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Potentially Toxic Element Transfer and Bioconcentration in Food Crops Across Contrasting Tropical Soils

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Abstract

Potentially toxic element (PTE) transfer to food crops depends strongly on soil properties. This study evaluated the accumulation of Ba, Cd, Cu, Ni, and Zn in lettuce, rice, sunflower, and tomato grown in an Entisol and an Oxisol under two crop-specific base saturation conditions representing contrasting levels of soil acidity correction by liming. Bioconcentration factors (BCF) and transfer factors (TF) were determined from PTE concentrations in soils and plant tissues. BCF and TF varied with crop species, soil type, and base saturation. In general, the sandy Entisol showed greater soil-to-plant transfer than the clayey Oxisol. For example, Cd BCF in lettuce shoots ranged from 17.0 to 26.9 in the Entisol and from 2.2 to 3.4 in the Oxisol. Cd showed the greatest overall transfer and internal translocation, especially in lettuce, sunflower, and tomato, whereas Ba and Cu were generally more restricted within plants. Nominal PTE additions were based on prevention values established by Companhia Ambiental do Estado de São Paulo (CETESB). These findings indicate that soil-specific properties should be incorporated into assessments of PTE transfer to crops and into soil management decisions aimed at limiting accumulation in edible tissues.

Keywords: base saturation; liming; translocation factor; pseudo-total concentration; food safety; edible tissues

1. Introduction

Potentially toxic element (PTE) contamination of soils is a global environmental concern because of the persistence of these elements, their accumulation in environmental compartments, and their potential transfer through food chains [1,2]. More than 5 million contaminated sites, covering approximately 20 million hectares, have been reported worldwide [3–5]. In agricultural systems, this issue is particularly relevant because PTEs present in soil may be transferred to crops, creating a direct link between soil contamination, food production, and potential human exposure. Major anthropogenic sources of PTEs include improper disposal of industrial, agricultural, and mining wastes, untreated industrial releases, indiscriminate use of agrochemicals, and mining and metal-smelting activities [1,4]. Elements such as Cd, Cu, Ni, Zn and Ba may accumulate in soils and become environmentally relevant under elevated concentrations [6,7]. Because many PTEs are persistent and bioaccumulative, they can accumulate in living organisms and cause toxic, genotoxic, and carcinogenic effects [8].

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Regulatory authorities in approximately 75 countries use Regulatory Guidance Values (RGVs) to manage PTE contamination in soils [9]. These values define soil PTE concentrations above which remediation or mitigation may be required for a given land use. However, there is no consensus between jurisdictions on the contamination values at which health risks begin. Brazilian legislation established prevention and intervention values for PTEs in soils, considering risks to environmental and human health under different land-use scenarios [10,11].

Although some PTEs such as Cu, Ni, and Zn are essential micronutrients, elevated concentrations may impair plant physiological processes, including photosynthesis, chlorophyll synthesis, stomatal regulation, and plant growth [12–16]. PTE accumulation in plants depends on climatic conditions, soil properties, and crop genotype [17,18]. Among soil attributes, pH, organic carbon, and oxide composition strongly influence metal mobility and bioavailability to plants [19–21]. BCF values are influenced by soil properties, plant species, climatic conditions, and PTE concentrations. Previous studies have reported differences among crops, cultivars, and soil conditions, with generally higher BCF values observed in humid tropical environments [22–26].

The selected crops represent contrasting agronomic groups and edible plant compartments, allowing comparison of PTE transfer to leaves, grains or seeds, and fruits. Lettuce is frequently used as a sensitive species in contamination studies and can accumulate substantial amounts of PTEs in edible leaves [27–30]. Rice is particularly relevant because root uptake does not necessarily result in proportional transfer to grains, reflecting strong internal regulation of PTE translocation [25,31–35]. Sunflower has been widely investigated for its capacity to accumulate and redistribute metals among vegetative and reproductive tissues [36–43], whereas tomato provides a contrasting fruit-bearing crop in which PTE uptake by roots and shoots may be partly restricted before reaching edible fruits [44–46]. Together, these crops provide complementary models for assessing species- and organ-specific patterns of soil-to-plant transfer.

The translocation and accumulation of PTEs in plants are associated with their availability in the soil. Bioconcentration factor (BCF) and transfer factor (TF) are widely used indices to evaluate the accumulation and internal transfer of PTEs in crops. BCF estimates the transfer of elements from soil to plant tissues, while TF relates metal concentrations in shoots to those in roots [22,47,48]. These indices are commonly applied in environmental and food safety risk assessments, including models estimating human exposure through crop consumption [49]. Previous studies in tropical soils have demonstrated substantial variation in TF values among elements and crops, indicating that root systems may regulate metal translocation to aerial plant parts [50].

Entisols and Oxisols represent contrasting physicochemical conditions relevant to PTE behavior in tropical soils. In the present study, the Entisol was predominantly sandy and had lower cation exchange capacity and organic carbon content, characteristics associated with lower retention capacity and greater mobility of metal ions [51–53]. In contrast, highly weathered Oxisols are commonly enriched in clay minerals and Fe and Al oxides, which provide reactive surfaces capable of retaining metal ions through adsorption and surface-complexation processes [54]. Organic carbon, pH, and cation exchange capacity further influence these interactions and may alter PTE mobility and subsequent uptake by plants [51–53,55]. These contrasting properties make Entisols and Oxisols useful models for evaluating how tropical soil characteristics influence PTE retention and soil-to-plant transfer.

