclusion of outliers. The assumptions of the analysis of variance (ANOVA) were then verified, considering the normality of the residues [26] and the homogeneity of the variances [27]. Data sets that did not meet these criteria were tested using the nonparametric Mann-Whitney test (Macfarland; Yates). The RStudio environment [28] was utilized to perform principal component analysis (PCA) and Pearson correlations using R software.

The formation of the clusters was performed by the hierarchical method of distances, using the UPGMA algorithm (Unweighted Pair-Group Method with Arithmetic Mean). For this procedure, the matrix of mean Euclidean distances obtained in the R software

(RStudio Team, Boston, MA, USA) was used. Then, non-metric multidimensional scaling analysis (NMDS) was applied, which made it possible to identify the greatest dispersion among the sample units, reflecting the highest levels of genetic dissimilarity. Statistical analyses were conducted using the Vegan package, available in the R environment [29].

Results and Discussion

Inorganic Elements in Rhizosphere Soils and Leaves of *Xanthosoma sagittifolium*

The multielemental analysis of soils associated with the occurrence of *Xanthosoma sagittifolium* indicated heterogeneity in the distribution of elements among the five municipalities evaluated. Aluminum and iron stood out as the main inorganic constituents. The highest aluminum concentration was observed in Manaus (69,800 mg·kg⁻¹), whereas Tabatinga presented lower values (48,405.00 mg·kg⁻¹). Similarly, iron reached its maximum value in Humaitá (40,417.32 mg·kg⁻¹), contrasting with the low concentration in Manaus (5,066 mg·kg⁻¹). Calcium showed high values in Novo Airão (178,400.00 mg·kg⁻¹), and titanium was predominant in Humaitá (6,091.44 mg·kg⁻¹). Trace elements such as cobalt, copper, bromine, and mercury showed reduced concentrations in all locations (Table 1).

In the leaves of *X. sagittifolium*, the macronutrients phosphorus, sulfur, chlorine, potassium, and calcium predominated, with variations between localities. The plants located in Humaitá showed high levels of phosphorus (7,977,696.00 mg·kg⁻¹), sulfur (5,867,316.50 mg·kg⁻¹), and chlorine (11,994,322.50 mg·kg⁻¹). In Tabatinga, high levels were observed for potassium (19,280,350.00 mg·kg⁻¹) and calcium (385,610 mg·kg⁻¹). Manaus, in turn, recorded lower concentrations in relation to most elements, especially iron (689.2 mg·kg⁻¹). Trace elements such as titanium, yttrium, barium, and mercury occurred at low concentrations, while manganese showed significant accumulation in Novo Airão (148.1 mg·kg⁻¹) (Table 2). Nevertheless, the TXRF technique does not quantify light elements such as nitrogen (N) and carbon (C), which constrains full nutritional profiling.

Principal Components Analysis (PCA)

The main component analysis (PCA) based on foliar data explained a significant part of the total variability, in which the first two components explained 42.97%

Table 1. Inorganic elements in soils with the occurrence of *Xanthosoma sagittifolium* in the municipalities of Humaitá, Itacoatiara, Manaus, Novo Airão, and Tabatinga, Amazonas, Brazil. Values are presented as mean±standard deviation (n = 3), expressed in mg·kg⁻¹ as significant values rounded to two decimal places.

Inorganic Components	Humaitá	Itacoatiara	Manaus	Novo Airão	Tabatinga
(mg·kg⁻¹)					
Aluminum	122,710±8589.70	102,580±7180.60	69,800±4886.00	125,100±8757	48,405±3388.35
Phosphorus	3,623.50±253.64	11,604±812.28	2,085±145.95	4,952±346.64	2,019±141.33
Sulfur	1,499.25±104.95	5,189.25±363.25	362.10±25.35	2,961.00±207.27	391.10±27.38
Chlorine	358.65±25.11	607.58±42.53	4,425.00±309.75	740.50±51.80	6,278.00±439.46
Potassium	28,845±2019.15	4,609.50±322.64	269,200±18844	1,169±81.83	3,676±257.32
Calcium	120,279.45±8419.56	69,340±4843	29,260±2048.20	178,400±12446	87,450±6121.50
Titanium	6,091.44±426.40	6,164±431.50	2,109±147.60	19,660±1376	2,130.50±569.10
Manganese	0.00	0.00	156,50±11,50	0.00	0.00
Iron	40,417,320±2829.20	74,762.50±5233.40	5,066±354.60	101,200±7084	8,199.50±573.97
Cobalt	223.90±15.63	218.23±15.28	112.40±7.84	318.00±22.26	54.17±3.80
Copper	70.37±4.92	74.30±5.20	5.19±0.36	10.41±0.73	30.34±2.12
Bromine	13.88±0.97	8.15±0.57	1.71±0.12	23.44±1.63	4.38±0.31
Rubidium	177.90±12.46	16.01±1.12	0.15±0.01	0.64±1.58	22.64±1.61
Yttrium	75.53±5.27	28.18±2.00	10.65±0.00	47.42±3.23	25.20±2.63
Barium	1,998.80±139.89	197.95±13.86	205.40±14.35	2,462.00±172.34	406.95±28.49
Ytterbium	0.00	0.00	0.00	0.00	0.00
Mercury	5.78±0.40	6.06±0.42	0.25±0.02	2.31±0.16	0.21±0.01

* Statistical differences among municipalities were evaluated using the non-parametric Kruskal–Wallis test ($p<0.05$).

