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Toxic inorganic elements in plant-based beverages: Total concentration, dietary exposure and bioaccessibility

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ABSTRACT

The growing demand in the plant-based beverages market has shown the need to carry out studies on the composition of inorganic elements. Thus, this study evaluated the presence of 11 elements with toxic potential in plant-based beverages marketed in Brazil using ICP-MS, including a dietary exposure assessment and determination of bioaccessibility. The total contents were Al (<200–15350), Cr (<4–66.5), Co (<4–30.6), Ni (6.1–437), As (<4–6.43), Mo (<4–591), Cd (<4–8.24), Ba (11.6–16110) and Pb (<4–7.2) μg kg^{-1}, while Sb and Hg were below the LOQ (4 μg kg^{-1}) for all samples. The levels of Cd, Pb and As are in agreement with the limits established by the Codex Alimentarius and the Brazilian authorities. The exposure assessment demonstrated that risks to health are unlikely for the elements Al, Cr, Co, As, Cd and Pb. However, higher levels of Ni, Mo and Ba observed in some samples indicate a need for monitoring these elements. Bioaccessibility above 50% was observed for Co (51–107%) and Ni (54–86%) for all samples studied, reinforcing the need for caution in the consumption of these products, especially by children. The present results can be a relevant tool in providing data on inorganic contaminants and their bioaccessibility in plant-based beverages.

1. Introduction

The replacement of cow's milk for plant-based beverages has increased worldwide (Escobar-Sáez et al., 2022; Pereira and Rodrigues, 2021; Silva et al., 2020). Plant-based beverages are made by disintegrating the plant material in water, followed by homogenization to break particles into a uniform mixture and impart a milk-like consistency. Thus, the nutritional properties of these beverages are influenced mainly by the type of raw material used, origin, processing conditions, and the addition of nutrients (Ruzik and Jakubowska, 2022).

The environmental and ethical benefits of plant-based beverages are well established; however, there have been concerns about their nutritional and safety profile due to the presence of toxic inorganic elements in foods (Astolfi et al., 2020; Zhou et al., 2021). In addition, the environmental pollution (Afonne & Ifediba, 2020), the scaling up, and lack of systematic information on functional and health claims (such as allergenicity and toxicity), and the bioaccessibility of these contaminants (Pereira and Rodrigues, 2021) are key factors contributing to this risk.

Although the occurrence of chemicals leached from plastics and antinutritional compounds in plant-based foods is known, the information is still limited. The presence of inorganic elements has been reported in raw materials such as nickel (Ni) in nuts, chromium (Cr) in cereals, legumes, and their products, which can lead to increased exposure, and long-term accumulation in the human body, causing serious health problems (Afonne and Ifediba, 2020; Banach et al., 2022; Ruzik and Jakubowska, 2022). Thus, understanding the profile of toxic inorganic elements is fundamental to ensuring the safety of consumers.

Knowledge of the fraction of inorganic elements that can be absorbed by the body is of full relevance (Fioravanti et al., 2020) and has been studied using in vitro digestion methods, simulating human gastrointestinal conditions (INFOGEST 2.0) (Duijsens et al., 2022). Studies on trace elements have used the inductively coupled plasma mass spectrometry (ICP-MS) technique due to the ability to detect the element at low levels, with high sensitivity, versatility, and isotopic capability (Astolfi et al., 2020; Hernández-Pellón et al., 2018; Kgabi and Ambushe,

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2021; Ren et al., 2014; Román-Ochoa et al., 2021; Squadrone et al., 2020; Thomas, 2013).

The growing consumption of plant-based beverages and the novel products available on the market has led to the need to evaluate the composition of inorganic elements in this food category. To date, there are no data in the literature regarding the presence of toxic elements or specific regulations about inorganic contaminants in plant-based foods marketed in Brazil. Thus, this study evaluated the presence of 11 inorganic elements with toxic potential in plant-based beverages marketed in Brazil, using the ICP-MS technique. Furthermore, the exposure assessment and the in vitro bioaccessibility of these elements in plant-based beverages were evaluated in order to provide information about the safety of these products.

2. Materials and methods

2.1. Instrumentation

The concentrations of inorganic elements were determined by ICP-MS (iCAP RQ, Thermo Scientific, Bremen, Germany), and the experimental conditions are described in our previous study (Rebellato et al., 2023).

For the bioaccessibility assays, a Dubnoff-type water bath (Nova Tecnica Piracicaba, Brazil), a pH meter equipped with a selective electrode (Ohaus, Parsippany, NJ, USA), and a refrigerated centrifuge (Eppendorf, Hamburg, Germany) were used.

2.2. Reagents and materials

Reagents of analytical grade or higher were used: reverse osmosis purified water (Gehaka, São Paulo, Brazil), concentrated nitric acid (HNO_3) purified by sub boiling distillation (Distillacid, Berghof, Eningen, Germany), 30% hydrogen peroxide (H_2O_2), and 37% hydrochloric acid (HCl) (Merck, Darmstadt, Germany), sodium hydroxide (NaOH), potassium chloride (KCl), monopotassium phosphate (KH_2PO_4), sodium bicarbonate ($NaHCO_3$), sodium chloride (NaCl), magnesium chloride hexahydrate ($MgCl_2(H_2O)_6$), ammonium carbonate ($(NH_4)_2CO_3$), calcium chloride dihydrate ($CaCl_2\ 2(H_2O)$), α-amylase from hog pancreas (50 U/mg), pepsin from porcine gastric mucosa (>3200 U/mg), pancreatin from porcine pancreas (8 USP) and bovine bile (Sigma Aldrich, St Louis, MO, USA). The solutions were prepared according to the recommendations of the INFOGEST 2.0 protocol (Brodkorb et al., 2019).

2.3. Sampling

Thirty samples of plant-based beverages were purchased in supermarkets in the municipality of Campinas (São Paulo, Brazil). The samples consisted of 7 different plant-based beverages and 10 different brands. The plant-based beverages had rice, almond, oat, cashew nut, peanut, coconut, and soybeans as the main ingredients, as described in Table 1.

2.4. Analytical quality control

For analytical quality control, assays were performed to evaluate the following figures of merit: limit of detection (LOD), limit of quantification (LOQ), accuracy, precision, and linearity. The method was validated according to the guidelines of INMETRO (2020) and AOAC (2016). The analytical curves were found to be linear (R^2 >0.99) for all elements; and in the range of 5–5000 µg L^{-1} for Al, and 0.1–1000 µg L^{-1} for all other elements.

Table 2 presents the results of the method validation. The LOD and LOQ were calculated as LOD = 3 * s * f and LOQ = 5 * s * f; where s = the standard deviation of the concentration of 10 blank experiments, and f = dilution factor (40x). The LODs and LOQs obtained were adequate for

Table 1
Identification and main information on the labels of plant-based beverages (n = 30).