Despite increasing knowledge of PTE behavior in agricultural soils, it remains insufficiently understood whether equivalent nominal PTE inputs result in comparable soil-to-plant transfer across tropical soils with contrasting physicochemical properties. Base

saturation is an important indicator of soil acidity correction, representing the proportion of the cation exchange capacity occupied by base cations and commonly being adjusted through liming [56]. We hypothesized that identical regulatory-based PTE additions would result in contrasting bioconcentration and translocation patterns depending on soil properties, crop species, and base saturation condition. These findings are also relevant to the United Nations Sustainable Development Goals related to sustainable agriculture and food security (SDG 2), environmentally sound management of contaminants (SDG 12), and protection of soils from degradation and contamination (SDG 15). Therefore, this study evaluated the soil-to-plant transfer and organ-specific distribution of Ba, Cd, Cu, Ni, and Zn in rice (*Oryza sativa* L.), lettuce (*Lactuca sativa* L.), sunflower (*Helianthus annuus* L.), and tomato (*Solanum lycopersicum* L.) cultivated in an Entisol and an Oxisol under crop-specific base saturation conditions, with emphasis on the potential transfer to edible tissues. This comparative approach advances understanding of how soil properties, crop species, and acidity management jointly influence PTE transfer in tropical agricultural systems.

2. Material and Methods

2.1. Soil Characterization

Two soils with contrasting physical and chemical properties were selected to represent distinct conditions affecting PTE retention and soil-to-plant transfer: a predominantly sandy Entisol with lower organic carbon and cation exchange capacity, and a clayey Oxisol with higher organic carbon and cation exchange capacity (Table 1), collected from São Pedro (−22.52868, −47.90665) and Piracicaba (−22.62182, −47.62935), São Paulo State, Brazil, respectively. Both sampling locations are within a Cwa climate region according to the Köppen classification, characterized by dry winters and hot, rainy summers [57]. Samples were collected from the 0–0.20 m layer, air-dried, sieved (<2 mm), and chemically and physically characterized (Table 1).

Table 1. Chemical and physical properties of the Oxisol and Entisol used in the experiment.

Soils	Ca	Mg	K	Al	H + Al	P
		$mmol_c\ kg^{-1}$				$mg\ kg^{-1}$
Oxisol	13.1	6.6	0.8	9.6	72.0	10.1
Entisol	2.3	1.0	0.3	4.8	21.0	5.6
	Organic Carbon	**CEC_e**	**$CEC_{7.0}$**	**V**	**m**	**pH**
	$g\ kg^{-1}$	$mmol_c\ kg^{-1}$		%		(0.01 M $CaCl_2$)
Oxisol	20.5	30.1	92.5	22.1	31.9	4.1
Entisol	5.4	8.4	24.3	14.7	56.9	4.2
			Granulometry ($g\ kg^{-1}$)			
	Clay		**Silt**		**Sand**	
Oxisol	593		123		284	
Entisol	63		31		906	

V: Base saturation; m: saturation by aluminum; CECe: Effective Cation Exchange Capacity at soil pH; $CEC_{7.0}$: Cation Exchange Capacity at pH 7.0.

Soil acidity was corrected using analytical-grade calcium and magnesium carbonates to adjust base saturation (V) to 30% and to the recommended levels for each crop, corresponding to 50% for rice and 70% for lettuce, sunflower, and tomato, according to Raij [56].

Soil characterization included determination of organic carbon [58], exchangeable Al, pH, and potential acidity [59], as well as bioavailable Ca, Mg, K, and P extracted

by ion-exchange resin [60]. Particle-size distribution was determined by the densimeter method [61].

2.2. Experimental Design

Four crops were cultivated under greenhouse conditions in a randomized block design with three replicates. For each crop, Ba, Cd, Cu, Ni, and Zn were evaluated individually, each in a separate PTE treatment with its corresponding non-spiked control. Within each PTE experiment, treatments consisted of two soils (Entisol and Oxisol) and two crop-specific base saturation conditions: 30 and 50% for rice, and 30 and 70% for lettuce, sunflower, and tomato, as proposed by Pinto and Alleoni [62].

Ba, Cd, Cu, Ni, and Zn were selected because they represent environmentally relevant PTEs with contrasting biological functions and plant behavior. Cd and Ba are non-essential elements of concern in contaminated soils, whereas Cu, Ni, and Zn are essential micronutrients that may become toxic at elevated concentrations. Their occurrence is associated with agricultural, industrial, mining, and metallurgical activities, and all five elements are included in the CETESB soil prevention framework used to define the nominal application rates in this study.

The crops were selected to represent agronomically relevant species with contrasting edible organs and physiological strategies—leafy vegetable (lettuce), cereal grain (rice), oilseed crop (sunflower), and fruiting vegetable (tomato)—allowing comparison of species- and organ-specific patterns of PTE uptake, bioaccumulation, and translocation.

2.3. Cultivation and Preparation of Samples

Polyethylene pots containing 6 kg of air-dried soil (ADS) were used for lettuce and rice, whereas 10 kg were used for sunflower and tomato cultivation. To avoid differences in nitrogen supply among treatments, nitrogen inputs were equalized using ammonium nitrate.