(Fig. 1). The first axis mainly separated Humaitá and Tabatinga from the other municipalities, due to the accumulation of phosphorus, potassium, and chlorine, while the second axis was influenced by calcium and manganese. The PCA of the soil (Fig. 2) indicated a strong presence of aluminum and iron, contributing to the differentiation of the localities and highlighting Humaitá and Tabatinga as distinct groups, in contrast to Manaus and Itacoatiara, which were grouped due to lower concentrations of these elements.

Pearson's Correlation

In the leaves of *X. sagittifolium* strong correlations (0.7>0.9) and positive correlations between P × S (0.9869), Si × K (0.8726), Cr × Yb (0.8973) and negative correlations between I × Mg (−0.367), I × Si (−0.369), I × P (−0.410), and I × K (−0.378) were observed (Fig. 3). As for the correlation matrix involving the composition of the rhizosphere soils of *X. sagittifolium* samples (Fig. 4), positive correlations were observed with several essential elements between Mg × Si (0.853), Mg × P (0.718), Mg × S (0.718), Mg × K (0.382), and Mg × Ca (0.836). Perfect type correlation was observed between P × S (1.00) (Fig. 4). Positive correlations were observed between the micronutrients Fe × Cu (0.873), Fe × Rb (0.796), and Fe × Ce (0.558). Strong and positive correlations were observed between Cr × Ni (0.996) and Cr × Ce (0.907), Cu × Ni (0.885), Cu × Ce (0.804), and Cu × Hg (0.744).

The results obtained indicate a consistent pattern of nutritional and geochemical plasticity, with strong sensitivity to soil conditions and, in some cases, to atmospheric deposition. This sensitivity gives the species the role of a bioindicator, since the mineral composition of its tissues reflects sensitively the geochemical conditions of the soils in which they develop. The observed accumulation pattern also suggests a potential phytoextractor, revealing that these plants may contribute to the reduction of bioavailability of heavy metals in degraded environments, in line with recent research on phytoremediation of Amazonian species [30, 31].

An important aspect is that taioba is a highly consumed and widely cultivated edible species in rural and urban communities, thus presenting relevant socioeconomic and nutritional importance in the Amazon [11]. In addition to providing leaves with high nutritional value, the species has potential as an environmental bioindicator, considering its ability to

Table 2. Inorganic elements in leaves with the occurrence of *Xanthosoma sagittifolium* in the municipalities of Humaitá, Itacoatiara, Manaus, Novo Airão, and Tabatinga, Amazonas, Brazil. Values are presented as mean±standard deviation (n = 3), expressed in $mg \cdot kg^{-1}$ as significant values rounded to two decimal places.

Inorganic Components	Humaitá	Itacoatiara	Manaus	Novo Airão	Tabatinga
($mg \cdot kg^{-1}$)					
Aluminum	3,162.50±221.38	11,290±790.30	2,048.00±143.36	0	1,934±135.38
Phosphorus	7,977,696±558.39	6,113±428.40	5,963,00±417.41	79,530±5567.10	1,383±96.81
Sulfur	5,867,316.50±410.71	20,600±1400	4,623±323.61	35,310±2471.70	5,256±367.92
Chlorine	11,994,322.50±839.60	42,055±2944	47,250±3307.50	86,160±5711.20	45,165±3161.55
Potassium	4,504,690.00±315.33	26,920±1886	23,010±1610	42,750±2992.50	19,280,350±1348.62
Calcium	34,813,400±2436.94	91,805±6416.00	113,290±7930.30	222,300±15561	385,610±27992.70
Titanium	182.00±12.74	74.56±5.22	16.38±6.57	93.88±6.57	10.73±0.00
Manganese	107.90±7.55	0.00	27.20±1.90	148.10±10.37	58.70±4.12
Iron	2,882,363±201.76	1,998.68±139.90	689.20±48.24	846.70±59.27	237.90±16.65
Cobalt	31.91±2.23	7.43±0.51	4.22±0.41	12.38±0.97	14.92±1.05
Copper	50.02±3.50	53.04±0.48	8.80±0.34	56.95±3.96	16.76±1.12
Bromine	14.73±1.03	50.95±3.57	4.37±0.31	63.60±4.42	23.56±1.65
Rubidium	191.96±12.56	256.83±17.96	32.94±1.30	86.18±4.13	34.52±2.48
Yttrium	7.68±0.54	15.91±0.29	2.36±0.00	8.32±2.04	5.02±0.36
Barium	0.00	0.00	0.00	12.00±0.00	0.00
Ytterbium	35.13±2.46	1.93±0.08	7.02±0.14	3.30±0.00	0.00
Mercury	0.45±0.91	1.00±0.08	0.39±0.14	0.00	0.00

* Statistical differences among municipalities were evaluated using the non-parametric Kruskal–Wallis test ($p<0.05$).

grow in different soil conditions, including dystrophic, sandy, and seasonally flooded lowlands [32]. Although the species has significant nutritional value, including high fiber, protein, and mineral content, the ability to accumulate metals implies risks to food safety. Some studies show that plant species cultivated in urban areas or near pollution sources may exceed the recommended limits for some metals, such as Cd and Pb, implying risks to human health [33-35].