Sample	Brand	Commercial name	List of Ingredients *	Ingredients ** (n)
S1	A	Rice	Water, rice flour, sugar, sunflower oil, sea salt, vitamins (E, A, D), minerals (calcium and zinc), and stabilizers (mono and diglycerides of fatty acids, guar gum, and xanthan gum).	8
S2	B	Rice + Calcium	Water, organic rice (14%), organic sunflower oil, natural calcium, and salt.	5
S3	C	Rice	Water, rice (6.7%), sunflower oil, calcium (tricalcium phosphate), salt, vitamin A (retinyl palmitate), vitamin D2 (ergocalciferol), stabilizer gellan gum, and natural flavoring.	9
S4	C	Coconut & Rice	Water, rice (6.7%), coconut powder (3.0%), sunflower oil, calcium (tricalcium phosphate), salt, vitamin A (retinyl palmitate), vitamin D2 (ergocalciferol), stabilizer gellan gum, and natural flavoring.	10
S5	C	Cocoa & Rice	Water, rice (8.0%), demerara sugar, cocoa powder (2.0%), sunflower oil, calcium (tricalcium phosphate), salt, vitamin A (retinyl palmitate), vitamin D2 (ergocalciferol), stabilizer gellan gum, and natural flavoring.	11
S6	C	Almond	Reconstituted almond paste (water and almond paste [1.9%]), calcium (tricalcium phosphate), salt, vitamin A (retinyl palmitate), vitamin D2 (ergocalciferol), stabilizer gellan gum, and emulsifier sunflower lecithin.	7
S7	D	Almond	Water, almond, maltodextrin, minerals (calcium and zinc), salt, vitamins (E, B6, folic acid, D, and B12), flavoring, emulsifier sunflower lecithin, stabilizers (xanthan gum and gellan gum).	9
S8	E	Almond &Cocoa	Reconstituted almond paste, sugar, cocoa, minerals (calcium and zinc), sea salt, vitamins (B2, D2, and B12), stabilizers (carob gum and gellan gum), antioxidant sodium ascorbate, emulsifier sunflower lecithin, and natural flavoring.	10
S9	F	Almond	Almond milk (water, almond paste), coconut cream, pea protein, tricalcium phosphate (calcium), vitamins (B6 and B12), stabilizers (guar gum, gellan gum, polyphosphates), emulsifier sunflower lecithin, natural	9

(continued on next page)

Table 1 (*continued*)

Sample	Brand	Commercial name	List of Ingredients *	Ingredients ** (n)
			flavoring, and sweetener stevia.	
S10	F	Almond	Water, almond paste, coconut cream, pea protein, tricalcium phosphate (calcium), vitamins (B6 and B12), stabilizers (guar gum, gellan gum), emulsifier sunflower lecithin, natural flavoring, and sweetener stevia.	10
S11	G	Oat	Water, oat, algae calcium (conventional ingredients), and sea salt.	4
S12	G	Oatmeal with Vanilla	Water, oat, algae calcium (conventional ingredients), sea salt, and natural vanilla extract.	5
S13	G	Oat &Cocoa	Water, oat, natural cocoa, algae calcium (conventional ingredients), and sea salt.	5
S14	B	Oat + Calcium	Water, organic whole oat (16%), organic sunflower oil, natural calcium, and salt.	5
S15	H	Original Cashew Nut	Water, organic cashew nuts.	2
S16	H	Cashew Nut + Brazil Nut	Water, organic cashew nuts, and Brazil nuts.	3
S17	H	Cashew Nut &Cocoa	Water, organic cashew nuts, organic demerara sugar, and cacao.	4
S18	C	Cashew Nut	Reconstituted cashew nut paste (water and cashew nut paste [1.9%]), calcium (tricalcium phosphate), salt, vitamin A (retinyl palmitate), vitamin D2 (ergocalciferol), stabilizer gellan gum, and emulsifier sunflower lecithin.	7
S19	E	Cashew Nut	Reconstituted cashew nut paste, minerals (calcium and zinc), sea salt, vitamins (B2, D2, and B12), stabilizers (carob and gellan gums), emulsifier sunflower lecithin, natural flavorings, and antioxidant sodium ascorbate.	8
S20	F	Cashew Nut	Water, cashew nuts, tricalcium phosphate (calcium), vitamins (B6 and B12), stabilizers (guar gum, gellan gum), emulsifier sunflower lecithin, natural flavoring, and sweetener stevia.	8
S21	I	Peanut + Coconut	Water, peanut, coconut cream, and natural sweetener stevia.	4
S22	E	Coconut	Reconstituted coconut milk, minerals (calcium and zinc), sea salt, vitamins (B2, D2, and B12), natural flavoring, emulsifier sunflower lecithin, stabilizers (carob gum and gellan gum), and antioxidant sodium ascorbate.	8
S23	F	Coconut	Water, coconut cream, pea protein, tricalcium phosphate (calcium), vitamins (B6 and B12), stabilizers (guar gum, gellan gum), emulsifier sunflower lecithin, natural flavoring, and sweetener stevia.	9
S24	D	Coconut	Water, coconut cream, sugar, maltodextrin, minerals (calcium and zinc), salt, vitamins (E, B6, A, folic acid, D, and B12), emulsifier (citric acid esters of mono and diglycerides), stabilizers (xanthan gum and gellan gum), and flavoring.	10
S25	D	Zero-Sugar Soybeans	Water, soybeans, minerals (calcium and zinc), maltodextrin, salt, vitamins (E, B6, folic acid, D, and B12), flavoring, stabilizers (sodium citrate, gellan gum, and xanthan gum), emulsifier soy lecithin, and sweetener sucralose.	10
S26	D	Soybeans	Water, soybeans, sugar, minerals (calcium and zinc), salt, vitamins (E, B6, folic acid, D, and B12), flavoring, stabilizers (sodium citrate, gellan gum, and xanthan gum), emulsifier soy lecithin, and sweetener sucralose.	10
S27	J	Original 3% fat	Water, coconut oil, chicory fiber, soy protein, sugar, pineapple juice concentrate, pea protein, sunflower oil, calcium carbonate, salt, monocalcium phosphate, cabbage juice concentrate, vitamins (D2, B12), natural flavoring, stabilizers (acacia gum, dipotassium phosphate, xanthan gum, and gellan gum).	15
S28	J	Caramel Coffee	Water, coconut oil, sugar, chicory fiber, soy protein, pineapple juice concentrate, pea protein, sunflower oil, calcium carbonate, instant coffee powder, salt, monocalcium phosphate, cabbage juice concentrate, vitamin D2, vitamin B12, natural flavoring, stabilizers (dipotassium phosphate, xanthan gum, and gellan gum).	17
S29	J	Cocoa	Water, sugar, soy protein, pea protein, chicory fiber, cocoa powder, coconut oil, pineapple juice concentrate, calcium carbonate, sunflower oil, salt, cabbage juice concentrate, vitamin D2, Vitamin B12, natural flavoring, stabilizers (acacia gum, gellan gum, and dipotassium phosphate).	16
S30	J	Cocoa	Water, sugar, soy protein, pea protein, chicory fiber, cocoa powder, coconut oil, pineapple juice concentrate, calcium carbonate, sunflower oil, salt, cabbage juice concentrate, vitamin D2, Vitamin B12, natural	16

(*continued on next page*)

Table 1 (*continued*)

Sample	Brand	Commercial name	List of Ingredients *	Ingredients ** (n)
			flavoring, stabilizers (acacia gum, gellan gum, and dipotassium phosphate).	

* Faithful transcription of the information presented on the label; ** Estimated number of ingredients due to variation in the way described on product labels.

the determination of the 11 elements in plant-based beverages; and ranged from 0.8 (Cd) to 119 (Al) µg kg^{-1} and 4 (Cr, Co, Ni, As, Mo, Cd, Ba, Pb, Hg, Sb) to 200 (Al) µg kg^{-1}, respectively.

Method accuracy was evaluated using certified reference materials (n = 3 analytical repetitions): Peach leaves (NIST - SRM 1547) (Al, Cr, Ni, As, Mo, Ba, Pb, Hg and Sb), Lobster Hepatopancreas (NRCC Tort-3) (Co), Skimmed milk powder (ERM-BD151) (Cd); and recovery assays (50 µg kg^{-1}) (Cr and Sb) (n = 7 analytical repetitions). Recovery mean values ranged from 81% (As) to 118% (Co). All the expanded uncertainties ($U\Delta = 2.\ u\Delta$) were larger than the difference between mean measured value and certified value ($\Delta_m = |C_m - C_{CRM}|$). The measured mean value is therefore not significantly different from the certified value (ERM, 2010).