Before PTE application, background pseudo-total concentrations of Ba, Cd, Cu, Ni, and Zn were determined by microwave-assisted acid digestion following EPA 3051A [63]. The Entisol presented lower background concentrations of these elements (3.6, 0.8, 15.2, 2.2, and 14.5 mg kg^{-1} for Ba, Cd, Cu, Ni, and Zn, respectively) than the Oxisol (60.2, 3.7, 44.9, 11.5, and 22.6 mg kg^{-1}, respectively). Potentially toxic elements were then individually added to the soils as nitrate solutions at nominal doses corresponding to the prevention values established by Cetesb [64]: 120 mg kg^{-1} soil of Ba, 1.3 mg kg^{-1} soil of Cd, 60 mg kg^{-1} soil of Cu, 30 mg kg^{-1} soil of Ni, and 86 mg kg^{-1} soil of Zn. After PTE application, soils remained at 95% WRC for an additional seven days before planting.

Tomato (cv. Santa Clara VF 5600) and lettuce (cv. Amanda) seedlings were transplanted, whereas sunflower (cv. Aguará 4) and rice (cv. IAC-202) were directly sown. After establishment and thinning, the final number of plants per pot was one tomato plant, three lettuce plants, one sunflower plant, and five rice plants. Irrigation was performed by direct addition of deionized water to each pot as required to maintain soil moisture at approximately 70% of the maximum water retention capacity (WRC) throughout cultivation. The soils were contained in plastic bags placed inside the pots to prevent leachate losses.

Basal fertilization was performed using analytical-grade reagents according to crop nutritional requirements recommended by Raij [56]. Supplemental fertilization and phytosanitary management were conducted when necessary to maintain adequate crop development and physiological vigor during cultivation.

Lettuce and tomato were harvested at 42 and 68 days after transplanting, respectively, while sunflower and rice were harvested at physiological maturity, corresponding to stages R9 and R8, at 82 and 98 days after sowing, respectively.

Shoots, fruits, grains, and roots were separated after harvest. Plant materials were washed with deionized water, oven-dried at 45 °C under forced air circulation until constant weight, weighed, and ground (<1 mm) for chemical analyses. Soil samples adhering to the roots were removed, homogenized, and dried under the same conditions.

2.4. Extraction and Determination of PTEs in Soils and Plant Tissues

Pseudo-total concentrations of Ba, Cd, Cu, Ni, and Zn in soil samples were determined following the EPA 3051A method [63]. Plant samples (0.25 g, <1 mm) were placed in Teflon vessels and treated with 2 mL H_2O_2 (30%) for 2 h, followed by the addition of 2 mL HNO_3 (65%) and overnight pre-digestion. Subsequently, 5 mL of ultrapure water was added, and the samples were subjected to microwave-assisted digestion using a MARSXpress system (CEM Corporation, Matthews, NC, USA), reaching a maximum temperature of 180 °C. After digestion, the extracts were cooled, filtered through quantitative filter paper, and diluted to 100 mL with ultrapure water. Quality assurance procedures included analytical blanks and reference materials for every 20 samples analyzed. Certified reference material 2709a (San Joaquin Soil; National Institute of Standards and Technology, Gaithersburg, MD, USA) was used for soil analyses, whereas the maize quality-control material designated as "Sample 1" in the 2014 Interlaboratory Program for Plant Tissue Analysis (PIATV), coordinated by ESALQ/USP, was used as the plant-tissue quality-control sample. Element concentrations were quantified by inductively coupled plasma optical emission spectrometry (ICP-OES) using a Thermo Scientific iCAP 6300 Duo spectrometer (Thermo Electron Manufacturing Ltd., Cambridge, UK). Quantification limits were 0.002 mg L^{-1} for Ba, Cd, Ni, and Zn, and 0.005 mg L^{-1} for Cu.

2.5. Bioconcentration and Transfer Factors

The transfer and internal distribution of potentially toxic elements (PTEs) in plants were evaluated using the bioconcentration factor (BCF) and transfer factor (TF).

The BCF was calculated as the ratio between the PTE concentration in plant tissues and the pseudo-total concentration in the soil (Equation (1)):

$$BCF = \frac{M_{plant}}{M_{soil}} \quad (1)$$

where M_{plant} (mg kg^{-1}) corresponds to the PTE concentration in roots, shoots, fruits, or grains, and M_{soil} (mg kg^{-1}) corresponds to the post-cultivation pseudo-total PTE concentration in the corresponding soil treatment determined following the EPA 3051A method [63].

The TF was calculated as the ratio between the PTE concentration in shoots and roots (Equation (2)):

$$TF = \frac{M_{shoot}}{M_{root}} \quad (2)$$

where M_{shoot} (mg kg^{-1}) represents the PTE concentration in the shoot, operationally defined in this study as all aboveground plant tissues (stems and leaves, including fruits or grains when present), and M_{root} (mg kg^{-1}) represents the PTE concentration in roots.

PTE accumulation in each plant compartment was calculated based on the dry mass and respective elemental concentration of each tissue. Total extraction was obtained by summing the accumulated amounts in roots, shoots, fruits, and grains. The proportion of the applied PTE recovered in each plant compartment was calculated as PTE recovery (%) = (PTE accumulated in the plant compartment/nominal PTE amount added to the pot) × 100, where the nominal amount added to each pot was calculated from the PTE dose (mg kg^{-1} soil) multiplied by the dry soil mass contained in the pot.

