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Essential and Toxic Elements in Cereal-Based Complementary Foods for Children: Concentrations, Intake Estimates, and Health Risk Assessment

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Abstract

Cereal-based complementary foods are widely consumed by children, yet limited data exist on their elemental composition and potential health risks. This study quantified As, Cd, Co, Cr, Cu, Fe, K, Mn, Mg, Mo, Ni, P, Pb, Se, Si, V, and Zn in eight commercial cereal-based products collected in Campo Grande, Brazil, using inductively coupled plasma optical emission spectrometry (ICP OES). Arsenic, cadmium, cobalt, and chromium were consistently below the detection limit. Phosphorus and potassium were the predominant elements across brands, followed by Fe, Mg, and Zn, with significant inter-brand variability (Kruskal–Wallis, $p < 0.05$). Lead was detected in Brands 1–5 (0.11–0.41 mg/kg), but it was below the limit of detection (LOD = 0.003 mg/L) in the other samples. Estimated daily intake (DI) values at 30 g/day and 90 g/day showed that Fe, Zn, Mn, and Se frequently met or exceeded dietary reference intakes for children aged 1–3 years, while Cu, Ni, and P remained below tolerable levels. Comparison with tolerable upper intake levels and ATSDR minimal risk levels indicated that higher consumption (90 g/day) could result in excess intake of Mn, Zn, and Se, with Pb contributing to cumulative hazard indices above the safety threshold (HI > 1). These findings emphasize the dual role of cereal-based foods as important nutrient sources and potential contributors to excessive trace element exposure in young children.

Keywords: cereal-based foods; essential elements; toxic metals; ICP-OES; health risk; children

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1. Introduction

Commercial complementary foods, also known as industrialized infant foods, based on cereals, are typically formulated with cereals, sugar, and variable additives [1]. In recent years, the role of these products in appropriate complementary feeding has been the subject of increasing debate, motivated by concerns regarding their nutritional content and potentially inappropriate marketing strategies associated with their promotion [2].

Since 2016, the World Health Organization (WHO) has recommended that countries adopt measures to restrict the inappropriate promotion of foods intended for infants and young children [3,4]. To support this recommendation, a nutrient profile model for

complementary foods designed for children under 36 months of age was developed, with the aim of identifying products unsuitable for promotion, particularly by limiting salt and free sugar intake [5]. In the European context, Directive 2006/125/EC establishes parameters for processed cereal-based foods, regulating the addition of sugars such as sucrose, fructose, syrups, and honey, but does not specify the total sugar content [6]. Therefore, such products must comply with strict guidelines regarding nutritional quality, additive inclusion, and labeling.

There is evidence that the quality and composition of these commercial foods may influence both current and future health outcomes in young children. During the critical period between 6 months and 3 years of age, when dietary choices are limited, commercial baby foods play an important role as sources of energy, essential nutrients, fiber, vitamins, and minerals, while also contributing to the establishment of taste preferences and long-term dietary patterns [7].

Infant formulas and prepared foods are designed to meet the elevated nutritional requirements of children, including macro- and micronutrients. Additionally, these products should provide an adequate lipid profile and a low sodium content [8]. However, recent studies have reported the presence of heavy metals such as arsenic (As), cadmium (Cd), lead (Pb), and mercury (Hg) in cereal-based baby foods [9,10].

However, findings across different regions remain controversial. For instance, a study conducted in Ethiopia reported no detectable levels of cadmium and lead in cereal-based infant foods, suggesting that these products might be safe from such contaminants in that context [11]. In contrast, investigations in Ghana and Turkey identified significant levels of cadmium and lead in locally available infant foods, with some concentrations exceeding international safety thresholds [12,13]. These conflicting results reinforce the heterogeneity of contamination risks worldwide and highlight the need for region-specific monitoring and regulatory strategies.

These data raise serious public health concerns, as infants are more vulnerable to toxic contaminants due to their high intestinal absorption and low body weight [14]. Adverse health effects caused by heavy metal exposure in infants and young children include developmental deficits in the nervous, reproductive, digestive, respiratory, and immune systems, as well as neurotoxic outcomes. In particular, Pb exposure has been linked to reductions in intelligence quotient (IQ), as well as impairments in cognitive and language skills [15].

Recent evidence underscores the dual role of trace and macro elements in human health, combining nutritional benefits with potential toxicological risks. Essential elements such as Fe, Cu, Mn, Zn, Mo, Se, Mg, P, and K are central to immune, metabolic, and cellular functions, while Si has been linked to connective tissue and bone integrity, though not formally classified as essential [16]. However, excessive intake may lead to adverse outcomes, including hepatotoxicity (Fe, Cu), neurodevelopmental effects (Mn), neurological and dermatological disorders (Se), and impaired mineral balance (Zn) [16]. Alongside these, toxic elements such as Pb, As, Cd, Co, Cr, Ni, and V remain of major concern, given their associations with neurotoxicity, renal damage, carcinogenicity, and systemic effects, even at low exposure levels [16]. As emphasized by Nriagu and Skaar (2015) [17], these toxicants may mimic or displace essential nutrients, thereby intensifying their harmful impact. Their presence in cereal-based foods highlights the need for systematic monitoring of both essential and toxic elements to safeguard children's nutrition and health.

Given this context, the present study aimed to quantify essential elements (Cu, Fe, K, Mn, Mg, Mo, P, Se, Si, and Zn) and toxic elements (As, Cd, Co, Cr, Ni, Pb, and V) in cereal-based products widely used as complementary foods for Brazilian children. Samples were collected from supermarkets in the city of Campo Grande, MS, Brazil, and elemental

concentrations were determined using inductively coupled plasma optical emission spectrometry (ICP OES). The study indicates that cereal-based complementary foods contain both essential and potentially toxic elements, with some formulations presenting concentrations that may exceed tolerable intake levels in young children. Thus, the results obtained in this study highlight the need for continuous monitoring, stricter quality control, and balanced fortification practices.

2. Materials and Methods

2.1. Acquisition of Commercial Cereal Products

All cereal-based product samples were purchased directly from supermarkets in Campo Grande, MS, Brazil, during June 2023. A total of 64 samples were included in this study: 48 samples representing six different types of cereal-based products manufactured by Manufacturer A (eight samples of each type, from the same production lot), and 16 samples representing two types of cereal-based products produced by Manufacturer B (eight samples of each type, also from the same lot). The compositions of these products vary, and Table 1 presents the eight products analyzed, along with their labeling descriptions and unit weight (g) as provided by the manufacturers. All products are marketed as suitable for children over six months of age. For confidentiality purposes, the real names of the companies have not been disclosed. The labels 'Manufacturer A' and 'Manufacturer B' represent two different companies. Within each manufacturer, the terms 'Brand 1,' 'Brand 2,' etc., are internal codes assigned by the authors to distinguish the different products analyzed.

Table 1. Composition of the commercial cereal-based products analyzed (coded by manufacturer and brand).

Composition	Unit Weight (g)	Code
Infant cereal based on 80% rice,	400	Manufacturer A—Brand 1
Infant cereal with 60% wheat flour enriched with iron and folic acid, sugar, and 14% corn flour enriched with iron and folic acid, plus 5.3% rice flour.	600	Manufacturer A—Brand 2
Infant cereal with 64% rice, 14% whole oat flour, sugar, and malt extract	180	Manufacturer A—Brand 3
55% wheat flour and 20% milk and sugar.	600	Manufacturer A—Brand 4
Infant cereal with 91% wheat, whole wheat flour, barley flour, and oat flour.	210	Manufacturer A—Brand 5
Whole wheat flour and sugar (29%), wheat flour (26%) enriched with folic acid, banana and pear preparation.	400	Manufacturer A—Brand 6
Powdered drink mix enriched with maltodextrin, skimmed milk powder, and sugar.	400	Manufacturer B—Brand 7
Powdered drink mix enriched with maltodextrin, skimmed milk powder, sugar, and lecithinated cocoa.	350	Manufacturer B—Brand 8

2.2. Preparation of Materials for Analysis

In this study, all laboratory materials used for the analyses including tubes, flasks, pipettes, and glassware in general were pre-treated to prevent mineral contamination. The materials were immersed in a 10% HNO_3 (65%, ultrapure grade, Merck, Darmstadt, Germany) solution for 24 h and subsequently rinsed with ultrapure water prior to use. Prior to analysis, the samples were homogenized and gently ground using a high-density polyethylene (HDPE) mortar and pestle (Praticoz®, São Paulo, Brazil) to ensure uniform particle size and to avoid metallic and silicon contamination. After grinding, the samples were transferred to pre-cleaned, airtight polyethylene containers and stored at room temperature (approximately 20–25 °C), protected from light and moisture, in a dry contamination-free environment until digestion and instrumental determination.