To determine the precision of the method, a plant-based beverage was analyzed with 7 independent analytical repetitions, and the coefficient of variation ($CV = (SD/C_m) * 100$, where SD is the standard deviation, C_m is the average concentration determined) was between 5% (Cr) and 15% (Mo); which is within the ranges defined by INMETRO (2020) and AOAC (2016).

2.5. Sample mineralization

The sample preparation procedure was based on the work of Rebellato et al., (2023): 0.5 g of sample was weighed into a 50 mL graduated tube, 4 mL HNO_3 and 2 mL H_2O_2 were added, and the tube was closed and allowed to stand overnight. After then, the tube was heated in an ultrasonic bath (80 °C for 35 min), chilled to room temperature, and the volume was adjusted to 20 mL with ultrapure water. The solution was filtered through a 0.45 µm filter. All analyzes were performed in triplicate, including the analytical blank.

2.6. Exposure assessment

Standard body weights (bw) of 60 kg (adults) and 15 kg (children) as well as a consumption of 200 mL of the beverage, serving size described on the labels (Brazil, 2020), were used to estimate the daily intake (DI = $\bar{x}$ *serving size/bw, were $\bar{x}$ is total concentration) of the elements studied. The DIs were calculated using the deterministic model (Kroes et al., 2002) and the results were expressed as micrograms of the element per kg body weight (µg kg^{-1} bw). The total concentrations of inorganic elements obtained were used in the calculations considering the samples individually. The elements with results below the LOQ were not considered.

To characterize the risk associated with exposure to inorganic elements, the DI values were compared to the available health-based guidance values established in the literature: Provisional Tolerable Weekly Intake (PTWI) and Tolerable Weekly Intake (TWI) values for Al; Benchmark Dose Lower Limit (BMDL) for As and Pb; Provisional Tolerable Monthly Intake (PTMI) for Cd; Tolerable Daily Intake (TDI) for Cr, Ni and Ba; Upper Intake Level (UL) for Mo and health-based guidance for Co (EFSA, 2008, 2010, 2012a, 2012b, 2013, 2020, 2021, 2022; FAO/WHO, 2011, 2022; WHO, 2004).

2.7. Bioaccessibility estimation

The estimation of the bioaccessibility of the inorganic elements was performed according to INFOGEST 2.0 standardized method (Brodkorb et al., 2019), with modifications. The gastric lipase step was not performed due to the unavailability of the material. Before starting the protocol, the enzyme activities were determined, and the protocol was adjusted for 2.5 g of sample. Once the digestion in vitro was completed, the resulting solution was centrifuged (3500 g, 30 min, 4 °C) and the supernatant was analyzed (Section 2.4). The bioaccessibility (B%) was calculated as %B = 100 x Y/Z, where Y is the element concentration of the bioaccessible fraction (µg element/kg sample) and Z is the total element concentration (µg element/kg sample).

2.8. Statistical analysis

The results were expressed as mean $\bar{x}$ ± SD of three independent replicates, and one-way ANOVA (95% confidence level) and principal components analysis (PCA) were performed using the software Statistic 7.0 (StatSoft, Tulsa, USA) and Pirouette 3.11 (Infometrix, Woodinville, USA), respectively.

3. Results and discussion

3.1. Total concentration of inorganic elements

The total contents of inorganic elements in the plant-based beverages are shown in Table 3, except for Sb and Hg, which were below the LOQ (4 µg kg^{-1}). The concentrations of As, Cd, and Pb were lower than the

Table 2
Results of the limit of detection (LOD), the limit of quantification (LOQ), accuracy (expected/certified values, experimental values, and recovery, n = 3), and precision (coefficient of variation, CV%; n = 7) for the inorganic elements.

Element	LOD (µg kg^{-1})	LOQ (µg kg^{-1})	Accuracy CRM / Spike	Certified / Expected value (mg kg^{-1})	Experimental Value (mg kg^{-1})	Recovery (%)	Precision (CV, %)
Al	119	200	NIST-SRM 1547	248.9 ± 6.5	240 ± 16	96	14
Cr	3.5	4	NIST-SRM 1547	1*	1 ± 0.04	100	5
			Spike (n = 7)	0.050	0.049 ± 0.04	98	
Co	1.4	4	NRCC Tort-3	1.06	1.25 ± 0.09	118	9
Ni	3.7	4	NIST-SRM 1547	0.689 ± 0.095	0.596 ± 0.005	86	6
As	1.1	4	NIST-SRM 1547	0.062 ± 0.014	0.050 ± 0.007	81	9
Mo	1.9	4	NIST-SRM 1547	0.0603 ± 0.0068	0.066 ± 0.003	109	15
Cd	0.8	4	ERM-BD 151	0.106 ± 0.013	0.111 ± 0.001	104	9
Ba	3.7	4	NIST-SRM 1547	123.7 ± 5.5	118 ± 4	95	10
Pb	3.6	4	NIST-SRM 1547	0.869 ± 0.018	0.851 ± 0.018	98	9
Hg	1.9	4	NIST-SRM 1547	0.0317 ± 0.0043	0.034 ± 0.007	109	9
Sb	1.2	4	NIST-SRM 1547	0.02*	0.02 ± 0.01	103	9
			Spike (n = 7)	0.050	0.047 ± 0.04	94	

* Reference value; CRM = Certified reference material; NIST-SRM 1547 = Peach leaves; NRCC Tort-3 = Lobster Hepatopancreas; ERM-BD 151 = Skimmed milk powder.

LOQ for most samples, except for rice-based (As, Cd, and Pb), almond-based (Cd), and soy-based (Pb) samples. Similar findings were reported by Astolfi et al. (2020), who observed low Sb and Hg levels in rice, almond, oat, cashew, coconut, and soy-based beverages and concluded that the elements As, Cd, and Pb posed no risk to consumers even at low concentrations. Marquès et al. (2017), studied 8 samples of plant-based beverages (rice, almond, oat and soy) and reported non-detectable levels of Hg and Co. For Pb, one oat-based sample presented detectable level, even though it did not contain cocoa in its composition.

The results of the statistical analysis (one-way ANOVA and Tukey's test) were analyzed for the samples made with the same plant base: rice, almond, oat, cashew nut, peanut/coconut, and soybeans. Although sample S21 is a peanut-based beverage, it was grouped with the coconut-based samples due to its composition (Table 1).

3.1.1. *Rice-based beverages*

Of the 5 samples studied, the brand A (sample S1) and B (S2) showed results below the LOQ for the elements Al, Cr, Co, Cd, and Pb, while the brand C (S3, S4, and S5) showed significantly different Al levels, and higher Cr levels in S5 (cocoa and rice), when compared to S3 and S4. Similar behavior was observed for Al, Ni, and Ba, besides being the only sample with quantifiable levels of Co, Cd, and Pb, with values of 30.6 ± 3.6, 8.24 ± 0.35, and 6.8 ± 1.0 μg kg^{-1}, respectively.

Although the guidelines of Codex CF/15 (FAO/WHO, 2022), and the Brazilian regulation RDC 722/22 and IN 160/22 (Brazil, 2022a, 2022b) have established tolerable maximum limits (TML) for some inorganic elements, there are no specific limits for plant-based beverages. For example, sample S5 can be classified into at least 3 categories: rice and derived products; non-alcoholic beverages, excluding fruit juices and nectars; and chocolates and cocoa products with less than 40% cocoa (Brazil, 2022b). The Cd and Pb levels found in the studied samples were below regulatory limits, with values from < 0.02–0.40 and < 0.05–0.20 mg kg^{-1} (<20–400 and <50–200 μg kg^{-1}) for Cd and Pb, respectively. As reported by Shi et al. (2016), rice is the largest contributor to human intake of Cd, followed by wheat, vegetables, and shellfish.