From a food safety perspective, the presence of high concentrations of essential nutrients in *X. sagittifolium* leaves presents a strategic resource against common nutritional deficiencies in rural and riverside populations [10, 12]. In addition, the identification of positive

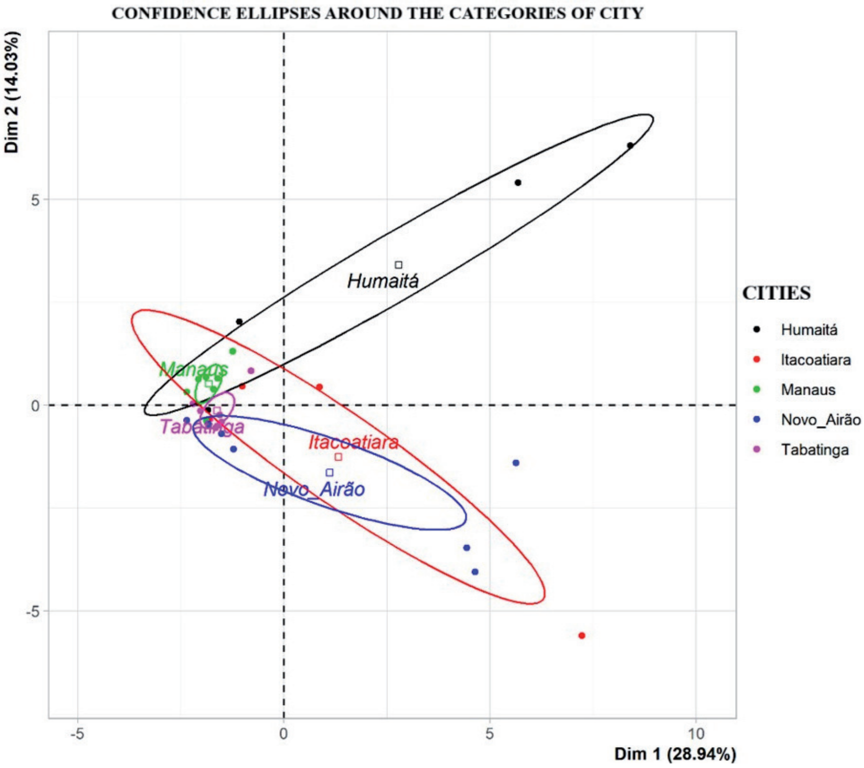

Fig. 1. Principal component analysis (PCA) in *Xanthosoma sagittifolium* leaves.

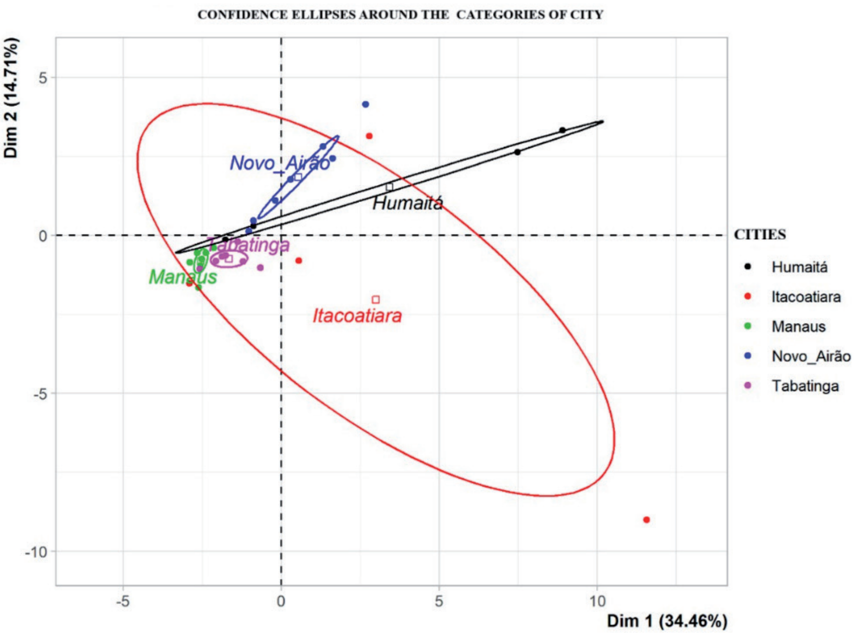

Fig. 2. Principal component analysis (PCA) in *Xanthosoma sagittifolim* soils.

correlations between nutrients such as P × S and Si × K reinforces that the plant maintains physiological mechanisms able to optimize the absorption and simultaneous accumulation of essential elements [36, 37], ensuring nutritional quality even in challenging environmental conditions.