2.3. Microwave-Assisted Sample Digestion

An amount of 0.25 g of each sample was weighed and individually placed in Teflon DAP60® vessels (Speedwave Four®, Berghof, Eningen, Germany). Subsequently, 2 mL of nitric acid (HNO_3, 65%, ultrapure grade, Merck, Darmstadt, Germany) and 1.5 mL of hydrogen peroxide (H_2O_2, 30%, ultrapure grade, Merck, Darmstadt, Germany) were added. The DAP60 vessels were then introduced into the microwave digestion system (Speedwave Four®, Berghof, Eningen, Germany), following the parameters detailed in Table 2.

Table 2. Microwave digestion program for cereal-based product samples.

Parameters	Steps		
	1	2	3
Temperature (°C)	170	200	50
Ramp time (min)	2	5	1
Hold time (min)	10	15	10
Energy (%)	90	90	0
Pressure (bar)	50	50	0

A blank solution was also prepared following the same procedure applied for sample digestion. After digestion, the samples were diluted to 50 mL with ultrapure water (18.2 MΩ·cm, Milli-Q system, Merck Millipore, Bedford, MA, USA). The sample digestion procedure was performed in triplicate.

2.4. Analysis of Metal(loid)s

The cereal-based products were analyzed in triplicate using Inductively Coupled Plasma Optical Emission Spectrometry (ICP-OES, iCAP 6300 Duo, Thermo Fisher Scientific, Bremen, Germany). The parameters used in the ICP OES for quantifying the elements are presented in Table 3.

Table 3. ICP OES operating conditions for elemental analysis.

Parameter	Configuration
Radiofrequency power	1150 W
Pump flow	50 rpm
Argon plasma flow	12.0 $L \cdot min^{-1}$
Argon auxiliary flow	0.50 $L \cdot min^{-1}$
Nebulizer gas flow	0.70 $L \cdot min^{-1}$
Viewing mode	Axial
Wavelengths (nm)	As (189.042), Cd (228.802), Co (228.616), Cr (283.563), Cu (324.754), Fe (259.940), K (766.490), Mg (279.553), Mn (257.610), Mo (202.030), Ni (221.647), P (177.495), Pb (220.353), Se (196.090), Si (251.611), V (309.311), Zn (213.856)

For the quantification of elements using ICP OES, an analytical calibration curve was prepared with seven concentration levels, based on a 1000 mg/L multielement stock solution (SpecSol, Quinlab, Jacareí, SP, Brazil). Seven concentrations were used to construct the calibration curve for the quantitative analysis of rice samples. The concentrations ranged from 0.01 to 5.0 mg/L.

A recovery test was performed by spiking the solutions with 0.5 ppm of the target elements. The spike solution was prepared from a single 1000 ppm multielement solution. Recovery results ranged from 83–114% (Table 4).

Table 4. Recovery of elements after spiking (0.5 ppm).

Elements	Spike Concentration (%)
As	99
Cd	100
Co	101
Cr	114
Cu	93
Fe	85
K	106
Mg	100
Mn	97
Mo	112
P	83
Pb	98
Se	103
Zn	97

The limit of detection (LOD) and limit of quantification (LOQ) were calculated using the standard deviation of replicate blank measurements (Sb) and the slope of the analytical calibration curve (b), according to LOD = 3Sb/b and LOQ = 10Sb/b. This procedure follows the recommendations established by the International Union of Pure and Applied Chemistry (IUPAC) and the European Commission Guidance Document on the Estimation of Limit of Detection (LOD) and Limit of Quantification (LOQ) for Measurements in the Field of Contaminants in Feed and Food [18], ensuring the analytical sensitivity and reproducibility of the method. Table 5 summarizes the results for the limits of detection (LOD), limits of quantification (LOQ), and correlation coefficients (R^2).

Table 5. Elements, values of limits of detection (LODs), limits of quantification (LOQs) and correlation coefficients (R^2).

Element	LOD (mg/L)	LOQ (mg/L)	Correlation Coefficient (R^2)
As	0.002	0.007	0.9991
Cd	0.0004	0.0013	0.9992
Co	0.0006	0.0020	0.9998
Cr	0.0007	0.0026	9.9999
Cu	0.0016	0.0053	0.9996
Fe	0.0008	0.0027	0.9998
K	0.004	0.013	0.9997
Mg	0.0008	0.0027	0.9995
Mn	0.0002	0.0007	0.9991
Mo	0.0008	0.0027	0.9994
P	0.004	0.013	0.9996
Pb	0.003	0.010	0.9998
Se	0.004	0.013	0.9997
Zn	0.0006	0.0019	0.9995

2.5. Dietary Exposure and Health Risks of Metal(loid)s in Cereal-Based Foods

The daily intake (DI) of metal(loid)s from cereal-based products was estimated according to the following Equation (1) [19,20]:

$$\mathbf{DI(mg/day)} = \mathbf{C(mg/kg)} \times \mathbf{M(kg/day)} \quad (1)$$

where C (mg/kg) represents the mean concentration of metal(loid)s quantified in cereal-based products by ICP OES, and M is the mass of cereal product ingested daily, which was assumed to be 0.03 and 0.09 kg/day. The intake was estimated considering the values reported on the label of each manufacturer (Table 1).

The chronic daily intake (CDI) of cereals (mg/kg/day) was calculated using Equation (2) [20],

$$\mathbf{CDI} = \frac{\mathbf{C} \times \mathbf{IR} \times \mathbf{EF} \times \mathbf{ED}}{\mathbf{BW} \times \mathbf{AT}} \quad (2)$$

where *C* is the mean concentration of heavy metals (mg/kg); *IR* is the ingestion rate (g/day); EF is the exposure frequency (days/year); ED is the exposure duration (years); BW is the body weight of children (kg), corresponding to the reference value for 3-year-old children, consistent with the recommended age range for cereal consumption indicated on product labels; and AT is the averaging time (days). The parameters used for the CDI estimation are presented in Table 6.

Table 6. Parameters used for the calculation of Chronic Daily Intake (CDI).

Parameters	Unit	Value
Ingestion rate (IR)	g/day	Minimum: 0.030 kg/day; Maximum: 0.090 kg/day
Exposure frequency (EF)	days/year	365
Exposure duration (ED)	year	1
Body weight (BW)	kg	3 years: max 18.37
Averaging time (AT = EF × ED)	days	365

The Non-Carcinogenic Risk (HQ) for potentially toxic elements can be calculated by dividing the CDI by the reference dose (RfD), as shown in Equation (3):

$$\mathbf{HQ} = \frac{\mathbf{CDI}}{\mathbf{RfD}} \quad (3)$$

The reference dose (RfD) values (mg/kg/day) considered in this study were as follows: Cu (4.0×10^{-2}), Fe (7.0×10^{-1}), Mg (12.0), Mn (2.4×10^{-2}), Mo (5.0×10^{-3}), Ni (2.0×10^{-2}), Pb (4.3×10^{-4}), Se (5.0×10^{-3}), V (1.0×10^{-3}), and Zn (3.0×10^{-1}). The RfD values were primarily obtained from the United States Environmental Protection Agency (USEPA) [21], which provides reference toxicity thresholds for non-carcinogenic risk assessment. Exceptions include Mg, whose value was derived from the National Research Council (US) Subcommittee on Flame-Retardant Chemicals [22], and Pb, for which the value (4.3×10^{-4} mg/kg/day) corresponds to the chronic acceptable intake derived by the U.S. EPA [23].