2.6. Statistical Analysis

Statistical analyses were performed separately for each crop and PTE using Sisvar software 6.6 [65]. For soil pseudo-total concentrations, data were analyzed considering soil type, base saturation condition, and PTE addition (control vs. PTE-amended soil) as fixed factors, with three replicates per treatment. For BCF and TF, only PTE-amended treatments were considered. For each crop and PTE, data were analyzed in a 2 × 2 factorial arrangement consisting of two soil types and two crop-specific base saturation conditions, with three replicates per treatment combination. The ANOVA model included the main effects of soil type and base saturation and their interaction (soil type × base saturation). Data were checked for normality and homogeneity of variances before analysis of variance (ANOVA). When significant effects were detected, treatment means were compared by Tukey's test at the 5% probability level ($p < 0.05$).

3. Results and Discussion

3.1. Contents of PTEs in the Soils

The pseudo-total concentrations of potentially toxic elements (PTEs) in the soils (Table 2) generally differed more strongly between soil types than among crops within the same soil type. These differences were likely associated with the contrasting mineralogical, chemical, and physical properties of the soils, as well as with the contribution of distinct parent materials [51,54]. The Oxisol, derived from igneous and metamorphic materials, naturally presented higher background concentrations of PTEs than the Entisol derived from sandstone [54].

The contrasting behavior between soils is environmentally relevant because soil attributes directly influence PTE retention and bioavailability. The Oxisol presented higher clay content, cation exchange capacity (CEC), and organic carbon, favoring greater sorption and reducing PTE mobility. In contrast, the sandy Entisol, characterized by lower buffering capacity and reduced adsorption sites, likely promoted greater availability of soluble PTE fractions. These differences reinforce that total soil concentrations alone may not adequately predict PTE behavior and plant uptake under contrasting tropical soil conditions.

Regardless of crop species, the addition of PTEs increased pseudo-total concentrations in both soils (Table 2). However, the environmental implications differed according to soil properties. Thus, equivalent nominal PTE additions resulted in contrasting soil PTE concentrations and soil-to-plant transfer patterns depending on the soil–crop combination.

3.2. Bioconcentration and Transfer Factor of PTEs in Crops

The accumulation and translocation of PTEs varied substantially according to crop species, soil type, and base saturation conditions (Figures 1–4). These variations were likely associated with differences in PTE bioavailability, which are controlled by soil physicochemical properties such as pH, CEC, organic carbon, texture, and ionic interactions [55].

In general, higher bioconcentration factors (BCFs) were observed in the Entisol, particularly under lower base saturation conditions. The lower clay and organic carbon contents of this soil likely reduced PTE retention, increasing the mobility of dissolved ions and their uptake by plants. Conversely, the Oxisol generally reduced PTE accumulation, indicating stronger sorption and lower bioavailability. However, the response to base saturation was element- and crop-dependent.

The use of BCF and transfer factor (TF) indices allowed the identification of important differences in PTE partitioning among roots, shoots, fruits, and grains. BCF was interpreted primarily as an index of soil-to-plant transfer, whereas TF reflected internal translocation from roots to aboveground tissues. Together, these indices identified soil-dependent transfer

patterns and potential pathways to edible tissues that are relevant for environmental monitoring and dietary-exposure screening.

Table 2. Average [1] pseudo-total [2] concentrations of Ba, Cd, Cu, Ni and Zn in control (C) and individual PTE treatments (M) in Entisol and Oxisol under two crop-specific base saturation conditions (V), after cultivation of lettuce, rice, sunflower and tomato.