Only the rice-based beverages presented the element As in their composition. The established TML for this element ranges from 0.05 to 0.20 mg kg^{-1} (50–200 μg kg^{-1}) (Brazil, 2022b) and 0.01–0.5 mg kg^{-1} (10–500 μg kg^{-1}) (FAO/WHO, 2022), and the samples of the present study were in accordance with these limits. As shown in Table 1, the sample with the highest As level (S2) has the lowest number of ingredients (5), which may have contributed to a higher concentration of the raw material (rice) in the product. The high As levels in this product are probably due to its natural bioaccumulation in rice plants (Allevato et al., 2019; Ciminelli et al., 2017; Domínguez-González et al., 2020).

Astolfi et al. (2020) reported higher As concentrations in hazelnut-based beverages (17.2 μg kg^{-1}), followed by rice-based (16.3 μg kg^{-1}) and soy-based (16 μg kg^{-1}) beverages. These results are higher than those reported by Ruzik and Jakubowska (2022), who evaluated the As concentrations in different plant-based beverages and observed higher concentrations in rice-based (2.34 μg kg^{-1}) and coconut and rice-based (1.27 μg kg^{-1}) beverages. Similar behavior was observed in this study, confirming the higher concentration of this element in rice-based products.

3.1.2. *Almond-based beverages*

Significant differences were observed for the Al and Cr concentrations among all beverages, except for S6 and S10, while the element Co was quantifiable only in S8 (almond and cocoa). This sample showed significantly higher Al, Cr, Ni, and Ba concentrations when compared to the other samples of the same plant base. Concerning Cd concentrations, only sample S6 showed quantifiable levels (4.19 ± 0.11 μg kg^{-1}), although below the TML range for the possible food categories that include this beverage (Brazil, 2022b; FAO/WHO, 2022). No data was found in the literature regarding the presence of Cd in almonds.

Table 3
Total concentration ($\bar{x}$ ± SD μg kg^{-1}) of nine potentially toxic inorganic elements found in plant-based beverages.

Plant base	Sample	Brand	$\bar{x}$ ± SD μg kg-^{1}								
			Al	Cr	Co	Ni	As	Mo	Cd	Ba	Pb
Rice	S1	A	<LOQ	<LOQ	<LOQ	6.1 ± 1.1^{c}	4.38 ± 0.15^{b}	15.3 ± 0.4^{c}	<LOQ	11.6 ± 0.7^{c}	<LOQ
	S2	B	<LOQ	<LOQ	<LOQ	51.8 ± 1.1^{b}	6.43 ± 0.03^{a}	40.6 ± 0.3^{a}	<LOQ	13.9 ± 0.4^{c}	<LOQ
	S3	C	1210 ± 60^{b}	12.7 ± 1.3^{b}	<LOQ	31.8 ± 1.4^{d}	5.12 ± 0.20^{b}	29.5 ± 1.7^{b}	<LOQ	14.3 ± 0.2^{c}	<LOQ
	S4	C	242 ± 46^{c}	11.6 ± 1.4^{b}	<LOQ	31.3 ± 2.4^{d}	4.89 ± 0.58^{b}	32.9 ± 3.4^{b}	<LOQ	50.0 ± 7.9^{b}	<LOQ
	S5	C	1510 ± 180^{a}	37.2 ± 1.0^{a}	30.6 ± 3.6^{a}	263 ± 12^{a}	5.08 ± 0.67^{b}	42.2 ± 4.4^{a}	8.24 ± 0.35^{a}	482 ± 23^{a}	6.8 ± 1.0^{a}
Almond	S6	C	352 ± 21^{c}	11.9 ± 0.1^{d}	<LOQ	27.0 ± 0.9^{c}	<LOQ	6.2 ± 1.5^{b}	4.19 ± 0.11^{a}	115 ± 6^{c}	<LOQ
	S7	D	1210 ± 80^{b}	8.53 ± 0.24^{d}	<LOQ	23.1 ± 1.4^{c}	<LOQ	<LOQ	<LOQ	135 ± 35^{c}	<LOQ
	S8	E	1730 ± 25^{a}	52.5 ± 3.5^{a}	15.9 ± 0.6^{a}	99.8 ± 3.0^{a}	<LOQ	8.5 ± 1.8^{b}	<LOQ	451 ± 12^{a}	<LOQ
	S9	F	<LOQ	43.7 ± 3.2^{b}	<LOQ	57.4 ± 2.2^{b}	<LOQ	32.9 ± 1.1^{a}	<LOQ	239 ± 7^{b}	<LOQ
	S10	F	307 ± 36^{c}	31.3 ± 1.7^{c}	<LOQ	58.3 ± 1.5^{b}	<LOQ	31.0 ± 1.4^{a}	<LOQ	128 ± 3^{c}	<LOQ
Oat	S11	G	877 ± 25^{b}	22.2 ± 3.7^{b}	<LOQ	52.6 ± 0.6^{d}	<LOQ	68.9 ± 3.2^{d}	<LOQ	112 ± 2^{b}	<LOQ
	S12	G	687 ± 76^{c}	24.6 ± 0.8^{b}	<LOQ	103 ± 1^{c}	<LOQ	133 ± 1^{c}	<LOQ	117 ± 2^{b}	<LOQ
	S13	G	1400 ± 9^{a}	66.5 ± 4.6^{a}	24.7 ± 1.4^{a}	244 ± 10^{a}	<LOQ	156 ± 4^{b}	<LOQ	487 ± 15^{a}	<LOQ
	S14	B	531 ± 45^{d}	19.8 ± 2.5^{b}	<LOQ	217 ± 4^{b}	<LOQ	181 ± 5^{a}	<LOQ	50.7 ± 1.2^{c}	<LOQ
Cashew Nut	S15	H	381 ± 69^{d}	<LOQ	<LOQ	353 ± 13^{c}	<LOQ	17.6 ± 0.3^{a}	<LOQ	108 ± 5^{b}	<LOQ
	S16	H	629 ± 25^{c}	<LOQ	13.5 ± 0.5^{b}	433 ± 8^{a}	<LOQ	15.1 ± 1.0^{b}	<LOQ	16110 ± 46^{a}	<LOQ
	S17	H	15350 ± 44^{a}	<LOQ	22.4 ± 1.5^{a}	437 ± 9^{a}	<LOQ	17.6 ± 0.8^{a}	<LOQ	241 ± 4^{b}	<LOQ
	S18	C	<LOQ	4.00 ± 0.55^{b}	<LOQ	74.3 ± 0.6^{d}	<LOQ	6.15 ± 0.19^{e}	<LOQ	28.9 ± 4.8^{b}	<LOQ
	S19	E	1340 ± 39^{b}	6.19 ± 0.69^{b}	<LOQ	96.6 ± 3.2^{d}	<LOQ	9.7 ± 1.1^{d}	<LOQ	199 ± 6^{b}	<LOQ
	S20	F	<LOQ	42.7 ± 2.0^{a}	<LOQ	408 ± 9^{b}	<LOQ	11.9 ± 0.9^{c}	<LOQ	94.8 ± 3.9^{b}	<LOQ
Peanut	S21	I	<LOQ	<LOQ	<LOQ	92.9 ± 1.8^{a}	<LOQ	66.0 ± 2.3^{a}	<LOQ	144 ± 7^{a}	<LOQ
Coconut	S22	E	2170 ± 94^{a}	<LOQ	<LOQ	20.2 ± 0.4^{c}	<LOQ	<LOQ	<LOQ	153 ± 7^{a}	<LOQ
	S23	F	529 ± 81^{c}	49 ± 11^{a}	4.00 ± 0.18^{b}	48.9 ± 5.3^{b}	<LOQ	41.6 ± 1.4^{b}	<LOQ	20.5 ± 2.2^{c}	<LOQ
	S24	D	1550 ± 67^{b}	<LOQ	6.30 ± 0.14^{a}	52.5 ± 1.4^{b}	<LOQ	<LOQ	<LOQ	101 ± 4^{b}	<LOQ
Soybean	S25	D	3570 ± 27^{a}	11.2 ± 0.5^{ab}	4.22 ± 0.37^{d}	73.1 ± 1.5^{d}	<LOQ	591 ± 20^{a}	<LOQ	197 ± 8^{e}	7.2 ± 1.8^{a}
	S26	D	3030 ± 20^{b}	<LOQ	6.40 ± 0.99^{c}	79.3 ± 2.2^{c}	<LOQ	450 ± 8^{b}	<LOQ	139 ± 6^{f}	<LOQ
	S27	J	1710 ± 12^{c}	9.69 ± 0.53^{b}	<LOQ	17.4 ± 2.8^{e}	<LOQ	40.3 ± 0.5^{de}	<LOQ	313 ± 7^{c}	<LOQ
	S28	J	666 ± 20^{e}	4.36 ± 0.19^{c}	<LOQ	12.8 ± 0.6^{e}	<LOQ	37.3 ± 1.3^{e}	<LOQ	257 ± 7^{d}	<LOQ
	S29	J	1680 ± 15^{c}	13.8 ± 2.6^{a}	13.9 ± 0.5^{b}	128 ± 4^{a}	<LOQ	64.5 ± 2.3^{c}	<LOQ	650 ± 25^{a}	<LOQ
	S30	J	1170 ± 72^{d}	11.7 ± 0.5^{ab}	16.0 ± 0.2^{a}	108 ± 2^{b}	<LOQ	62.8 ± 0.9^{cd}	<LOQ	530 ± 4^{b}	<LOQ