The Hazard Index (HI) is the sum of risk quotients (Equation (3)) from simultaneous exposure to multiple metal(loid)s (Equation (4)). The hazard quotient (HQ) is a numerical indicator employed to assess the likelihood of non-carcinogenic effects in a given population [24]. Values below 1 indicate safe cereal consumption, whereas values above 1 suggest potential health risks.

$$HI = HQ_{Cu} + HQ_{Fe} + HQ_{Mg} + HQ_{Mn} + HQ_{Mo} + HQ_{Ni} + HQ_{P} + HQ_{Se} + HQ_{V} + QH_{Zn} \quad (4)$$

2.6. Statiscal Analysis

All measurements were performed in triplicate, and results are expressed as mean ± standard deviation (SD). Prior to hypothesis testing, the data were checked for normality (Shapiro–Wilk test) and homogeneity of variances (Levene's test). Since the majority of variables did not meet the assumptions of parametric tests, inter-brand comparisons were conducted using the non-parametric Kruskal–Wallis test, followed by pairwise comparisons with Dunn's post hoc test. Differences were considered statistically significant at $p < 0.05$. All statistical analyses and graphical outputs were performed using R software (version 4.3.2, R Core Team, Vienna, Austria).

3. Results

3.1. Quantification of Metals(loid)s in Cereal-Based Samples

The concentrations of elements quantified in the eight cereal-based products are summarized in Table 7. The elements As, Co, Cd, and Cr were consistently below the quantification limit. For each brand, the concentrations of the quantified elements decreased in the following order (Table 7):

Brand 1: P > K > Fe > Mg > Zn > Si > Mn > Se > Cu > Mo > V > Ni > Pb
Brand 2: P > K > Mg > Fe > Zn > Si > Mn > Cu > Se > V > Mo > Ni > Pb
Brand 3: P > K > Mg > Fe > Zn > Si > Mn > Cu > Se > V > Mo > Ni > Pb
Brand 4: P > K > Mg > Fe > Zn > Si > Mn > Se > Cu > V > Mo > Pb > Ni
Brand 5: K > P > Mg > Fe > Si > Mn > Zn > Cu > Se > V > Mo > Ni > Pb
Brand 6: P > K > Mg > Fe > Si > Mn > Zn > Cu > Se > V > Mo > Ni (Pb < LOD)
Brand 7: P > K > Mg > Fe > Zn > Si > Mn > Cu > Se > V > Mo > Ni (Pb < LOD)
Brand 8: K > P > Mg > Fe > Zn > Si > Mn > Cu > Se > V > Ni > Mo (Pb < LOD)

Table 7. Elements quantified in cereal-based products (mg/kg, mean ± SD) using ICP OES.

Elements	**Samples**							
	Brand 1	Brand 2	Brand 3	Brand 4	Brand 5	Brand 6	Brand 7	Brand 8
As	<LOD	<LOD	<LOD	<LOD	<LOD	<LOD	<LOD	<LOD
Cd	<LOD	<LOD	<LOD	<LOD	<LOD	<LOD	<LOD	<LOD
Co	<LOD	<LOD	<LOD	<LOD	<LOD	<LOD	<LOD	<LOD
Cr	<LOD	<LOD	<LOD	<LOD	<LOD	<LOD	<LOD	<LOD
Cu	1.163 ± 0.013	0.913 ± 0.039	1.682 ± 0.062	1.00 ± 0.048	2.02 ± 0.06	1.290 ± 0.053	4.655 ± 0.127	5.624 ± 0.01
Fe	226.0 ± 1.5	263.9 ± 3.6	266.4 ± 6.7	81.1 ± 2.0	89.9 ± 2.5	82.9 ± 1.2	120.4 ± 3.4	118.1 ± 0.5
K	997.0 ± 18.0	1517.0 ± 27.0	1615 ± 70	4025.0 ± 5.0	7137 ± 116	2196 ± 33	1903 ± 38	3158 ± 32
Mg	169.3 ± 1.9	215.7 ± 4.0	269.2 ± 8.2	333.0 ± 5.5	433.8 ± 10.6	355.5 ± 8.1	304.4 ± 5.7	326.1 ± 1.8
Mn	6.82 ± 0.06	6.16 ± 0.09	11.71 ± 0.29	7.73 ± 0.20	19.99 ± 0.53	15.10 ± 0.22	15.20 ± 0.40	16.51 ± 0.09
Mo	0.490 ± 0.020	0.285 ± 0.016	0.531 ± 0.038	0.443 ± 0.016	0.339 ± 0.022	0.252 ± 0.001	0.227 ± 0.033	0.296 ± 0.008
Ni	0.197 ± 0.029	0.116 ± 0.016	0.311 ± 0.057	0.108 ± 0.028	0.213 ± 0.035	0.129 ± 0.002	0.066 ± 0.045	0.535 ± 0.014
P	1994.8 ± 19.1	2239.1 ± 64.7	3252.8 ± 51.2	3838.9 ± 84.3	6046.9 ± 116.3	3677.4 ± 90.5	3388.7 ± 66.6	2803.2 ± 59.5
Pb	0.174 ± 0.076	0.162 ± 0.086	0.207 ± 0.233	0.411 ± 0.137	0.111 ± 0.127	<LOD	<LOD	<LOD
Se	1.34 ± 0.17	1.37 ± 0.08	1.46 ± 0.13	1.08 ± 0.02	1.09 ± 0.08	1.09 ± 0.08	0.98 ± 0.11	0.98 ± 0.11
Si	19.73 ± 0.56	26.24 ± 0.53	42.15 ± 1.05	26.12 ± 0.02	47.99 ± 1.59	36.43 ± 0.67	26.75 ± 1.05	19.15 ± 0.71
V	0.331 ± 0.012	0.458 ± 0.027	0.629 ± 0.050	0.845 ± 0.024	1.25 ± 0.03	0.916 ± 0.047	0.795 ± 0.012	0.884 ± 0.012
Zn	78.04 ± 0.33	66.83 ± 1.44	84.59 ± 1.22	30.78 ± 0.18	15.95 ± 0.17	12.32 ± 0.22	71.02 ± 0.74	59.18 ± 0.66

3.2. Risk Assessment Due to the Intake of Metal(loid)s in Cereal-Based Products

The estimated daily intake (DI) of trace elements in cereal-based products, calculated for consumption scenarios of 30 g/day and 90 g/day, is presented in Table 8. Essential elements such as Fe, K, Mg, and P showed the highest intake values across all brands, reflecting their natural abundance and nutritional relevance in cereal-based products. These elements play fundamental roles in metabolism, enzymatic activation, and bone development [16]. Conversely, toxic elements such as Pb were detected at very low concentrations, with some samples below the detection limit. This variability reinforces the need to evaluate multiple products within the same food group to better estimate population-level exposures.

Table 8. Daily Intake (DI, mg/day) for cereal-based products at 30 g/day and 90 g/day.

Element	Brand 1		Brand 2		Brand 3		Brand 4		Brand 5		Brand 6		Brand 7		Brand 8	
	30 g/day	90 g/day	30 g/day	90 g/day	30 g/day	90 g/day	30 g/day	90 g/day	30 g/day	90 g/day	30 g/day	90 g/day	30 g/day	90 g/day	30 g/day	90 g/day
Cu	0.035	0.105	0.027	0.082	0.050	0.151	0.030	0.090	0.060	0.181	0.039	0.116	0.140	0.419	0.169	0.506
Fe	6.780	20.340	7.916	23.747	4.993	14.979	2.434	7.301	2.697	8.092	2.485	7.456	3.613	10.838	3.544	10.632
K	29.901	89.704	45.503	136.508	48.45	55.326	120.750	362.249	214.125	642.375	65.880	197.639	57.097	171.291	94.733	284.200
Mg	5.079	15.236	6.472	19.416	8.075	24.224	9.991	29.973	13.014	39.042	10.664	31.991	9.132	27.395	9.783	29.348
Mn	0.205	0.614	0.185	0.554	0.351	1.054	0.232	0.696	0.600	1.799	0.453	1.359	0.456	1.368	0.495	1.486
Mo	0.015	0.044	0.009	0.026	0.016	0.048	0.013	0.040	0.010	0.031	0.008	0.023	0.007	0.020	0.009	0.027
Ni	0.006	0.018	0.003	0.010	0.009	0.028	0.003	0.010	0.006	0.019	0.004	0.012	0.002	0.006	0.016	0.048
P	59.846	179.539	67.172	201.517	45.357	136.070	115.169	345.506	181.405	544.214	110.323	330.968	101.661	304.982	84.096	252.287
Pb	0.005	0.016	0.005	0.015	0.006	0.018	0.012	0.037	0.003	0.010	0.008	0.024	<LOD	<LOD	<LOD	<LOD
Se	0.040	0.121	0.041	0.123	0.047	0.141	0.044	0.131	0.038	0.114	0.032	0.097	0.033	0.098	0.029	0.088
Si	0.592	1.776	0.787	2.361	0.729	2.188	0.784	2.351	1.440	4.320	1.270	3.810	0.802	2.407	0.575	1.724
V	0.010	0.030	0.014	0.041	0.019	0.056	0.025	0.076	0.038	0.113	0.027	0.082	0.024	0.072	0.027	0.080
Zn	2.341	7.024	2.005	6.015	1.038	3.113	0.923	2.770	0.478	1.435	0.369	1.108	2.131	6.392	1.776	5.327

Overall, while essential elements (Fe, K, Mg, P, Zn) may contribute beneficially to dietary intake, the potential accumulation of non-essential or toxic elements (Pb, Ni, V) should not be overlooked. The calculated DI values provide a quantitative basis for subsequent hazard quotient (HQ) and hazard index (HI) assessments, which are necessary to determine whether cereal consumption poses potential health risks under different exposure scenarios.