Soil	V (%)	Treat.	Ba	Cd	Cu	Ni	Zn
			Lettuce (mg kg^{-1})				
Entisol	30	C	4.2 f ± 0.2	0.99 d ± 0.16	14.7 c ± 0.6	2.2 c ± 0.3	11.0 c ± 0.2
		M	125.2 c ± 3.0	1.99 c ± 0.14	69.7 a ± 2.2	29.1 a ± 1.8	91.7 a ± 3.1
	70	C	4.5 f ± 0.4	0.79 d ± 0.06	14.5 c ± 0.8	2.3 c ± 0.2	10.5 c ± 0.6
		M	100.5 d ± 5.4	1.95 c ± 0.15	74.2 a ± 10.0	29.4 a ± 1.1	84.8 a ± 8.0
Oxisol	30	C	72.8 e ± 8.8	3.03 b ± 0.21	42.8 b ± 1.6	12.2 b ± 0.8	20.6 b ± 1.5
		M	203.4 a ± 12.1	4.33 a ± 0.08	85.5 a ± 6.9	34.6 a ± 4.3	94.7 a ± 5.2
	70	C	72.2 e ± 8.6	3.00 b ± 0.16	40.7 b ± 1.7	11.6 b ± 0.5	19.2 b ± 0.4
		M	170.3 b ± 14.8	4.30 a ± 0.15	83.4 a ± 10.6	29.7 a ± 6.9	80.1 a ± 26.1
			Rice (mg kg^{-1})				
Entisol	30	C	3.6 d ± 0.5	0.89 e ± 0.04	15.9 e ± 0.9	2.1 d ± 0.2	18.0 c ± 4.6
		M	123.6 b ± 14.8	2.20 d ± 0.32	94.7 b ± 16.0	42.2 b ± 1.0	109.2 b ± 13.4
	50	C	3.7 d ± 0.6	0.87 e ± 0.01	15.3 e ± 0.5	2.2 d ± 0.3	12.8 c ± 1.7
		M	164.1 b ± 35.1	2.49 d ± 0.54	68.0 c ± 9.6	40.0 b ± 3.0	98.8 a ± 9.2
Oxisol	30	C	50.3 c ± 1.5	4.33 b ± 0.19	43.8 d ± 1.0	10.6 c ± 0.3	22.0 c ± 1.2
		M	224.8 a ± 85.2	5.48 a ± 0.55	131.7 a ± 11.0	49.0 a ± 8.5	147.9 a ± 21.8
	50	C	51.8 c± 7.5	3.87 c ± 0.11	41.6 d ± 1.1	10.8 c ± 1.4	22.6 c ± 0.8
		M	171.8 a ± 37.4	5.17 a ± 0.21	101.6 a ± 4.3	40.8 a ± 8.6	108.6 a ± 7.3
			Sunflower (mg kg^{-1})				
Entisol	30	C	3.2 d ± 0.2	0.68 d ± 0.05	15.2 e ± 0.6	2.2 d ± 0.2	16.5 d ± 4.9
		M	113.3 b ± 17.5	1.59 c ± 0.07	72.1 c ± 8.5	30.9 b ± 12.4	77.9 b ± 7.5
	70	C	3.7 d ± 0.4	0.63 d ± 0.06	15.4 e ± 0.5	2.4 d ± 0.3	11.5 d ± 0.6
		M	111.7 b ± 12.7	1.82 c ± 0.30	74.5 c ± 10.2	29.3 b ± 3.7	95.7 b ± 9.8
Oxisol	30	C	47.1 c ± 5.4	3.34 b ± 0.07	46.7 d ± 2.1	11.0 c ± 1.9	23.7 c ± 2.4
		M	160.3 a ± 33.9	4.20 a ± 0.11	100.1 b ± 5.1	51.5 a ± 6.7	149.0 a ± 17.8
	70	C	54.3 c ± 8.6	3.23 b ± 0.08	49.6 d ± 1.3	13.4 c ± 3.3	25.4 c ± 1.4
		M	168.5 a ± 38.1	4.20 a ± 0.58	134.2 a ± 8.7	43.1 a ± 9.0	107.3 a b ± 32.5
			Tomato (mg kg^{-1})				
Entisol	30	C	3.2 d ± 0.3	0.69 c ± 0.01	15.1 c ± 0.8	2.2 c ± 0.3	12.4 c ± 1.6
		M	106.4 b ± 24.7	1.58 b ± 0.20	66.8 a ± 8.6	23.2 a ± 3.1	79.6 a ± 12.3
	70	C	3.5 d ± 0.3	0.74 c ± 0.02	15.4 c ± 0.9	2.3 c ± 0.3	11.1 c ± 1.5
		M	106.8 b ± 13.1	1.45 b ± 0.33	64.4 a ± 15.2	25.2 a ± 2.7	67.4 a ± 18.1
Oxisol	30	C	70.7 c ± 23.3	3.94 a ± 0.26	46.4 b ± 4.3	12.3 b ± 2.4	24.1 b ± 3.0
		M	146.9 a ± 23.2	5.24 a ± 0.15	82.0 a ± 5.3	30.3 a ± 0.3	75.3 a ± 6.0
	70	C	45.9 c ± 3.6	3.80 a ± 0.11	42.9 b ± 1.1	11.4 b ± 1.3	22.8 b ± 2.3
		M	153.1 a ± 35.8	5.10 a ± 0.26	77.4 a ± 14.3	29.2 a ± 7.1	75.7 a ± 2.2

[1] Arithmetic mean (n = 3) ± standard deviation; [2] Pseudo-total concentrations determined by EPA 3051A. Means followed by the same letter within each PTE and plant compartment do not differ according to Tukey's test ($p < 0.05$).

The responses observed in the crops demonstrated that equivalent nominal PTE additions based on regulatory prevention values may result in different environmental outcomes depending on soil properties. In the Entisol, Cu, Ni, and Zn restricted plant development under some treatments, and failure of plant development occurred in specific

cases. These responses demonstrate that plant effects following regulatory-based additions can vary substantially with tropical soil properties and PTE bioavailability.