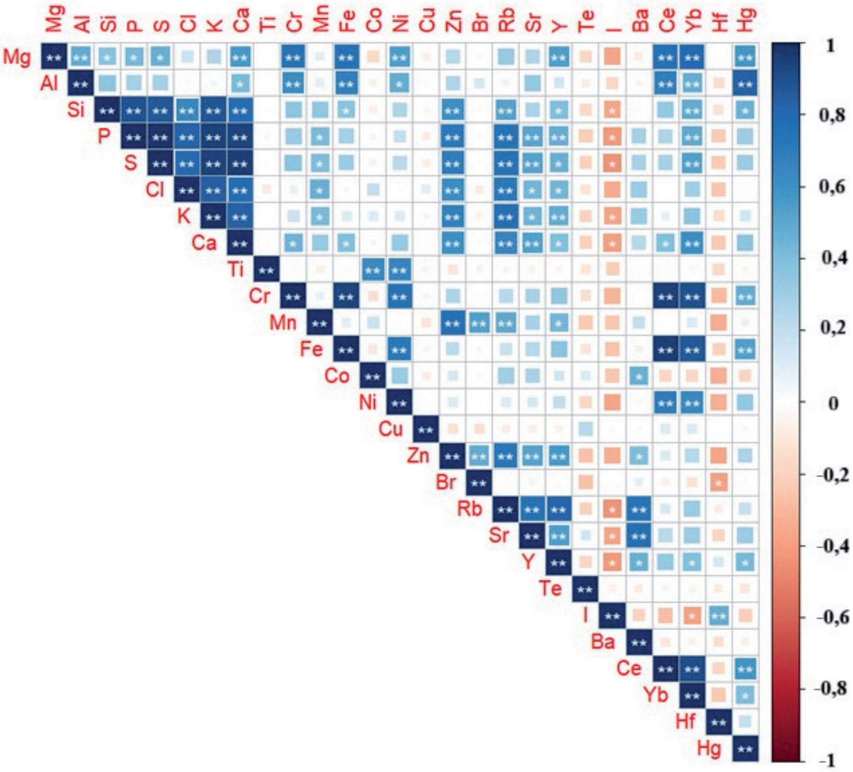

Fig. 3. Pearson's correlation matrix of the composition of chemical elements observed in *X. sagittifolium* leaves.

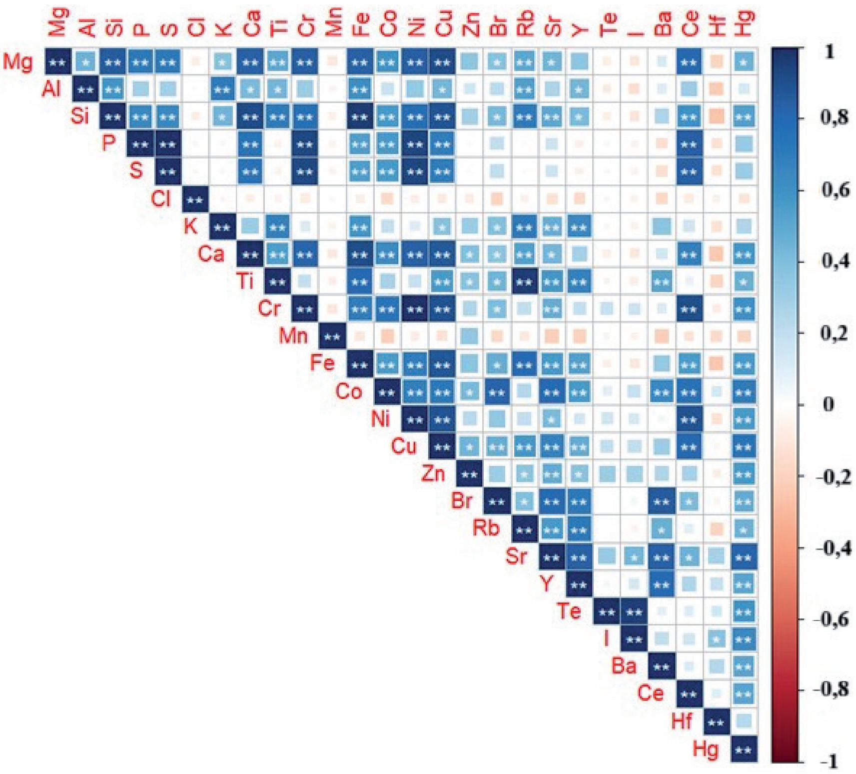

Fig. 4. Pearson's correlation matrix for the composition of chemical elements observed in *X. sagittifolium* soils.

The low concentration of trace metals such as Hg suggests that, in general, the species presents safety for consumption. However, Codex Alimentarius and DRC 722/2022 (ANVISA) establish maximum tolerated limits (LMTs) of contaminants in food, and WHO/FAO reference values point to, for example, 0.2 mg·kg^{-1} of Cd as a limit in leafy vegetables. Thus, promoting PANCs as functional foods must be accompanied by continuous environmental monitoring in urban environments subject to contamination to ensure safety [38, 39]. Biomonitoring is essential to ensure that the availability of *X. sagittifolium* as a safe food resource is not compromised by external factors related to environmental pollution.