3.2.1. Results—Chronic Daily Intake (CDI)

The chronic daily intake (CDI) values of the analyzed cereal-based products are summarized in Table 9 (IR = 30 g/day) and Table 10 (IR = 90 g/day), based on a reference body weight of 18.37 kg for a 3-year-old child, consistent with the age group recommended for cereal consumption. As expected, increasing the ingestion rate from 30 g/day to 90 g/day resulted in a proportional threefold increase in CDI values across all elements and brands.

Table 9. Chronic Daily Intake (CDI, mg/kg/day) for cereal-based products by brand. Parameters: IR = 30 g/day, EF = 365 days/year, ED = 1 year, AT = 365 days, BW = 18.37 kg.

Element	Brand 1	Brand 2	Brand 3	Brand 4	Brand 5	Brand 6	Brand 7	Brand 8
Cu	0.001899	0.001491	0.002747	0.001633	0.003292	0.002107	0.007602	0.009185
Fe	0.369078	0.430907	0.435109	0.132487	0.146829	0.135301	0.196658	0.192928
K	1.627731	2.477012	2.637016	6.573206	11.656233	3.586256	3.108168	5.156951
Mg	0.276457	0.352308	0.439555	0.543870	0.708439	0.580496	0.497092	0.532530
Mn	0.011141	0.010053	0.019122	0.012621	0.032639	0.024660	0.024830	0.026961
Mo	0.000800	0.000465	0.000867	0.000723	0.000554	0.000412	0.000371	0.000483
Ni	0.000321	0.000190	0.000509	0.000176	0.000346	0.000211	0.000108	0.000874
P	3.257749	3.656641	5.312102	6.269295	9.875043	6.005580	5.534054	4.577881
Pb	0.000284	0.000265	0.000329	0.000671	0.000182	0.000436	<LOD	<LOD
Se	0.002194	0.002229	0.002556	0.002386	0.002070	0.001769	0.001782	0.001595
Si	0.032226	0.042844	0.094298	0.042652	0.078384	0.069139	0.043677	0.031279
V	0.000540	0.000748	0.001021	0.001379	0.002049	0.001495	0.001298	0.001444
Zn	0.127453	0.109145	0.138145	0.050272	0.026046	0.020112	0.115990	0.096655

Table 10. Chronic Daily Intake (CDI, mg/kg/day) for cereal-based products by brand. Parameters: IR = 90 g/day, EF = 365 days/year, ED = 1 year, AT = 365 days, BW = 18.37 kg.

Element	Brand 1	Brand 2	Brand 3	Brand 4	Brand 5	Brand 6	Brand 7	Brand 8
Cu	0.005697	0.004474	0.008241	0.004899	0.009876	0.006320	0.022806	0.027555
Fe	1.107235	1.292722	1.305328	0.397460	0.440487	0.405902	0.589973	0.578783
K	4.883193	7.431036	7.911049	19.719617	34.968699	10.758768	9.324505	15.470853
Mg	0.829372	1.056924	1.318664	1.631611	2.125318	1.741488	1.491276	1.597591
Mn	0.033423	0.030160	0.057366	0.037862	0.097917	0.073979	0.074489	0.080882
Mo	0.002401	0.001396	0.002602	0.002170	0.001661	0.001235	0.001112	0.001450
Ni	0.000964	0.000570	0.001526	0.000528	0.001038	0.000632	0.000323	0.002623
P	9.773246	10.969922	15.936305	18.807884	29.625129	18.016741	16.602163	13.733642
Pb	0.000851	0.000795	0.000988	0.002013	0.000547	0.001308	<LOD	<LOD
Se	0.006582	0.006688	0.007667	0.007158	0.006209	0.005306	0.005346	0.004785
Si	0.096678	0.128533	0.282895	0.127955	0.235151	0.207416	0.131032	0.093836
V	0.001620	0.002243	0.003062	0.004138	0.006147	0.004486	0.003895	0.004332
Zn	0.382360	0.327434	0.414436	0.150815	0.078139	0.060335	0.347970	0.289965

Among the essential elements, potassium (K) and phosphorus (P) exhibited the highest CDI values, particularly in Brand 5, which reached 11.65 and 9.87 mg/kg/day at IR = 30 g/day and 34.97 and 29.63 mg/kg/day at IR = 90 g/day, respectively. Other essential nutrients such as magnesium (Mg), iron (Fe), and zinc (Zn) also showed relevant contributions, with Brand 5 and Brand 4 generally presenting elevated values compared to the other products.

For the toxic element lead (Pb), CDI values were consistently low, ranging from 0.00018 to 0.00046 mg/kg/day at IR = 30 g/day, and from 0.00055 to 0.00130 mg/kg/day at IR = 90 g/day. Notably, Pb was below the detection limit in Brands 7 and 8. This indicates limited exposure from these products with respect to lead.

In general, the results highlight the strong variability among brands, with Brand 5 showing the highest dietary exposure for most elements, while Brands 1 and 2 remained at intermediate levels. The calculated CDI values provide the basis for subsequent risk characterization using hazard quotient (HQ) and hazard index (HI).

The calculated Hazard Quotient (HQ) values for each element and brand, as well as the Hazard Index (HI), are presented in Table 11 (IR = 30 g/day) and Table 12 (IR = 90 g/day). For IR = 30 g/day, HI values ranged from 3.30 (Brand 1) to 4.81 (Brand 5). For IR = 90 g/day, HI values increased proportionally, ranging from 9.83 (Brand 1) to 14.44 (Brand 5).

Table 11. Hazard Quotient (HQ) and Hazard Index (HI) for cereal-based products at IR = 30 g/day (BW = 18.37 kg).

Element	Brand 1	Brand 2	Brand 3	Brand 4	Brand 5	Brand 6	Brand 7	Brand 8
Cu	0.047	0.037	0.069	0.041	0.082	0.053	0.190	0.230
Fe	0.527	0.616	0.622	0.189	0.210	0.193	0.281	0.276
Mg	0.023	0.029	0.037	0.045	0.059	0.048	0.041	0.044
Mn	0.464	0.419	0.797	0.526	1.360	1.028	1.035	1.124
Mo	0.160	0.093	0.173	0.145	0.111	0.082	0.074	0.097
Ni	0.016	0.010	0.025	0.009	0.012	0.011	0.005	0.044
Pb	0.660	0.616	0.765	1.560	0.423	1.014	<LOD	<LOD
Se	0.439	0.446	0.511	0.477	0.414	0.354	0.356	0.319
V	0.540	0.748	1.021	1.379	2.049	1.495	1.290	1.144
Zn	0.425	0.364	0.460	0.168	0.087	0.067	0.387	0.322
HI	**3.30**	**3.37**	**4.08**	**4.49**	**4.81**	**4.34**	**4.62**	**3.60**

Table 12. Hazard Quotient (HQ) and Hazard Index (HI) for cereal-based products at IR = 90 g/day (BW = 18.37 kg).