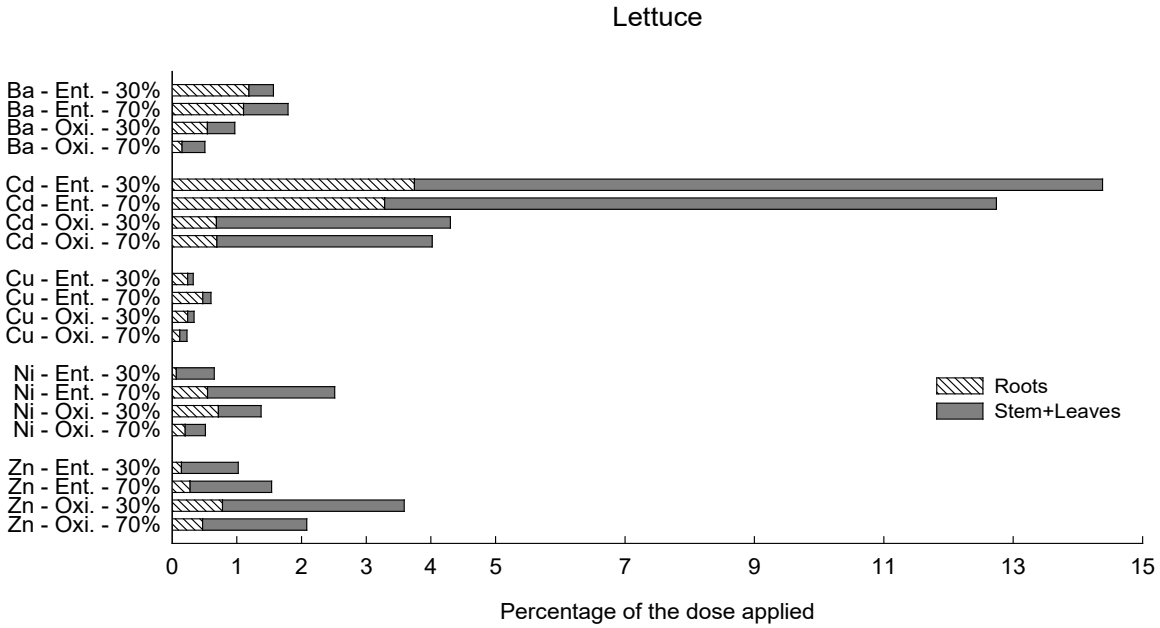


Figure 1. Percentage of Ba, Cd, Cu, Ni and Zn in relation to the doses applied to an Entisol (Ent.) and an Oxisol (Oxi.) under two base saturation levels (30 and 70%) for root and stem + leaves of lettuce.

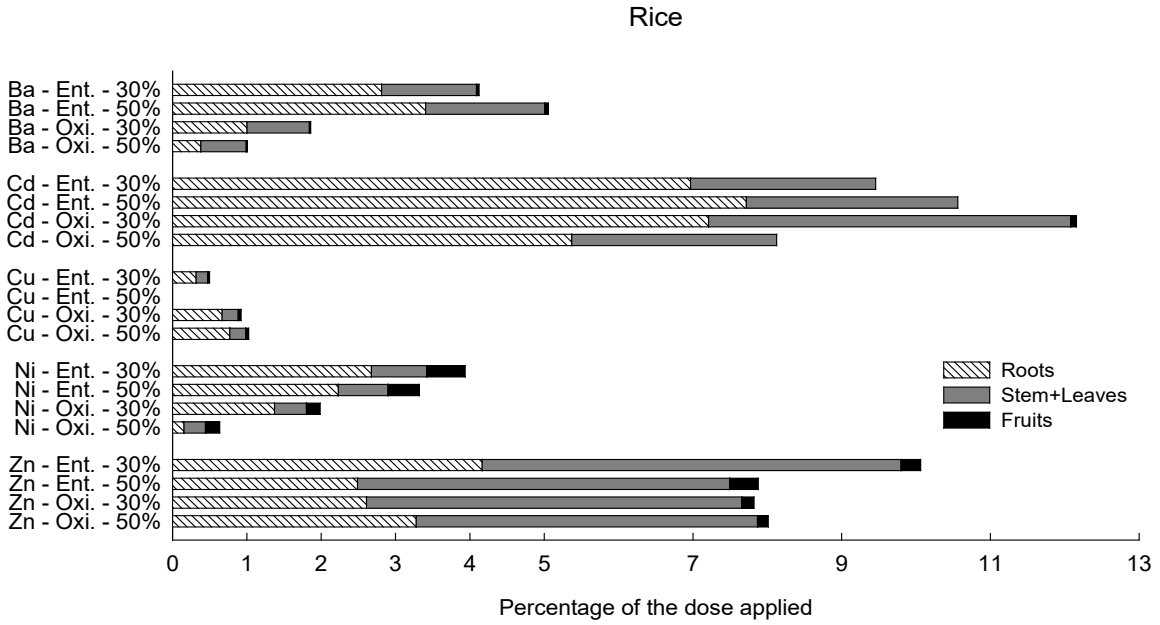


Figure 2. Percentage of Ba, Cd, Cu, Ni and Zn in relation to the doses applied to an Entisol (Ent.) and an Oxisol (Oxi.) under two base saturation levels (30 and 50%) for root, stem + leaves and grains of rice.

The higher BCF values observed in the Entisol are consistent with the lower adsorption capacity of sandy soils with reduced CEC and organic carbon [52]. Similar behavior was reported by [53], who observed greater availability and uptake of Cd, Ni, and Pb in a sandy Typic Quartzipsamment. These findings reinforce the importance of considering soil-specific properties in environmental risk assessments involving PTE-contaminated agricultural soils.

Overall, the results support our hypothesis that equivalent nominal PTE additions produce contrasting soil-to-plant transfer and translocation patterns depending on soil properties, crop species, and base saturation condition. The sandy Entisol generally showed higher BCF values than the Oxisol, whereas the magnitude and direction of the base-saturation effect varied among elements and crops. Cd showed particularly high soil-to-plant transfer in lettuce and sunflower, while its transfer to rice grains remained limited. These findings demonstrate that PTE transfer cannot be inferred from nominal soil additions alone and depends on the specific soil–crop combination.