Total reflection X-ray fluorescence analysis (TXRF) for *X. sagittifolium* indicates differences in the pattern of elemental distribution between the study sites, reflected in the main components of soil (Al and Fe) and leaves (P, K, and Cl), resulting in the clear separation of the localities Humaitá and Tabatinga. Moreover, in comparison with studies conducted on other Amazonian species, it validates the findings of this research. In *Stryphnodendron pulcherrimum,* accumulation of Cr, Y, and Yb in leaves and roots in urban forest fragments of Manaus was observed, characterizing the species as sensitive to atmospheric and edaphic contamination. In addition, there was a clear separation between forest fragment areas and anthropized areas [16]. Similarly, *Urena lobata* analyzed in várzea and dry land areas was identified as a hyperaccumulator of Hf and Yb, besides presenting capacity for phytoextraction of Cr and Ni and separation between the studied areas [15]. These results show that tree, herbaceous, food, and medicinal species share adaptive plasticity and potential for biomonitoring in Amazonian environments under anthropogenic pressure. In the case of *X. sagittifolium*, there were significant concentrations of P, K, Ca, and Mn in certain localities and metals at levels that varied according to local conditions, as observed in the reference studies. Furthermore, they confirm that elementary signatures of the substrate and environment are determinants in the organization of sampling point communities and foliar composition, according to related studies.

In the specific case of taioba, the literature confirms the sensitivity of aroids (*Colocasia*/*Xanthosoma*) to the environment, with recent reports of metal characterization in *X. sagittifolium* under different pollution contexts, reinforcing the need for surveillance when destined for food. These studies align with this research´s findings, which detected high concentrations of Al, Fe, and Ti in soils and leaves that are rich in P, K, and Ca; these elements can coexist with detectable traces of Cr, Ni, and Hg at low levels sufficient for bioindicator function. In scenarios of higher anthropic intake, these levels could reach a range of health concerns [8].

The correlation matrix showed associations between macronutrients and micronutrients in soil (Mg, Si, Mg P, Mg S, and Mg Ca), as well as strong foliar correlations between P, S, Si, K, and trace elements (Cr, Yb). Patterns of this nature, simultaneous accumulation and high correlation between transition metals and alkaline and alkaline-earth elements, also occurred in *Coffea canephora*, which exhibited significant correlations between elements in leaves and grains (Co Ni, Fe Ni, K Rb), as well as negative correlations involving K in roasted grains with transition metals [14].

Regarding the nutritional standard, the multielemental analysis found the accumulation of essential macronutrients in different localities of the Amazon. This nutritional profile reinforces the species with high nutritional content by promoting food security in traditional communities. Taioba provides affordable, nutrient-rich, and culturally integrated alternatives to everyday eating practices where dependence on local resources is limited [9].

The variability observed among municipalities located in the Amazon indicates that edaphic and hydrological conditions directly influence the nutritional value of the species. In Tabatinga and Humaitá, for example, the accumulation of P, K, and Ca in leaves demonstrates that várzea environments and irrigable soils favor greater nutrient availability [10, 11]. This heterogeneity has direct implications for community agricultural management, where the choice of cultivation areas in more fertile environments can maximize the nutritional value of the species, while the cultivation on dystrophic soil, as in Manaus, may require complementary organic fertilization practices [5, 6, 40, 41].

The populations of *X. sagittifolium* based on the results indicate that the species is adapted to different geochemical contexts, highlighting the importance of in situ conservation strategies that consider local soil variability. Although trace elements such as mercury have been detected at low concentrations, their presence in urban and lowland environments points to the need for continuous monitoring, aiming to avoid potential risks of bioaccumulation. In addition, the high variability in elementary distribution among the municipalities analyzed indicates that cultivation and sustainable management strategies of the species can be directed to specific agroecological contexts, favoring both genetic conservation and food safety.

From a social and environmental standpoint, these results provide relevant insights for public-health indicators by identifying potential risks associated with the consumption of plant species grown in contaminated areas. In addition, they strengthen environmental education by raising awareness among farmers and consumers about the importance of assessing the quality of soil and water used in the cultivation of PANCs. They also open perspectives for phytoremediation policies, using local species of rapid growth and popular acceptance in projects to recover degraded areas at reduced costs and with lasting environmental benefits. Finally, they value the use of PANCs but emphasize the need to balance their promotion with health surveillance measures, ensuring that their nutritional benefits are not compromised by environmental contamination. Future research should investigate the bioavailability of trace elements under controlled cultivation and seasonal variation to refine its use as a biomonitor

Thus, this study illustrates that *X. sagittifolium* can simultaneously function as an environmental quality bioindicator and a food source of high nutritional value, although this potential should be managed with caution due to the risk of heavy metal bioaccumulation. The integration of these findings with the results observed in other Amazonian species strengthens the understanding of the role of regional flora both in phytoremediation and food security, pointing paths for future public policies that reconcile health, environment, and sustainability. In addition, in all the studies, including the present one, total reflection X-ray fluorescence (TXRF) proved to be an efficient technique for multielemental detection at very low levels, allowing for simultaneous identification of nutrients and contaminants. This approach contributes to the understanding of the dynamics of the elements in the soil-plant system and expands the possibilities of application in environmental biomonitoring programs.