Element	Brand 1	Brand 2	Brand 3	Brand 4	Brand 5	Brand 6	Brand 7	Brand 8
Cu	0.142	0.112	0.206	0.122	0.247	0.158	0.570	0.689
Fe	1.582	1.847	1.865	0.568	0.629	0.580	0.843	0.827
Mg	0.069	0.088	0.110	0.136	0.177	0.145	0.124	0.133
Mn	1.393	1.257	2.390	1.578	4.080	3.082	3.104	3.370
Mo	0.480	0.279	0.520	0.434	0.332	0.247	0.222	0.290
Ni	0.048	0.029	0.076	0.026	0.052	0.032	0.016	0.131
Pb	1.980	1.849	2.298	4.681	1.272	3.042	<LOD	<LOD
Se	1.316	1.338	1.533	1.432	1.242	1.061	1.069	0.957
V	1.620	2.243	3.062	4.138	6.147	4.486	3.895	4.332
Zn	1.275	1.091	1.381	0.503	0.260	0.201	1.160	0.967
HI	**9.83**	**10.14**	**13.44**	**13.66**	**14.44**	**12.03**	**10.90**	**10.60**

3.2.2. Results—Non-Carcinogenic Risk Assessment

The calculated Hazard Quotient (HQ) values for each element and brand, as well as the Hazard Index (HI), are presented in Table 11 (IR = 30 g/day) and Table 12 (IR = 90 g/day). For IR = 30 g/day, HI values ranged from 3.30 (Brand 1) to 4.81 (Brand 5). For IR = 90 g/day, HI values increased proportionally, ranging from 9.83 (Brand 1) to 14.44 (Brand 5). The results of the non-carcinogenic risk assessment for each cereal-based product are presented in Tables 11 and 12 are visually summarized in Figure 1, which compares the total HI values across all brands under both exposure scenarios. Each bar in Figure 1 represents the cumulative non-carcinogenic risk (ΣHQ) for each product, demonstrating the increase in total risk with higher ingestion rates.

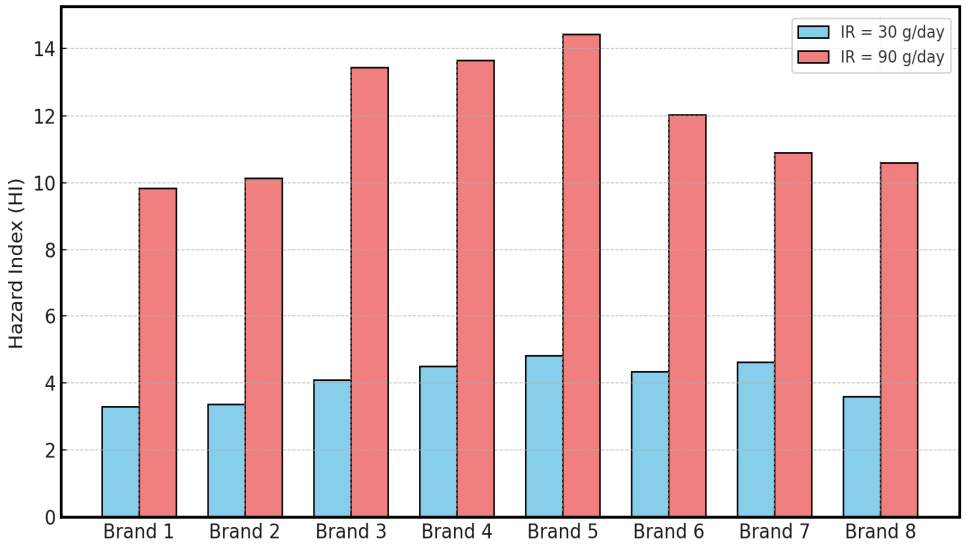

Figure 1. Comparison of Hazard Index (HI) for cereal-based products at different ingestion rates (IR = 30 g/day and 90 g/day; BW = 18.37 kg). Each bar represents the total non-carcinogenic risk (ΣHQ) per brand under the two exposure scenarios.

4. Discussion

This section discusses the results of metal(loid) quantification and health risk assessment in cereal-based samples. For clarity, the discussion was organized into four subsections aligned with the main results. Section 4.1 addresses the concentrations of essential and toxic elements, comparing variations among brands and regulatory limits. Section 4.2 focuses on risk assessment, with Section 4.2.1 discussing chronic daily intake

(CDI) in relation to reference doses and Section 4.2.2 analyzing non-carcinogenic risk based on hazard quotient (HQ) and hazard index (HI).

4.1. Discussion on the Quantification of Metal(loid)s in Cereal-Based Samples

In Table 7, the elemental composition of the eight cereal-based products showed consistent patterns, with arsenic, cobalt, cadmium, and chromium remaining below the quantification limit in all cases. Across brands, phosphorus (P) and potassium (K) were the predominant elements, though their relative dominance varied with formulation. Brands 1–4 and Brand 7, primarily wheat- and rice-based, were characterized by phosphorus dominance, whereas potassium prevailed in Brands 5 and 8, which contained higher proportions of oat, barley, or cocoa (Table 1).

Magnesium (Mg) and iron (Fe) consistently followed as major constituents in Table 7, while zinc (Zn), silicon (Si), and manganese (Mn) occupied intermediate positions, reflecting the contribution of whole grains and processing ingredients. Selenium (Se), copper (Cu), molybdenum (Mo), vanadium (V), and nickel (Ni) appeared at lower levels, although selenium was relatively higher in some wheat-based formulations (e.g., Brand 4). Lead (Pb) was detected in several products (Brands 1–5) but remained below the detection limit in Brands 6–8, indicating differences in raw material quality and manufacturing practices.

The rank order of elements varied by brand, with wheat- and rice-based formulations (Table 1) showing predominantly phosphorus-rich profiles, whereas products containing oat or cocoa shifted toward potassium dominance. These findings emphasize the influence of raw material selection and product formulation on the mineral composition of cereal-based foods. In fact, statistical analysis revealed significant inter-brand variability in the concentrations of essential and toxic elements (Kruskal–Wallis, $p < 0.05$). Potassium and phosphorus were the predominant elements, with Brand 5 showing markedly higher levels, also reflected in magnesium and manganese. Iron was significantly higher in Brands 1–3, whereas zinc varied inversely, with Brand 3 at the highest and Brand 5 at the lowest levels. Copper and nickel were elevated in Brands 7 and 8, while Brand 4 presented the highest lead concentration, contrasting with undetectable Pb in Brands 6–8. Selenium, silicon, and vanadium also showed significant but brand-dependent variation. Therefore, the results confirm that the elemental composition of cereal-based products is highly heterogeneous and strongly influenced by brand-specific formulations and enrichment practices.

The concentrations of essential and toxic elements quantified in the cereal-based products (Table 7) were subsequently compared with the reference concentration ranges established by the U.S. Food and Drug Administration (FDA) for cereals, as reported in the Total Diet Study (TDS) FY2018–FY2020: Summary of Analytical Results [25]. A detailed interpretation of these comparisons is presented in the text below.

Copper levels ranged from 0.9131 ± 0.0386 to 5.6243 ± 0.0132 mg/kg, exceeding the FDA range of 0.318–0.470 mg/kg [25]. Iron concentrations (81.126 ± 1.963 to 266.432 ± 6.657 mg/kg) were within the FDA reference range of 95.462–333.333 mg/kg. Magnesium concentrations (169.284 ± 1.904 to 433.801 ± 10.551 mg/kg) were consistently above the FDA range of 66–109 mg/kg [25]. Manganese values (6.156 ± 0.090 to 19.986 ± 0.526 mg/kg) also exceeded the FDA reference (0.530–2.892 mg/kg).

Potassium levels varied widely (996.714 ± 17.50 to 7137.50 ± 115.978 mg/kg), with most brands far above the FDA reference range of 548–1200 mg/kg [25]. Phosphorus concentrations (1994.828 ± 19.092 to 6046.818 ± 116.263 mg/kg) substantially exceeded the FDA values (510–647 mg/kg). Zinc levels (12.315 ± 2.161 to 84.591 ± 1.220 mg/kg) were within or above the FDA reference range of 1.667–19.923 mg/kg, depending on the brand.