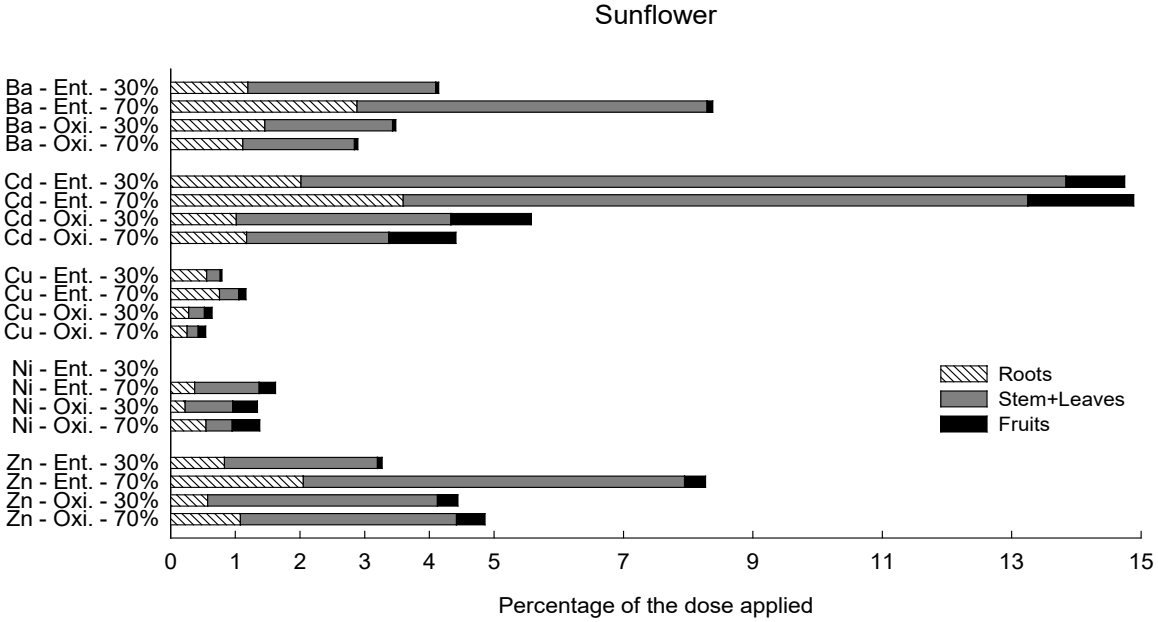


Figure 3. Percentage of Ba, Cd, Cu, Ni and Zn in relation to the doses applied to an Entisol (Ent.) and an Oxisol (Oxi.) under two base saturation levels (30 and 70%) for root, stem + leaves and fruit of sunflower.

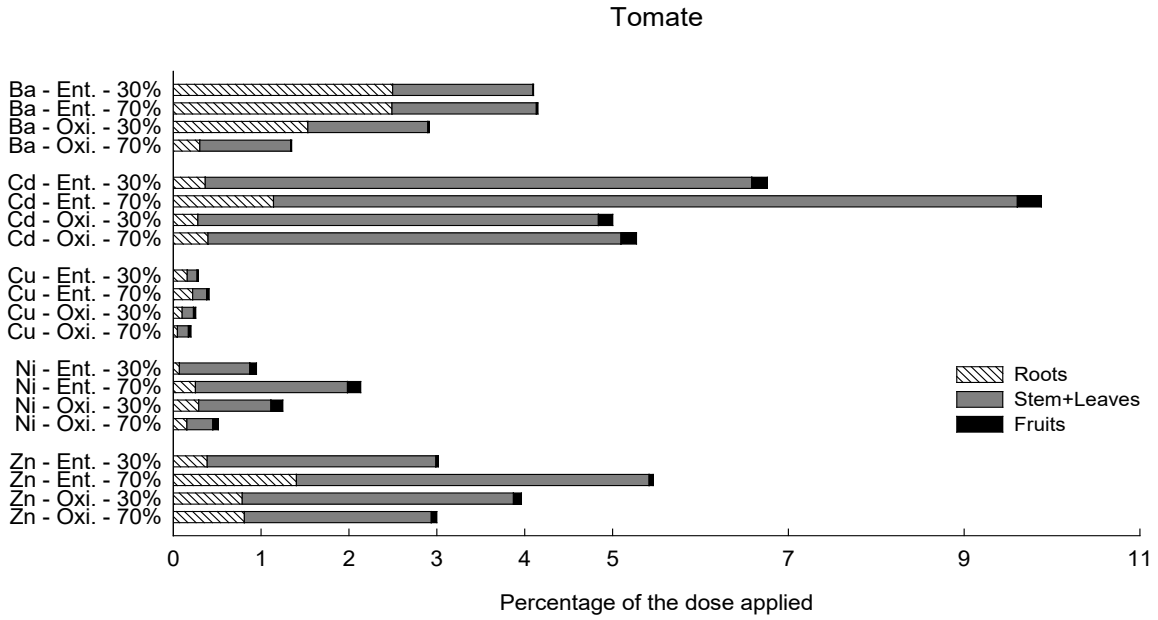


Figure 4. Percentage of Ba, Cd, Cu, Ni and Zn in relation to the doses applied to an Entisol (Ent.) and an Oxisol (Oxi.) under two base saturation levels (30 and 70%) for root, stem + leaves and fruit of tomato.

3.3. PTEs in Lettuce

Lettuce is considered a sensitive bioindicator species for evaluating environmental contamination and abiotic stress [27–29]. In the present study, lettuce accumulated relatively low proportions of Ba, Cu, Ni, and Zn, generally below 4% of the total applied doses (Figure 1). However, Cd showed substantially greater uptake and translocation, particularly in the Entisol under the lowest base saturation level (30%), where more than 14% of the applied Cd was accumulated in roots and leaves.