Conclusions

The results show that *Xanthosoma sagittifolium* has nutritional and adaptive plasticity, able to reflect the geochemical variability of Amazonian soils through its leaf composition. The accumulation of essential nutrients such as P, K, Ca, and S highlights the role of the species as a strategic resource for food security in rural and urban communities, especially in contexts where the availability of mineral-rich foods is limited. At the same time, the detection of positive correlations between nutritional and trace elements suggests the existence of efficient physiological mechanisms of integrated absorption, ensuring nutritional stability even in contrasting soil conditions.

The correlations observed between macro and microelements indicate efficient physiological mechanisms of element uptake and translocation, reinforcing the suitability of the species for both nutritional enhancement and environmental biomonitoring.

The presence of trace metals such as Cr, Ni, and Hg, even at low concentrations, demonstrates the relevance of the species as an environmental bioindicator, sensitive to both soil characteristics and anthropic pressures. This dual purpose, as both a high-nutritional-value food and a biomonitoring tool, reinforces the importance of taioba in integrating sustainable production strategies, health surveillance policies, and phytoremediation programs in areas at risk of contamination. Thus, the species is consolidated as a multifunctional resource, whose proper management can simultaneously promote health, environmental conservation, and valorization of non-conventional food plants in the Amazon.

Future research should explore the seasonal dynamics of metal uptake and promote the integration of TXRF-based monitoring into community agricultural programs. The safe cultivation of taioba thus contributes to sustainable food systems, phytoremediation, and environmental health surveillance across tropical regions.

Author Contributions

Conceptualization, R.V.B., M.T.G.L., J.S.T., C.S.B., C.K.G.D.B., C.H.S.G.M., and R.L.; methodology, R.V.B., J.S.T., C.S.B., R.L.S.M., and M.T.G.L.; software M.S.F.V., R.L.S.M., and A.M.P.; validation, R.V.B., J.S.T., C.S.B., R.L.S.M., R.L., and M.T.G.L.; formal analysis, R.V.B., J.S.T., M.S.F.V., and M.T.G.L.; resources R.L., R.L.S.M., A.M.P., S.L.F.R., and M.T.G.L.; writing – original draft preparation, R.V.B., J.S.T., C.S.B., C.K.G.D.B., R.L., A.M.P., M.T.G.L., and S.L.F.R.; writing – review and editing, R.V.B., M.T.G.L., J.S.T., C.S.B., C.K.G.D.B., R.L.S.M., R.L., A.M.P., M.S.F.V, and S.L.F.R.; funding acquisition, M.T.G.L. A.M.P. and All authors have read and agreed to the published version of the manuscript.

Acknowledgments

Ronaldo Vitoriano Bastos was supported by fellowships from Coordination of Improvement of Personnel of Higher Level- CAPES. The authors also wish to thank CNPq for providing the research productivity grant that allowed this research to be completed: Santiago Linorio Ferreyra Ramos (Process no. 305280/2022-8), Ricardo Lopes (Process no. 308815/2023-8) and Maria Teresa Gomes Lopes (Process no. 306943/2025-5).

Funding

This study was financed by the Coordination for the Improvement of Higher Education Personnel Brazil (CAPES) − Edital nº 16/2020 – PROCAD-SPCF, Process Number: 88881.516217/2020-01, and Edital nº 16/2022 – Programa de Desenvolvimento da Pós-Graduação (CAPES–PDPG) Pós-doutorado Estratégico, Process Number: 88887.692247/2022-00.

Conflict of Interest

The authors declare no conflict of interest.

Data Availability Statement

The datasets generated and analyzed during the current study are available from the corresponding author upon reasonable request