For molybdenum, concentrations (0.227 ± 0.034 to 0.531 ± 0.038 mg/kg) partially overlapped with the FDA range (0.144–0.160 mg/kg), while selenium levels (0.9767 ± 0.1140 to

1.465 ± 0.186 mg/kg) exceeded the FDA reference (0.017–0.032 mg/kg) [25]. Vanadium (0.3307 ± 0.0124 to 1.2547 ± 0.0383 mg/kg) and lead (0.1117 ± 0.1272 to 0.4108 ± 0.137 mg/kg concentrations were notably higher than FDA reference ranges (0.001 mg/kg and 0.0015 mg/kg, respectively). For nickel and silicon, no FDA reference values are available, preventing direct comparison. Thus, the results demonstrate that several elements, particularly Cu, Mg, Mn, K, P, Zn, Se, V, and Pb, were present at concentrations substantially higher than FDA reference ranges, raising potential concerns regarding food safety and dietary exposure.

The elevated levels of metals(loid)s quantified in the samples (Table 7) can be better explained by their formulation and raw material composition, as described in Table 1. In our study, products dominated by rice and wheat flour (Brands 1–2) showed phosphorus (P), potassium (K), iron (Fe), and magnesium (Mg) as the most abundant elements, which is consistent with the mineral composition of wheat and rice flours reported in food composition studies [26,27]. Brand 3, containing whole oat flour, exhibited relatively higher zinc (Zn) and silicon (Si), reflecting the contribution of oat, which is naturally rich in Fe, Mg, Zn, and K [28]. Similarly, the markedly higher concentrations of K, P, Mg, and Mn observed in Brand 5 can be attributed to the inclusion of whole wheat, barley, and oat, in agreement with reports showing that whole-grain flours and malted cereals retain elevated levels of minerals compared to refined products [29,30]. Therefore, the high values found in our study reflect, at least in part, the intrinsic mineral content of the cereal ingredients used in these formulations.

When compared to previous studies, our results partially corroborate published values but also indicate higher concentrations for several elements, which can be explained by the inclusion of whole grains, oats, barley, or fortified flours (Table 1). Alemu et al. (2022) reported Fe (8.5–11.1 mg/kg), Mn (3.2–8.5 mg/kg), Cu (1.6–4.2 mg/kg), Zn (2.3–2.7 mg/kg), Ni (0.15–0.85 mg/kg), Cd (0.04–0.21 mg/kg), and Pb (<0.043 mg/kg) in Ethiopian wheat flours [31]. Compared to these values, our wheat-based brands showed substantially higher Fe (up to 266.4 mg/kg), Zn (up to 84.6 mg/kg), and Mn (up to 19.9 mg/kg), which may be attributed to declared fortification and the use of multigrain formulations.

Kumar et al. [32] summarized heavy metal(loid) concentrations in rice grains by reporting both historical global mean values from international surveys (e.g., As 1.9 mg/kg, Fe 214 mg/kg, Zn 38 mg/kg) and updated meta-analysis results based on more than 10,000 rice samples collected worldwide between 2010 and 2023. Their meta-analysis indicated substantially lower average concentrations for several elements (e.g., As ≈ 0.26 mg/kg, Fe ≈ 62 mg/kg, Zn ≈ 25 mg/kg), with variations depending on soil origin and production systems [32]. In our study, focused on elements quantified in cereal-based products, the concentrations of Fe (81–266 mg/kg) and Zn (12–84 mg/kg) were generally higher than both the historical global means and the more recent meta-analysis values for rice [32]. Similarly, Cu (0.91–5.62 mg/kg) and Mn (6.1–19.9 mg/kg) in our products exceeded typical rice values, reflecting the contribution of wheat, oat, and barley in multigrain formulations. Importantly, As was consistently below the detection limit in all brands, contrasting with both the global mean value (1.9 mg/kg) and the average level reported in the meta-analysis (≈0.26 mg/kg). These comparisons emphasize that the mineral and toxic element profiles observed in our cereal-based products cannot be directly explained by rice alone, but rather by the combination of multiple raw materials and, in some cases, fortification practices.

Kayisoglu et al. [33] recently evaluated wheat milling processes and demonstrated that processing can redistribute or even introduce metals such as Al, Cd, Cr, Cu, Fe, Ni, Pb, and Zn [33]. They showed that bran and coarse milling fractions retained higher concentrations of metals, whereas refined flours presented substantially lower levels. For instance, Al

decreased from 13.63 mg/kg in raw wheat to 0.36 mg/kg in refined flour. Moreover, Cd, which was initially undetected, appeared at 0.58 mg/kg during crushing, while Cu and Cr were also introduced during mechanical processing, most likely from milling equipment. Pb and As remained consistently below detection limits across all fractions.

These findings in Ref. [33] are particularly relevant for our samples (Table 1), since several products analyzed (Brands 2, 4, 5, and 6) were based largely on wheat flour, either refined or whole. The higher concentrations of Fe, Zn, and Cu observed in these brands may thus reflect both the intrinsic composition of whole grains and the redistribution effects described by Kayisoglu et al. (2025) [33]. Conversely, Brands 1 and 3, predominantly based on rice and oat flour, and Brands 7 and 8, enriched with maltodextrin, milk powder, and cocoa, exhibited different elemental profiles, consistent with their distinct formulations.

This comparison highlights that both the choice of raw materials and technological processing play a decisive role in shaping the mineral composition of cereal-based products. Our results align with general patterns described in the literature; however, several brands exhibited markedly higher concentrations of certain elements, particularly Fe, Zn, P, and K, than baseline values typically reported for wheat and rice flours. These elevated levels can be attributed to the use of whole grains such as wheat, oat, and barley, the inclusion of cocoa, and declared fortification practices, all of which contribute to the enhanced mineral contents observed in our samples.

4.2. Discussion on Risk Assessment Due to the Intake of Metal(loid)s

The Daily Intake (DI, mg/day) of elements from cereal-based samples at 30 g/day and 90 g/day is summarized in Table 8. As expected, DIs increased proportionally with higher consumption. Products from Manufacturer A (Brands 1–6), based mainly on rice and wheat, provided moderate DIs of Fe (6.8–7.9 mg/day at 30 g; 20.3–23.7 mg/day at 90 g), Mg (5.1–6.5 mg/day; 15.2–19.4 mg/day), and Zn (2.0–2.3 mg/day; 6.0–7.0 mg/day). In contrast, whole-grain–based products (Brands 5 and 6) showed the highest DIs for K and P, reaching 642 mg/day and 545 mg/day, respectively, at 90 g intake, and also elevated Mn (1.4–1.8 mg/day at 90 g). Intermediate DIs were found in Brands 3 and 4, with Brand 3 reaching higher Fe (15.0 mg/day) and Zn (3.1 mg/day) at 90 g, while Brand 4 showed elevated Fe (7.3 mg/day at 30 g; 22.0 mg/day at 90 g), consistent with milk addition.

According to our results, manufacturer B products (Brands 7 and 8), both cocoa-based mixes, exhibited higher Cu and Zn. At 90 g intake, Brand 7 reached 0.42 mg/day of Cu and 6.39 mg/day of Zn, while Brand 8 provided 0.51 mg/day of Cu and 5.33 mg/day of Zn.

For toxic elements, Pb DIs were measurable only in Brands 1–5, with a maximum of 0.025 mg/day (Brand 4, 90 g), while Ni and V varied among brands, peaking in Brand 8 (Ni: 0.027 mg/day) and Brand 5 (V: 0.095 mg/day) at 90 g intake. Therefore, DI values confirm that rice- and wheat-based brands contributed moderate but balanced mineral intakes, whole-grain–enriched products (Brands 5–6) supplied the highest K, P, Mg, and Mn, and cocoa-based products (Brands 7–8) were enriched in Cu and Zn, with Pb consistently undetectable.

When compared with the Dietary Reference Intakes (DRIs) established for children aged 1–3 years [34], the daily intake (DI) values calculated for the cereal-based products in this study (Table 8) revealed both deficiencies and potential excesses depending on the element and consumption level. For iron (Fe), with a recommended intake of 7 mg/day, several brands already met or exceeded the DRI at 30 g/day, and all brands largely surpassed the recommendation at 90 g/day (7.3–23.7 mg/day). Manganese (Mn), with a DRI of 1.2 mg/day, also showed levels exceeding the recommendation in some brands at 30 g/day and consistently surpassing it at 90 g/day (up to ~5.4 mg/day). Selenium (Se) presented the most pronounced differences, since all products exceeded the DRI of 0.020 mg/day even

at the lowest consumption scenario, reaching up to sevenfold higher values at 90 g/day. Molybdenum (Mo) similarly surpassed the DRI of 0.017 mg/day at higher intake levels.