Results are expressed as $\bar{x}$ ± SD, mean ± standard deviation ($n = 3$). Different letters for the same element (column) and same plant base indicates significant difference ($p < 0.05$), according to Tukey's test at a 95% confidence level. <LOQ: level below the limit of quantification.

Regarding the samples S9 and S10, the type of packaging (carton and plastic bottle, respectively) may have affected the content of inorganic elements. Similar Ni and Mo concentrations were observed in both beverages, and S10 exhibited lower quantifiable results for the element Al, and lower Cr and Ba levels when compared to the sample S9.

Similar results were reported by Astolfi et al. (2020), who studied almond-based beverages from the Italian market and found lower Co, As, Cd, and Pb levels than the LOQ, and similar Mo levels (16 ± 6 μg kg^{-1}). In the present study, lower Ni and higher Al, Cr, and Ba levels were found, evidencing that the concentration of potentially toxic elements can vary with the origin of the raw material.

3.1.3. *Oat-based beverages*

All samples presented significantly different Al, Ni, and Mo concentrations, although three samples were from the same brand. Only the Cr (S11, S12, and S14) and Ba (S11 and S12) concentrations were similar, showing that the composition affects the total concentration of inorganic elements. The sample S13 (oat and cocoa) had the highest Al, Cr, Ni, and Ba concentrations, and was the only sample with a Co level above the LOQ. The Al, Cr, and Ni concentrations in the oat-based beverages were higher than those reported by Astolfi et al. (2020), which were similar for the elements Ba and Mo, and lower for As (>8 μg kg^{-1}).

3.1.4. *Cashew nut-based beverages*

The cashew nut-based beverages consisted of 3 samples from brand H (S15, S16, and S17), and a sample from brands C, E, and F, corresponding to S18, S19, and S20, respectively. The samples S18 and S20 presented Al concentrations lower than the LOQ, which were significantly different from the other samples. The element Cr was not quantified in the samples of brand H, and the highest Cr concentration was observed for sample S20. Regarding samples S18 and S19, the results were significantly similar for Cr, Ni, and Ba. Quantifiable Co levels were observed only for the beverages containing Brazil nuts (S16) and cocoa (S17). This type of nut may have contributed to the high Ba levels (S16 = 16110 ± 46 μg kg^{-1}), which were significantly higher when compared to the other samples (more than 100 times). Cereal products and nuts can contain high Ba concentrations (0.007 mg g^{-1} in walnuts, and up to 4 mg g^{-1} in Brazil nuts) (WHO, 2004). Concerning the element Ni, the cashew nut-based beverages presented the highest concentrations (S15, S16, S17, and S20).

3.1.5. *Coconut-based beverages*

This group is composed of beverages from the brands E, F, D, and I, corresponding to the samples S22, S23, S24, and S21, respectively. The Ni and Mo concentrations were significantly higher in S21. Overall, the coconut-based beverages presented significant differences, except for the elements Ni (S23 and S24), and Ba (S21 and S22). High Ni levels in coconut-based beverages were reported by Astolfi et al. (2020), which was not observed in the present study.

3.1.6. *Soy-based beverages*

Six soy-based beverages from two different brands were studied, corresponding to brands D (S25 and S26) and J (S27, S28, S29, and S30). The samples from brand J contained more ingredients in their composition, from 15 to 17 ingredients (Table 1), which contributes to the differences in the element studied. The element Pb was quantified only in S25 (7.2 ± 1.8 μg kg^{-1}). Astolfi et al. (2020) reported high Mo levels in similar beverages, and Milani et al. (2018) studied inorganic elements in soy-based beverages (apple, grape, and orange) and reported that the ingredients of the formulation can affect the concentrations of inorganic elements.

3.2. *Principal component analysis (PCA)*

Data in Table 3 allowed assessing the correlation between the 30 plant-based beverages and the concentrations of the inorganic elements through principal component analysis (PCA). The data were arranged in a 30 × 7 matrix representing 210 trials, where the rows refer to samples and the columns correspond to the elements with quantifiable contents. The data were auto-scaled and the samples S5 and S25 (containing Pb) and S16 (containing Ba) were considered outliers. Fig. 1 shows the samples/scores plot (A) and variables loadings plots (B) of PC1, forming 4 groups of samples (1, 2, 3, and 4) according to the composition of the inorganic element. Sample S6 (almonds) was not classified in these groups due to its distinct composition, with high Cd levels.

- Group 1: formed by the rice-based samples (S1, S2, S3, and S4), which had the highest total concentration of the element As;
- Groups 3 (S8, S29, S30) and 4 (S13 and S17): formed by cocoa-based beverages and sample S26. These groups evidenced the effect of the number of ingredients, which was higher than 10 in Group 3 (high Al, Cr, and Ba levels) and lower than 5 in Group 4 (low Co and Ni levels);
- Group 2: formed by the remaining samples (S7, S9, S10, S11, S12, S14, S15, S18, S19, S20, S21, S22, S23, S24, S27, and S28). A new PCA was applied to Group 2, and the results are shown as samples/scores plot (C) and variables loadings plot (D). The samples were classified into four distinct groups: Group 5 (S27, S28), composed of soy-based samples, without the addition of cocoa and with high Ba levels; Group 6 (S9, S10, S11, S12, S14, and S23) mainly composed of the samples from the brands F and G, with high concentrations of the elements Mo and Cr; Group 7 (S15, S18, and S20) composed of cashew nut-based samples with higher Ni levels; Group 8 (S7, S24, S19, and S22) mainly composed of samples from the brands D and E, with high Al levels.

3.3. *Exposure assessment*

Table 4 presents the daily intake (DI) values for adults and children, using standard body weights of 60 kg (adults) and 15 kg (children), considering a daily consumption of 200 mL of plant-based beverage, serving size described on the labels (Brazil, 2020). It is worth mentioning that this food does not represent the only source of these elements in a regular diet.

To date, few authors have reported data on inorganic elements of plant-based beverages. Astolfi et al. (2020) studied the dietary intake considering a 240 mL serving of the product and reported that the potentially toxic or toxic elements were within the levels allowed by the references. Godebo et al. (2023) studied toxic metals and essential elements contents in commercially available fruit juices and other non-alcoholic beverages (including ten plant-based beverages) from the United States and reported that the toxicity of these products is unlikely, but more attention should be paid toward moderate beverage consumption, especially to protect the health of infants and young children.