References

1. DAMBIEC M., KLINK A., POLECHOŃSKA L. Concentration and translocation of trace metals in Solidago gigantea in urban areas: a potential bioindicator. International Journal of Environmental Science and Technology, **19** (11), 11729, **2022**.
2. PALLOTTINI M., GORETTI E., ARGENTI C., LA PORTA G., TOSITTI L., DINELLI E., MORONI B., PETROSELLI C., GRAVINA P., SELVAGGI R., CAPPELLETTI D. Butterflies as bioindicators of metal contamination. Environmental Science and Pollution Research, **30** (56), 95606, **2023**.
3. CAKAJ A., LISIAK-ZIELIŃSKA M., HANĆ A., MAŁECKA A., BOROWIAK K., DRAPIKOWSKA M. Common weeds as heavy metal bioindicators: a new approach in biomonitoring. Scientific Reports, **13** (1), 34019, **2023**.
4. ABRICA-GONZÁLEZ P., GÓMEZ-ARROYO S., JAZCILEVICH-DIAMANT A., SOTELO-LÓPEZ A., FLORES-MÁRQUEZ A.R., CORTÉS-ESLAVA J. Evaluation of Toxicological Effects of ZnO and CuO Nanoparticles with *Taraxacum officinale* as Bioindicator. Water, Air & Soil Pollution, **234** (443), 1, **2023**.
5. REHMAN Z.U., JUNAID M.F., IJAZ N., KHALID U., IJAZ Z. Remediation methods of heavy metal contaminated soils from environmental and geotechnical standpoints. Science of the Total Environment, **867**, 161468, **2023**.
6. POURESMAIELI M., ATAEI M., FOROUZANDEH P., AZIZOLLAHI P., MAHMOUDIFARD M. Recent progress on sustainable phytoremediation of heavy metals from soil. Journal of Environmental Chemical Engineering, **10** (1), 108482, **2022**.
7. MBAH C.N., NJOKU C. Yields and heavy metal uptake of cocoyam (*Xanthosoma sagittifolium*) and effects on soil properties of different tillage practices and application of burnt rice husk dust in Abakaliki, south-east Nigeria. Biological Agriculture & Horticulture, **39** (1), 62, **2022**.
8. ALVAN M., OSUJI J.O., OCHEKWU E.B. Heavy metal characterization of edible aroids (*Colocasia esculenta* (Taro) and *Xanthosoma sagittifolium* (Tannia) growing in parts of Rivers State). Global Academic and Scientific Journal of Multidisciplinary Studies, **3** (6), 35, **2025**.
9. CALLE J., BENAVENT-GIL Y., ROSELL C.M. Use of flour from cormels of *Xanthosoma sagittifolium* (L.) Schott and *Colocasia esculenta* (L.) Schott to develop pastes foods: Physico-chemical, functional and nutritional characterization. Food Chemistry, **338**, 128666, **2020**.
10. DJUIDJE K.P.F., ASULTAN W., BEAULIEU C., WONG M.Y., BOUDJEKO T. Characterization of endophytic Streptomyces strains from roots of cocoyam (*Xanthosoma sagittifolium* L. Schott) in the South West Region of Cameroon, their in vitro plant growth promoting abilities and biocontrol efficacy against *Pythium myriotylum*. South African Journal of Botany, **144**, 145, **2022**.
11. FIOROTO A.M., TONIAZZO T., GIUNTINI E.B., OLIVEIRA P.V., PURGATTO E. Mineral nutrients and protein composition of non-conventional food plants (*Pereskia aculeata* Miller, *Sonchus oleraceus* L. and *Xanthosoma sagittifolium* (L.) Schott). Journal of Food Composition and Analysis, **136**, 106825, **2024**.
12. OYEFESO B.O., AKINTOLA A., AKINTUNDE M.M., AYANDOKUN O.C., FADELE O.K., OGUNLADE C.A. Proximate composition of tannia (*Xanthosoma sagittifolium*) flour as influenced by pretreatment and drying temperature. LAUTECH Journal of Engineering and Technology, **17** (2), 58, **2023**.
13. MARGUÍ E., DALIPI R., BORGESE L., DEPERO LE, QUERALT I. Possibilities and drawbacks of total reflection X-ray fluorescence spectrometry as a fast, simple and cost-effective technique for multielement analyses of cosmetics. Analítica Química Acta, **1075**, 27, **2019**.
14. BEZERRA C.D.S., TOMAZ J.S., VALENTE M.S.F., ESPINDULA M.C., MARQUES R.L.S., TADEU H.C., FERREIRA F.M., SILVA G.S., MENESES C.H.S.G., LOPES M.T.G. Phenotypic Diversity and Genetic Parameters of Coffea canephora Clones. Plants, **12** (23), 4052, **2023**.
15. GOMES L.M., BEZERRA C.S., TOMAZ J.S., MENESES C.H.S.G., MARQUES R.L.S., PEREIRA A.M., LOPES R., VALENTE M.S.F., RAMOS S.L.F., LOPES M.T.G. Variation of Heavy Metals Accumulation by Malva in Amazonian Ecosystems of Drylands and Floodplains. Polish Journal of Environmental Studies, **2024**.
16. TOMAZ J.S., BEZERRA C.S., MENESES C.H.S.G., MARQUES R.L.S., FRAXE T.J.P., LOPES R., VALENTE M.S.F., RAMOS S.L.F., LIMA S.C.S., LOPES M.T.G. Plant Tissues of *Stryphnodendron pulcherrimum* (Willd.) Hochr. as Environmental Bioindicators. Polish Journal of Environmental Studies, **34** (4), 4807, **2025**.
17. MARIJAN M., JABLAN J., JAKUPOVI´C L., JUG M., MARGUÍ E., DALIPI R., SANGIORGI E., ZOVKO KONˇCI´C M. Plants from urban parks as valuable cosmetic ingredients: green extraction, chemical composition and activity. Agronomy, **12** (1), 204, **2022**.
18. ANTONANGELO J., ZHANG H. Soil and plant nutrient analysis with a portable XRF probe using a single calibration. Agronomy, **11** (11), 2118, **2021**.
19. ALLEGRETTA I., BILO F., MARGUÍ E., PASHKOVA G.V., TERZANO R. Development and Application of X-rays in Metal Analysis of Soil and Plants. Agronomia, **13** (1), 114, **2022**.
20. DALIPI R., MARGUÍ E., BORGESE L., DEPERO L.E. Multi-element analysis of vegetal foodstuff by means of low power total reflection X-ray fluorescence (TXRF) spectrometry. Food Chemistry, **218**, 348, **2017**.
21. QUESADA C.A., LLOYD J., ANDERSON L.O., FYLLAS N.M., SCHWARZ M., CZIMCZIK C. I. Soils of Amazonia with particular reference to the RAINFOR sites. Biogeosciences, **8** (6), 1415, **2011**.
22. EMBRAPA SOLOS. Sistema brasileiro de classificação de solos. Centro Nacional de Pesquisa de Solos: Rio de Janeiro, **3**, **2013**.
23. SOUZA E.S.D., FERNANDES A.R., SOUZA BRAZ A.M., OLIVEIRA F.J.D., ALLEONI L.R.F., CAMPOS M.C.C. Physical, chemical, and mineralogical attributes of a representative group of soils from the eastern Amazon region in Brazil. Soil, **4** (3), 195, **2018**.
24. FRANCO G.F., SOUZA J.J.L.L., FARIA A.L.L., CAMPOS M.C.C., COSTA L.M. Spatial Distribution of Soil Organic Carbon in Amazonia. Journal of Agricultural Science, **10** (9), 153, **2018**.
25. KLOCKENKAMPER R., VON BOHLEN A. Determination of the critical thickness and the sensitivity for the thin-film analysis by total reflection X-ray fluorescence spectrometry. Spectrochimica Acta, **44** (5), 461, **1989**.
26. DICKSON A., LEAF A., HOSNER J.F. Quality appraisal of white spruce and white pine seedling stock in nurseries. The Forest Chronicle, **36** (1), 10, **1960**.