In contrast, potassium (K) and magnesium (Mg), whose DRIs are 2000 mg/day and 80 mg/day, respectively, remained below the recommended levels in both consumption scenarios, even in the most enriched formulations. Zinc (Zn) and copper (Cu) exhibited brand-dependent variability: Zn values ranged from below the DRI of 3 mg/day at 30 g/day to exceeding it at 90 g/day in some formulations (e.g., Brands 1 and 7), while Cu, with a DRI of 0.34 mg/day, remained below at 30 g/day but exceeded the recommendation in some brands at 90 g/day. Phosphorus (P), recommended at 460 mg/day, was below the DRI in all cases at 30 g/day but surpassed it in certain formulations (e.g., Brand 5) when consumption reached 90 g/day.

Taken together, these results demonstrate that while some element such as K and Mg contribute only modestly to dietary requirements, others including Fe, Mn, Se, and Mo may reach or exceed recommended intakes even at relatively low consumption levels. The variability observed across brands reflects differences in raw material composition (e.g., inclusion of whole wheat, barley, or cocoa), as well as fortification practices. These findings highlight the dual role of cereal-based products as both important contributors to essential nutrient intake and potential sources of excessive exposure to specific elements in young children.

The daily intake (DI) values estimated in our study (Table 8) can be compared with the Tolerable Upper Intake Levels (ULs) established by the Dietary Reference Intakes (DRIs), which represent the thresholds above which adverse health effects may occur [35]. This comparison reveals that, under moderate consumption (30 g/day), most elements remained below the established ULs for children aged 1–3 years. However, at higher consumption (90 g/day), several elements approached or exceeded these safety thresholds.

For iron (Fe), the UL is 40 mg/day [35]. In our study, intakes ranged from 2.4–7.9 mg/day at 30 g/day and up to 23.7 mg/day at 90 g/day (Brand 2), values below the UL but representing more than half of the tolerable limit. Magnesium (Mg), with a UL of 65 mg/day, showed intakes of <30 mg/day at 30 g/day and up to 39 mg/day at 90 g/day (Brand 5), remaining within safe margins but indicating that frequent consumption could lead to levels approaching the UL.

High intakes of iron and magnesium have been associated with significant health risks in children. For iron, ingestions above approximately 20 mg/kg of elemental iron can cause systemic toxicity in pediatric populations, with clinical manifestations including abdominal pain, vomiting, gastrointestinal bleeding, and, in severe cases, hepatic failure or death [36]. Similarly, excessive intake of magnesium—most often from supplements or medications rather than food can result in hypermagnesemia, particularly in individuals with impaired renal function. Symptoms of magnesium toxicity include lethargy, confusion, muscle weakness, respiratory depression, and, in severe cases, arrhythmias or cardiac arrest [37]. A reported clinical case described a 20-month-old child who developed life-threatening hypermagnesemia after prescribed oral magnesium supplementation as a laxative, presenting with coma and generalized weakness [38].

For manganese (Mn), the UL is only 2 mg/day [35]. While at 30 g/day most brands were below this threshold, high intake (90 g/day) led to values ranging from 0.6–5.4 mg/day (Table 8), meaning that several brands exceeded the UL, particularly Brand 5. Similarly, selenium (Se) (UL = 0.09 mg/day) exceeded the limit in some cases, with values up to 0.114 mg/day at 90 g/day (Brand 5). Zinc (Zn) also presented concern, as the UL is 7 mg/day; while most brands at 30 g/day remained below this value, higher intakes surpassed the UL, with Brand 1 reaching 7.0 mg/day and Brand 7 6.4 mg/day at 90 mg/day. Several studies underscore that elevated daily intake of certain chemical elements can

carry health risks, particularly for children. For zinc (Zn), Ceballos-Rasgado et al. (2022) documented adverse effects in infants and young children from high intakes including gastrointestinal disturbances and impaired copper absorption when consumption substantially exceeds dietary recommendations [39]. For manganese (Mn), Coetzee et al. (2016) reviewed evidence that high exposure is linked with neurodevelopmental deficits and cognitive impairment in children, especially in those exposed via environmental or dietary sources [40]. Regarding selenium (Se), Dobrzyńska et al. (2023) caution that although it is critical for antioxidant defense and growth, excess intake particularly through supplements may lead to toxicity, manifested in dermatological problems, hair and nail changes, and neurological symptoms [41]

By contrast, copper (Cu) (UL = 1 mg/day), nickel (Ni) (UL = 0.2 mg/day), and phosphorus (P) (UL = 3000 mg/day) [35] remained below tolerable levels across all scenarios.

Although the estimated daily intake (DI) values for copper (Cu), nickel (Ni), and phosphorus (P) in our samples remained below the established tolerable limits, literature evidence shows that excessive exposure to these elements can pose risks, particularly in young children. For copper, chronic intake above nutritional requirements has been associated with hepatotoxicity. A pediatric case report described fatal liver failure in a child chronically exposed to environmental Cu, underscoring the potential severity of long-term excessive intake [42]. Similarly, the ATSDR notes that sustained intakes above ~30 mg/day may produce hepatic and gastrointestinal toxicity [42]. Nickel exposure through food and drinking water has also raised concerns. According to the updated EFSA risk assessment, children are among the most vulnerable groups, with dietary intake occasionally exceeding safe thresholds and associated with allergic contact dermatitis and immune effects in sensitized individuals [43]. For phosphorus, while it is an essential nutrient, excess intake from fortified foods and food additives can be problematic. High or prolonged phosphorus intake has been linked to nephrocalcinosis and renal tubular dysfunction in children, particularly those with phosphate-handling disorders or chronic kidney disease. Clinical reports confirm that excessive supplementation can induce renal and bone complications, underscoring the need for careful intake monitoring in pediatric population [44,45].

Our findings suggest that although Cu, Ni, and P remained within safe margins, continued monitoring is necessary due to the particular susceptibility of children to cumulative dietary exposure. In contrast, Mn, Se, and Zn require greater attention, as their estimated intakes frequently approached or even exceeded established ULs under higher consumption scenarios. This emphasizes the importance of balancing nutrient adequacy with the prevention of excessive intake, especially in fortified and whole-grain cereal formulations intended for young children.

4.2.1. Discussion on Chronic Daily Intake (CDI)

The Chronic Daily Intake (CDI) values estimated for the cereal-based products (Tables 9 and 10) were compared with the most recent Minimal Risk Levels (MRLs) established by ATSDR (2025) for oral chronic or intermediate exposure [46]. Among the elements considered, MRLs are available for Cu, Mo, Se, V, and Zn, while no oral chronic values are defined for Fe, K, Mg, Mn, P, Si, or Pb, which require complementary evaluation using alternative toxicological references (e.g., RfD or UL values).

Under the lower intake scenario (30 g/day), all CDI values remained below the corresponding MRLs. For example, Cu ranged from 0.0015 to 0.0092 mg/kg/day, which is <50% of the chronic oral MRL of 0.02 mg/kg/day. Similarly, Se intake reached a maximum of ~0.0026 mg/kg/day, corresponding to approximately half of the MRL (0.005 mg/kg/day), while Zn peaked at ~0.14 mg/kg/day, or about 46% of the MRL (0.3 mg/kg/day). These

findings indicate that at moderate consumption levels, the cereal-based products tested do not pose significant toxicological concern relative to current MRL thresholds.

In contrast, under the higher intake scenario (90 g/day), some elements approached or exceeded MRLs. Cu reached up to 0.0276 mg/kg/day in certain brands, surpassing the chronic oral MRL (0.02 mg/kg/day). Se ranged between 0.0048 and 0.0077 mg/kg/day, with several brands exceeding the MRL of 0.005 mg/kg/day. Zn intake varied from 0.06 to 0.41 mg/kg/day, with brands 1 and 3 exceeding the oral MRL of 0.3 mg/kg/day. These exceedances suggest potential chronic health risks, particularly gastrointestinal disturbances (Cu), dermatological and hair effects (Se), and hematological alterations (Zn), which are consistent with the toxicological endpoints reported by ATSDR.