3.3.1. *Aluminum*

The DI for the element Al ranged from 0.81 to 11.9 and 3.22–47.5 μg kg^{-1} bw for adults and children, respectively (Table 4). When considering the PTWI of 2 mg kg^{-1} bw (2000 μg kg^{-1} bw) (FAO/WHO, 2022), and the sample S25 with the highest Al concentration, the maximum estimated exposure of this sample was 4.2% and 16.6% PTWI for adults and children, respectively. The European Food Safety Authority - EFSA (2008) reassessed Al from all sources, including food additives, and established a TWI of 1 mg kg^{-1} bw (1000 μg kg^{-1} bw). Following this literature, estimated exposure to a portion of the S25 sample was 8.3% and 33.3% TWI for adults and children, respectively. Considering only the consumption of plant-based beverages, an adult and a child should ingest 2.4 and 0.6 L of the S25 sample, respectively, to reach 100% of the TWI.

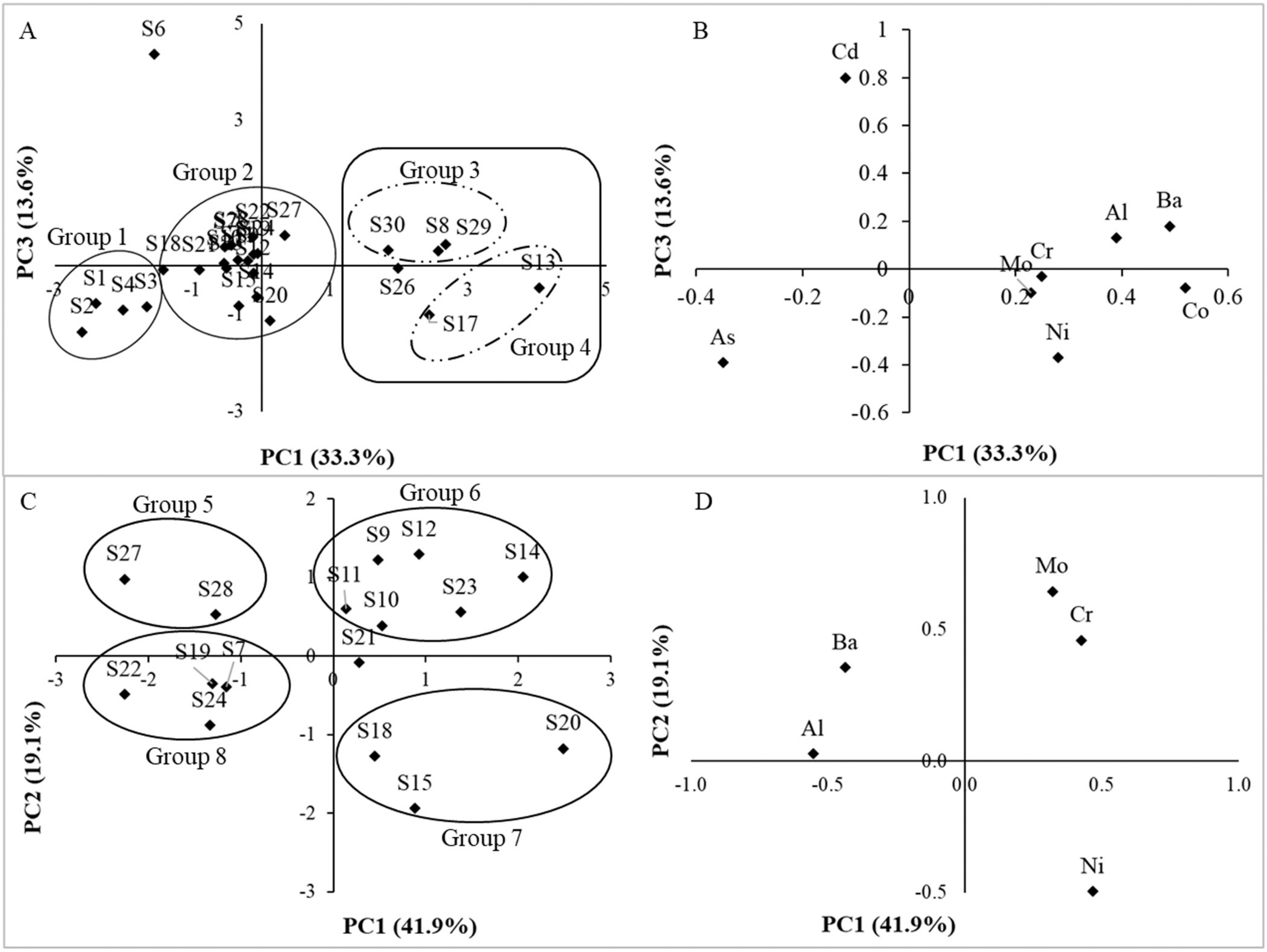

Fig. 1. Principal component analysis of inorganic element concentrations of plant-based beverages: (A and C) score plots and (B and D) loadings plots. Group 1 - rice based samples; Group 3 and 4 - cocoa based samples; Group 5 - soy-based samples without cocoa; Group 6 - brand F and G samples; Group 7 - cashew based samples; Group 8 - brand D and E samples.

3.3.2. *Chromium and Cobalt*

The estimated DI for the element Cr (samples S18 and S13) ranged from 0.01 to 0.22 and 0.05–0.89 μg kg^{-1} bw for adults and children, respectively. Concerning the element Co (S23 and S5), the estimated DI ranged from 0.01 to 0.10 and 0.05–0.41 μg kg^{-1} bw for adults and children, respectively. Data from EFSA (2014) showed a TDI of 300 μg Cr (III) kg^{-1} bw per day, due to effects of Cr (III) on reproduction and developmental toxicity. For the Co, according to EFSA (2012b), a health-based guidance for chronic exposure would be 1.6 μg kg^{-1} bw per day for threshold effects of oral cobalt, values which are higher than the levels found in the present study for adults, calculated under the same conditions.

3.3.3. *Nickel*

The estimated DI for the element Ni ranged from 0.02 to 1.46 and 0.08–5.82 μg kg^{-1} bw for adults and children, respectively. Considering the TDI of 13 μg kg^{-1} bw, derived from the BMDL$_{10}$ of 1.3 mg Ni kg^{-1} bw per day (1300 μg Ni kg^{-1} bw per day), due to the critical effect of the increased incidence of post-implantation loss (developmental toxicity) in rats in the one- and two-generation studies (EFSA, 2020), the consumption of 200 mL of the sample S17 corresponds to 11.2% and 44.8% of the TDI established for adults and children, respectively. Thus, the consumption of this product by children should be viewed with caution, as 90% of the TDI is reached when consuming 2 daily servings of the product (400 mL). Regarding samples S5, S13, S14, S15, S20, and S26, 100% of the TDI is reached when considering the consumption of 1 L of the product (typical volume of the packages). Literature data have shown that grains and grain-derived products are major contributors to Ni exposure in the European diet, with a higher susceptibility for individuals with Ni hypersensitivity or kidney disease (Rubio-Armendáriz et al., 2021).

3.3.4. *Arsenic*

In rice-based beverages, the estimated DI for the element As ranged from 0.01 to 0.02 and 0.06–0.09 μg kg^{-1} bw, for adults and children, respectively (Table 4). Whereas the BMDL$_{0.5}$ for inorganic As is 3.0 μg kg^{-1} bw day (FAO/WHO, 2011), the As intakes resulting from the consumption of sample S2 is approximately 30 times less than BMDL$_{0.5}$ ($3/0.09 = 33.33$), for children. Daily dietary exposure values established by EFSA (2021) to inorganic As ranged between 0.03 and 0.61 μg kg^{-1} bw, which are higher than the exposure values of the 30 samples of the present study. Ruzik and Jakubowska (2022) studied the estimated daily intake of inorganic As from the consumption of plant-based beverages and found results above the reference values from EFSA (BMDL$_{0.1}$ = 0.3–8 μg kg^{-1} bw day).