27. SHAPIRO S.S., WILK M.B. Um teste de análise de variância para normalidade (amostra completa). Biometrika, **53** (3-4), 591, **1965**.
28. RCoreTeam. R:ALanguage and Environment for Statistical Computing; R Foundation for Statistical Computing: Vienna, Austria, 2010. Available online: https://www.R-project.org/ (accessed on 15 January 2025).
29. OKSANEN J., BLANCHET F.G., KINDT R. Vegan: Community Ecology Package, R Package Version 2.2-0; R Foundation for Statistical Computing: Vienna, Austria, 2014. Available online: http://CRAN.Rproject.org/package=vegan(accessed on 15 January 2025).
30. MOCEK-PŁÓCINIAK A., MENCEL J., ZAKRZEWSKI W., ROSZKOWSKI S. Phytoremediation as an effective remedy for removing trace elements from ecosystems. Plants, **12** (8), 1653, **2023**.
31. OUBOHSSAINE M., DAHMANI I. Phytoremediation: Harnessing plant power and innovative technologies for effective soil remediation. Plant Stress, **14**, 100578, **2024**.
32. CAKAJ A., DRZEWIECKA K., HANĆ A., LISIAK-ZIELIŃSKA M., CISZEWSKA L., DRAPIKOWSKA M. Plants as effective bioindicators for heavy metal pollution monitoring. Environmental Research, **256**, 119222, **2024**.
33. MAO Y., WANG M., WEI H., GONG N., WANG F., ZHU C. Heavy Metal Pollution and Risk Assessment of Vegetables and Soil in Jinhua City of China. Sustainability, **15** (4241), **2023**.
34. CHOWDHURY A.I., SHILL L.C., RAIHAN M.M., RASHID R., BHUIYAN M.N.H., REZA S., ALAM M.R. Human health risk assessment of heavy metals in vegetables of Bangladesh. Scientific Reports, **14** (1), 65734, **2024**.
35. SHAHRIAR S.M.S., HOSSAIN M.S., DIPTI S., SALAM S.M.A. Heavy Metal Contamination in Soil and Vegetables: A Review with Health Risk Assessments. Journal of Science and Engineering Papers, **1** (1), 40, **2024**.
36. GRIFFITHS M., ROY S., GUO H., SEETHEPALLI A., HUHMAN D., GE Y., SHARP R.E., FRITSCHI F.B., YORK L.M. A multiple ion-uptake phenotyping platform reveals shared mechanisms affecting nutrient uptake by roots. Plant Physiology, **185** (3), 81, **2021**.
37. SOLANGI F., ZHU X., CAO W., DAI X., SOLANGI K.A., ZHOU G., ALWASEL Y.A. Nutrient uptake potential of nonleguminous species and its interaction with soil characteristics and enzyme activities in the agro-ecosystem. ACS Omega, **9** (9), 13860, **2024**.
38. SILVA J., BACHEGA R.G., SGANZERLA G.W., FERRAREZE P.J., SIMIONI J.F., CAMPOS L.M. Strategies and prospects in the recovery of contaminated soils by phytoremediation: an updated overview. Communications in Plant Sciences, **13**, 1, **2023**.
39. CÓRDOBA-TOVAR L., MARRUGO-MADRID S., CASTRO L.P., TAPIA-CONTRERAS E.E., MARRUGO-NEGRETE J., DÍEZ S. Exploring the phytoremediation potential of plant species in soils impacted by gold mining in Northern Colombia. Environmental Science and Pollution Research, **32** (7), 3795, **2025**.
40. OLADOYE P.O., OLOWE O.M., ASEMOLOYE M.D. Phytoremediation technology and food security impacts of heavy metal contaminated soils: A review of literature. Chemosphere, **288**, 132555, **2022**.
41. SHI L., LI J., PALANSOORIYA K.N., CHEN Y., HOU D., MEERS E., OK, Y.S. Modeling phytoremediation of heavy metal contaminated soils through machine learning. Journal of Hazardous Materials, **441**, 129904, **2023**.