Mo and V, by contrast, remained well below their respective MRLs (0.06 mg/kg/day for Mo and 0.01 mg/kg/day for V) across both intake scenarios, supporting the conclusion that these elements are not of immediate concern in the studied products.

Taken together, these results demonstrate that while the mineral composition of cereal-based products contributes positively to dietary intake of essential elements, high consumption levels, especially of fortified or multi-ingredient formulations, may lead to chronic exposures that exceed safe thresholds for specific chemical elements. This underscores the importance of considering both serving size and brand-specific formulation in dietary risk assessments of infant and children's cereals.

4.2.2. Discussion on Non-Carcinogenic Risk Assessment

The assessment of Hazard Quotients (HQ) and Hazard Index (HI) provides critical insights into the potential health risks associated with chronic exposure to chemical elements through cereal-based products. As shown in Table 11, when considering an intake of 30 g/day, HQ values for individual elements were generally below 1.0, except for vanadium (V), which reached HQ > 1.0 in several brands (Brands 3–6), and manganese (Mn), which exceeded 1.0 in Brands 5–8. Lead (Pb) also approached or surpassed HQ = 1.0 in some samples (Brands 3, 4, and 6), suggesting potential concern. Although most essential elements such as Cu, Fe, Zn, and Se remained within acceptable margins, the cumulative Hazard Index (HI) across all brands ranged from 3.30 (Brand 1) to 4.81 (Brand 5), exceeding the safety threshold of 1.0. This indicates that simultaneous exposure to multiple elements, even at relatively low individual concentrations, may contribute to an overall non-negligible risk.

At a higher intake level of 90 g/day (Table 12), the risk profile was more pronounced. HQ values for Fe, Mn, Pb, V, and Se exceeded 1.0 in most brands, with Pb particularly critical in Brands 3, 4, and 6, where HQ > 2.0–4.0. Mn and V also showed HQ values ranging from 2.39 to 6.14, underscoring their significant contribution to potential non-carcinogenic risk. In contrast, Cu and Mo remained consistently below the threshold, suggesting limited concern. Importantly, the cumulative HI values increased substantially, ranging from 9.83 (Brand 1) to 14.44 (Brand 5), indicating a high cumulative burden of exposure when children consume larger portions of these products.

The comparison of the Hazard Index (HI) values presented in Tables 11 and 12 and summarized in Figure 1 reveals a clear increase in the cumulative non-carcinogenic risk with higher ingestion rates. When the daily intake increased from 30 g/day to 90 g/day, all brands exhibited higher HI values, indicating a direct relationship between the consumption rate and potential exposure to elemental contaminants. Among the evaluated products, Brand 4 and Brand 5 showed the highest HI values in both scenarios, suggesting that the concentration and combination of specific metals particularly vanadium (V), manganese (Mn), and lead (Pb) may have contributed most significantly to the overall hazard index.

These results highlight two critical aspects. First, although some essential elements (Fe, Zn, Mg) are beneficial at moderate levels, their elevated intake together with toxic metals (Pb, Ni) and elements with narrow safety margins (Mn, V) raises concerns about cumulative toxicity. Second, the difference between 30 g/day and 90 g/day scenarios illustrates the sensitivity of risk estimates to consumption levels, reinforcing that dietary exposure assessments must consider portion sizes relevant to children.

In general, the elevated HI values across all brands suggest that long-term daily consumption of these cereal-based products may pose non-negligible health risks, especially for young children with lower body weights. This underscores the importance of continuous monitoring of elemental content in infant and child-targeted foods and the enforcement of stricter quality control measures to minimize exposure to both toxic and essential elements at levels above nutritional requirements.

Recent international investigations have demonstrated that complementary foods and infant cereals are significant contributors to children's dietary exposure to toxic metals such as lead (Pb), cadmium (Cd), and arsenic (As). Studies conducted in the United States and Europe indicate that grains and cereal-based products account for a large portion of infants' exposure to these elements [47,48]. The U.S. Food and Drug Administration (FDA), through its Closer to Zero initiative, has recently proposed action levels to progressively reduce heavy metals in foods intended for babies and young children [49]. Similarly, the European Food Safety Authority (EFSA) continues to identify infants and toddlers as the population most vulnerable to inorganic arsenic and lead exposure [48,50]. Furthermore, systematic reviews confirm that commercially available infant foods often contain detectable levels of toxic elements, reinforcing the importance of ongoing monitoring and risk assessment to safeguard child health [51].

5. Conclusions

This study quantified As, Cd, Co, Cr, Cu, Fe, K, Mn, Mg, Mo, Ni, P, Pb, Se, Si, V, and Zn in cereal-based products widely consumed as complementary foods for Brazilian children using ICP OES. Arsenic, cadmium, cobalt, and chromium were consistently below detection limits, while phosphorus and potassium predominated across all brands, followed by Fe, Zn, and Mg. Significant variability between products was observed, reflecting differences in raw material composition, fortification practices, and processing.

The findings provide a comprehensive characterization of the elemental composition of eight cereal-based products consumed by children, revealing pronounced heterogeneity driven by formulation and ingredient selection. Phosphorus and potassium consistently emerged as the predominant elements, while Mg, Fe, and Zn also contributed substantially to the overall mineral load. Notably, toxic elements such as Pb were detected in several brands but absent in others, underscoring brand-dependent variation in raw material quality and manufacturing practices.

Comparisons with FDA reference concentrations demonstrated that multiple elements, including Cu, Mg, Mn, K, P, Zn, Se, V, and Pb, were present at levels exceeding established ranges. In addition, comparisons with international studies confirmed that our products frequently contained higher Fe, Zn, and Mn than reported for wheat and rice flours, consistent with the inclusion of whole grains, oats, barley, and declared fortification.

The dietary intake (DI) estimates showed that cereal-based products contribute substantially to essential nutrient requirements, but in several cases, particularly for Fe, Zn, Mn, and Se, intakes approached or exceeded the Dietary Reference Intakes (DRIs) and even the Tolerable Upper Intake Levels (ULs) for children aged 1–3 years. Comparison with ATSDR Minimal Risk Levels (MRLs) further indicated that under high-consumption scenarios (90 g/day), Cu, Se, and Zn surpassed toxicological thresholds, suggesting possible long-

term health risks. Hazard Quotient (HQ) and Hazard Index (HI) analysis corroborated these findings: while moderate consumption (30 g/day) already resulted in HI values above the safety threshold of 1.0, higher intake (90 g/day) elevated HI values up to 14.4, with Mn, V, and Pb being the major contributors to overall risk.

This study highlights the dual role of cereal-based products as both valuable contributors to children's micronutrient intake and potential sources of excessive exposure to specific chemical elements. The results underscore the need for continuous monitoring of elemental composition, stricter regulatory oversight of fortification practices, and careful consideration of portion sizes to ensure nutritional adequacy while minimizing toxicological risks in vulnerable populations such as young children.

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Abbreviations

The following abbreviations are used in this manuscript:

ADI	Acceptable Daily Intake
AI	Adequate Intake
ANVISA	Agência Nacional de Vigilância Sanitária (Brazilian Health Regulatory Agency)
AT	Averaging Time
ATSDR	Agency for Toxic Substances and Disease Registry
BW	Body Weight
CDI	Chronic Daily Intake
CDC	Centers for Disease Control and Prevention
Co	Cobalt
Cr	Chromium
Cu	Copper
CV	Coefficient of Variation
DI	Daily Intake
DRI	Dietary Reference Intake
EAR	Estimated Average Requirement
EF	Exposure Frequency
EPA	Environmental Protection Agency (U.S.)
FAO	Food and Agriculture Organization of the United Nations
Fe	Iron
FDA	Food and Drug Administration (U.S.)

HI	Hazard Index
HQ	Hazard Quotient
ICP-OES	Inductively Coupled Plasma Optical Emission Spectrometry
IR	Ingestion Rate
K	Potassium
LOQ	Limit of Quantification
NAAQS	National Ambient Air Quality Standard
Mg	Magnesium
Mn	Manganese
Mo	Molybdenum
MRL	Minimal Risk Level
Ni	Nickel
P	Phosphorus
Pb	Lead
RfD	Reference Dose
Se	Selenium
Si	Silicon
TDS	Total Diet Study
UL	Tolerable Upper Intake Level
US	United States
V	Vanadium
WHO	World Health Organization
Zn	Zinc

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