3.3.5. *Molybdenum*

The estimated DI for Mo ranged from 0.02 to 1.97 and 0.08–7.88 μg kg^{-1} bw for adult and children, respectively. When considering a UL equivalent to 600 μg per day, for adults, including

Table 4
Estimated Daily Intake (DI= $\bar{x}$ *serving size/bw) values of toxic inorganic elements for adults/children (µg kg^{-1} bw), considering a 200 mL serving and body weights of 60 kg and 15 kg.

Plant base	Sample	Daily intake (Adults/Children) µg kg^{-1} bw								
		Al	Cr	Co	Ni	As	Mo	Cd	Ba	Pb
Rice	S1	-	-	-	0.02/0.08	0.01/0.06	0.05/0.20	-	0.04/0.15	-
	S2	-	-	-	0.17/0.69	0.02/0.09	0.14/0.54	-	0.05/0.19	-
	S3	4.02/16.1	0.04/0.17	-	0.11/0.42	0.02/0.07	0.10/0.39	-	0.05/0.19	-
	S4	0.81/3.22	0.04/0.16	-	0.10/0.42	0.02/0.07	0.11/0.44	-	0.17/0.67	-
	S5	5.05/20.2	0.12/0.50	0.10/0.41	0.88/3.51	0.02/0.07	0.14/0.56	0.03/0.11	1.61/6.43	0.02/0.09
Almond	S6	1.17/4.70	0.04/0.16	-	0.09/0.36	-	0.02/0.08	0.01/0.06	0.38/1.54	-
	S7	4.05/16.2	0.03/0.11	-	0.08/0.31	-	-	-	0.45/1.80	-
	S8	5.75/23.0	0.17/0.70	0.05/0.21	0.33/1.33	-	0.03/0.11	-	1.50/6.01	-
	S9	-	0.15/0.58	-	0.19/0.76	-	0.11/0.44	-	0.80/3.19	-
	S10	1.02/4.09	0.10/0.42	-	0.19/0.78	-	0.10/0.41	-	0.43/1.71	-
Oat	S11	2.92/11.7	0.07/0.30	-	0.18/0.70	-	0.23/0.92	-	0.37/1.49	-
	S12	2.29/9.16	0.08/0.33	-	0.34/1.37	-	0.44/1.77	-	0.39/1.56	-
	S13	4.67/18.7	0.22/0.89	0.08/0.33	0.81/3.25	-	0.52/2.08	-	1.62/6.49	-
	S14	1.77/7.08	0.07/0.26	-	0.72/2.89	-	0.60/2.42	-	0.17/0.68	-
Cashew nut	S15	1.27/5.07	-	-	1.18/4.71	-	0.06/0.23	-	0.36/1.43	-
	S16	2.10/8.39	-	0.04/0.18	1.44/5.78	-	0.05/0.20	-	53.7/215	-
	S17	5.12/20.5	-	0.07/0.30	1.46/5.82	-	0.06/0.23	-	0.80/3.21	-
	S18	-	0.01/0.05	-	0.25/0.99	-	0.02/0.08	-	0.10/0.39	-
	S19	4.48/16.2	0.02/0.08	-	0.32/1.29	-	0.03/0.13	-	0.66/2.65	-
	S20	-	0.14/0.57	-	1.36/5.44	-	0.04/0.16	-	0.32/1.26	-
Peanut	S21	-	-	-	0.31/1.24	-	0.22/0.88	-	0.48/1.92	-
Coconut	S22	7.25/29.0	-	-	0.07/0.27	-	-	-	0.51/2.04	-
	S23	1.76/7.05	0.16/0.65	0.01/0.05	0.16/0.65	-	0.14/0.55	-	0.07/0.27	-
	S24	5.16/20.7	-	0.02/0.08	0.17/0.70	-	-	-	0.34/1.34	-
Soybean	S25	11.9/47.5	0.04/0.15	0.01/0.06	0.24/0.97	-	1.97/7.88	-	0.66/2.62	0.02/0.10
	S26	10.1/40.4	-	0.02/0.09	0.26/1.06	-	1.50/6.00	-	0.46/1.85	-
	S27	5.69/22.8	0.03/0.13	-	0.06/0.23	-	0.13/0.54	-	1.04/4.17	-
	S28	2.22/8.89	0.01/0.06	-	0.04/0.17	-	0.12/0.50	-	0.86/3.43	-
	S29	5.61/22.5	0.05/0.18	0.05/0.18	0.43/1.70	-	0.21/0.86	-	2.17/8.67	-
	S30	3.90/15.6	0.04/0.16	0.05/0.21	0.36/1.45	-	0.21/0.84	-	1.77/7.07	-

pregnant and lactating women, and a UL of 100 µg per day for children from one year of age onwards (EFSA, 2013), the sample S25 (soy base) resulted in a DI value of 118 µg per day, above the recommended for children. Thus, the consumption of these products should be moderate for children. However, it is important to emphasize that the calculation was performed considering a 15 kg bw and that the value may be overestimated for a one year old child, who must have a smaller bw and, consequently, a lower Mo intake in ug per day.

3.3.6. *Cadmium*

Regarding the samples S6 and S5 in which the element Cd was quantified, the daily intake ranged from 0.01 to 0.03 and 0.06–0.11 µg kg^{-1} bw for adults and children, respectively. The Joint FAO/WHO Expert Committee on Food Additives (JECFA) has adopted a PTMI of 25 µg Cd kg^{-1} bw per month (FAO/WHO, 2022), while the EFSA has established a lower tolerable weekly intake (TWI) of 2.5 µg kg^{-1} bw week (EFSA, 2012a). The Cd concentration in sample S5 resulted in intakes that corresponded to 3.3% and 13.2% of the PTMI and 7.7% and 30.8% of the TWI for adults and children, respectively. Rubio-Armendáriz et al. (2021) evaluated several plant-based foods and reported a Cd intake of 4.09% TWI for adults, considering a portion of 100 g and body weight of 68.48 kg, which is similar to the present study when considering the same conditions.

3.3.7. *Barium*

The sample S16 (cashew nut and Brazil nut base) resulted in a DI of 53.7 and 215 µg kg^{-1} bw for adults and children, while the other samples presented DI ranging from 0.04 to 2.17 and 0.15–8.67 µg kg^{-1} bw for adults and children, respectively. It is worth noting that Ba is not an essential element for human nutrition, and can lead to an increase in blood pressure at high concentrations and other adverse effects (WHO, 2004). EFSA (2022) established a TDI of 200 µg kg^{-1} bw per day for Ba considering nephropathy as the most sensitive effect. Thus, the consumption of sample S16 represents 107.4% of the TDI.

3.3.8. *Lead*

The EFSA (2010) has established a $BMDL_{01}$ of 12 µg Pb kg^{-1} bw day for developmental neurotoxicity in 6-year-old children, which corresponds to a dietary intake of 0.50 µg kg^{-1} bw day. The sample S25 presented DI of 0.10 µg kg^{-1} bw for children (Table 4), resulting in margins of exposure (MOE) of 5.0. The CONTAM Panel concluded that a MOE of 10 or greater should be sufficient to ensure that there was no appreciable risk of a clinically significant effect on IQ. At lower MOEs, but greater than 1.0 (as the S25), the risk is likely to be low, but not such that it could be dismissed as of no potential concern. For adults, a $BMDL_{10}$ of 15 µg kg^{-1} bw day was established considering effects on prevalence of chronic kidney disease which corresponds to dietary exposure of 0.63 µg kg^{-1} bw day (EFSA, 2010). The samples S5 and S25 presented DI of 0.02 µg kg^{-1} bw for adults (Table 4), resulting in an MOE of 31.5 (greater than 10) indicating that there is no appreciable risk of a clinically significant effect.

3.4. *Bioaccessibility of inorganic elements of plant-based beverages*

Five plant-based beverages containing cocoa in their formulation (S5, S8, S13, S17, and S30) and a beverage containing Brazil nuts (S16) were evaluated for bioaccessibility (%B) of potentially toxic elements. The mean results ($n = 3$, expressed in µg kg^{-1}) are shown in Table 5, and % B is presented in Fig. 2. Levels below the LOQ were observed for the elements As, Cd, Pb, Sb, and Hg.

Although the total Al concentration was determined for all samples, only the samples S17 (169 ± 140 µg kg^{-1}) and S30 (409 ± 20 µg kg^{-1}) showed quantifiable levels in the bioaccessible fraction, with % B of 11% and 35%, respectively. De Paiva et al. (2020) investigated the percent bioaccessibility by the dialyzable fraction of Al in infant foods and reported values from 0.5% to 48%, depending on the composition of the sample. In turn, Milani et al. (2020) found a % B (soluble fraction) for Al corresponding to 50% of the total concentration in teas and stated that the presence of different ingredients in the formulations can affect the

Table 5
Average concentrations (n = 3) of potentially toxic elements in the bioaccessible fraction of plant-based beverages.

Element	$\bar{x}$ ± SD μg kg^{-1}					
	S5	S8	S13	S17	S30	S16
Al	<LOQ	<LOQ	<LOQ	169 ± 140	409 ± 20	<LOQ
Cr	<LOQ	4.33 ± 0.81	13.1 ± 0.6	<LOQ	<LOQ	<LOQ
Co	15.7 ± 0.4	13.5 ± 2.4	15.5 ± 0.9	24.0 ± 0.1	10.1 ± 0.5	11.4 ± 1.7
Ni	143 ± 15	66.5 ± 2.9	165 ± 3	375 ± 7	62.8 ± 1.4	240 ± 2
Mo	<LOQ	<LOQ	14.8 ± 3.0	<LOQ	<LOQ	9.5 ± 1.1
Ba	45 ± 13	337 ± 24	336 ± 68	221 ± 14	305 ± 20	3110 ± 310

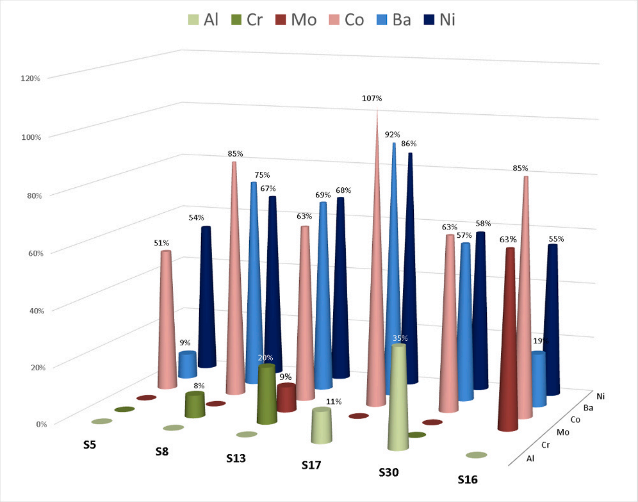

Fig. 2. Percent bioaccessibility (%) of toxic elements in plant-based beverages.

bioaccessibility of the elements studied.

Cr was quantified in the samples S8 (4.33 ± 0.81 μg kg^{-1}) and S13 (13.1 ± 0.6 μg kg^{-1}), corresponding to 8% and 20% bioaccessibility, respectively. As reported for the elements Ca, Fe, and Zn, the element Cr is naturally present in foods in the bound form, which affects its bioavailability and is generally poorly absorbed (Hazell, 1985). The higher %B of Cr observed for sample S13 (oat base) may be due to the high content of organic Cr in unrefined cereals (Hazell, 1985).

Although total Mo was found in all samples, the concentration of the bioaccessible fraction was observed only for the samples S13 (14.8 ± 3.0 μg kg^{-1}) and S16 (9.5 ± 1.1 μg kg^{-1}), with % B of 9% and 63%, respectively. This result may be due to the higher total Mo concentrations of sample S13 due to the composition of the S16 (with Brazil nut). However, studies on the percent bioaccessibility of inorganic elements in samples containing Brazil nut or cashew nut are still scarce.

The elements Co, Ni, and Ba were detected in all samples, with a higher %B observed for sample S17 and a lower %B for S5. Co showed % B between 51% and 107% for all samples, which was expected once its main natural source (vitamin B12) is highly bioavailable and its deficiency is caused by low dietary intake (Hazell, 1985). Although samples S8 and S30 contained vitamin B12 in their composition, the presence of many ingredients in the formulations (10 and 16, respectively) may explain the low bioaccessibility. Great differences were observed for the element Ba, both for the total concentration and bioaccessibility, which varied from 45 ± 13–3110 ± 310 μg kg^{-1}, and 9–92%, respectively, corresponding to the samples S5, S16, S5, and S17. Sample S17 presented the lowest total concentration of Ba and the highest %B (241 ± 4 μg kg^{-1} and 92%), while sample S16 had the highest total Ba and the lowest %B (16,110 ± 46 μg kg^{-1} and 19%). This behavior shows the importance of bioaccessibility studies since low bioaccessibility does not necessarily represent a low mineral intake. Regarding the element Ni, the bioaccessible Ni fraction ranged from 62.8 ± 1.4–375 ± 7 μg kg^{-1}, and %B from 54% to 86% for the samples S30, S17, S5, and S17, respectively (Table 5 and Fig. 2). Although stable Ni complexes with phytic acid can inhibit Ca and Fe absorption, studies have found that the addition of phytic acid does not affect their absorption (Hazell, 1985). The presence of cashew nuts in the composition of plant-based beverages may have contributed to the higher bioaccessible Ni fraction since the sample S17 (cashew and cocoa base) presented the highest bioaccessibility for this element.

4. Conclusion

The data form this study allowed assessing the inorganic element contents in 30 plant-based beverages. The results were similar in samples with same base or main ingredients, such as the As levels in rice-based beverages, higher Co, Ni, and Ba contents in cocoa containing beverages, and Ni levels in cashew nut-based beverages. The dietary exposure assessment showed safe intake values for the elements Al, Cr, Co, As, Cd and Pb, while worrying results were observed for the elements Ni, Mo and Ba due to their high concentration and the possibility of higher consumption, especially for children, who are at the greatest risk of exposure. The estimated bioaccessibility of inorganic elements in plant-based beverages was evaluated using the INFOGEST 2.0 standardized method, with bioaccessibility values above 50% for Co and Ni, for all samples studied, reinforcing the need for caution in the consumption of this product by children. The results of this study can be a relevant tool in providing data on inorganic contaminants and bioaccessibility of toxic elements in plant-based beverages, besides contributing to future regulations for this food category. Further research is needed for beverages containing Brazil nuts once studies on the presence of potentially toxic elements in this matrix are scarce in the literature.

CRediT authorship contribution statement

Maria Isabel Andrekowisk Fioravanti: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing. **Ana Paula Rebellato**: Methodology, Validation, Formal analysis, Investigation, Data curation, Writing – review & editing. **Raquel Fernanda Milani**: Methodology, Validation, Formal analysis, Investigation, Data curation, Writing – review & editing. **Marcelo Antonio Morgano**: Conceptualization, Writing – review & editing, Resources, Supervision. **Adriana Pavesi Arisseto Bragotto**: Conceptualization, Writing – review & editing, Resources.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

Data will be made available on request.

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