The higher accumulation observed in the Entisol suggests that the lower CEC, reduced clay fraction, and lower organic carbon content increased Cd mobility and availability to plants. In contrast, the Oxisol reduced Cd uptake, likely due to stronger adsorption and greater retention capacity associated with higher clay and organic matter contents. Similar responses were observed by [30], who reported reduced Cd uptake in lettuce cultivated in soils with higher clay content and after liming.

The elevated Cd bioconcentration factors observed in lettuce indicate considerable soil-to-plant transfer of this element under low-buffer tropical soil conditions (Table 3). In the Entisol, Cd presented the highest BCF values among the evaluated PTEs, particularly in shoots and leaves, demonstrating substantial transfer to edible tissues. These results are environmentally relevant because leafy vegetables may represent an important pathway for PTE transfer to the food chain.

In contrast, Cu presented comparatively lower BCF and TF values, indicating stronger retention in roots and lower internal mobility. This lower mobility is possibly associated with stronger adsorption to soil colloids and greater affinity for organic and mineral fractions [66].

The lower BCF values observed in the Oxisol reinforce the importance of soil properties in regulating PTE bioavailability. For Cd, the BCF in shoots and leaves was approximately 12 times lower in the Oxisol (V = 70%) than in the Entisol (V = 30%). Similar soil-dependent reductions were observed for Ni and Zn, although the magnitude of the response to base saturation differed among elements.

Transfer factors close to or above unity for Cd and Ni indicate substantial mobility from roots to shoots under specific conditions, especially in the Entisol. However, the magnitude of TF should be interpreted together with BCF, because these indices describe distinct components of PTE transfer: BCF reflects soil-to-plant accumulation, whereas TF describes the internal distribution of the element between roots and shoots. Thus, the comparatively high TF values observed for Cd and Ni indicate efficient root-to-shoot translocation under specific soil conditions, without necessarily implying similarly high overall accumulation from the soil. For lettuce, the combined BCF and TF patterns highlighted Cd and Zn as elements with high soil-to-plant transfer and/or internal translocation relative to Ba and Cu.

3.4. PTEs in Rice

Rice showed greater Cu uptake than lettuce, and Cu exposure severely impaired plant development in the Entisol regardless of base saturation level (Figure 2). These responses indicate that the nominal Cu addition based on the Cetesb prevention value was sufficient to induce phytotoxic effects under conditions of greater bioavailability.

The higher Cu accumulation observed in the Entisol was likely associated with reduced sorption capacity and increased availability of soluble Cu fractions. Similar reductions in rice productivity under elevated Cu concentrations were reported by [31], particularly in soils with lower buffering capacity. The present findings demonstrate that plant responses to a regulatory-based Cu addition differed according to soil conditions.

Table 3. Bioconcentration factors [1] (BCF) and transfer factor [1] (TF) of barium (Ba), cadmium (Cd), copper (Cu), nickel (Ni) and zinc (Zn) applied to two soils cultivated with lettuce at two base saturation levels (V).

Soil	V (%)	BCF_{Roots}	$BCF_{Stem+Leaves}$	TF
			Ba	
Entisol	30	15.3 a ± 1.7	1.1 b ± 0.1	0.1 b ± 0.0
	70	16.4 a ± 3.7	1.9 a ± 0.5	0.1 b ± 0.1
Oxisol	30	5.5 b ± 0.7	0.7 c ± 0.0	0.1 b ± 0.0
	70	1.7 c ± 0.4	0.5 d ± 0.0	0.3 a ± 0.1
			Cd	
Entisol	30	29.5 a ± 7.6	26.9 a ± 1.3	1.0 a ± 0.2
	70	24.8 a ± 2.8	17.0 b ± 1.0	0.7 b ± 0.1
Oxisol	30	3.4 a ± 0.7	3.4 a ± 0.3	1.0 a ± 0.1
	70	3.2 a ± 0.5	2.2 b ± 0.2	0.7 b ± 0.1
			Cu	
Entisol	30	13.2 a ± 5.1	1.0 a ± 0.4	0.1 a ± 0.0
	70	8.0 b ± 2.2	0.3 b ± 0.1	0.0 a ± 0.0
Oxisol	30	3.1 c ± 0.7	0.2 b ± 0.0	0.1 a ± 0.0
	70	1.6 d ± 0.4	0.2 b ± 0.0	0.1 a ± 0.0
			Ni	
Entisol	30	25.6 a ± 12.0	24.5 a ± 1.3	1.2 a ± 0.8
	70	28.5 a ± 8.1	13.0 b ± 1.9	0.5 b ± 0.1
Oxisol	30	12.5 b ± 0.7	2.0 c ± 0.2	0.2 c ± 0.0
	70	3.0 c ± 0.8	0.6 d ± 0.2	0.2 c ± 0.0
			Zn	
Entisol	30	27.7 a ± 6.2	15.4 a ± 3.6	0.6 a ± 0.3
	70	28.4 a ± 17.3	15.4 a ± 4.4	0.6 a ± 0.2
Oxisol	30	12.4 b ± 2.6	7.7 b ± 2.0	0.6 a ± 0.1
	70	9.5 b ± 4.7	4.2 b ± 2.2	0.4 b ± 0.1

[1] Arithmetic mean (n = 3) ± standard deviation; BCF: PTE concentration in a specific plant compartment/corresponding pseudo-total PTE concentration in soil; TF: PTE concentration in shoots (stem and leaves)/PTE concentration in roots. Means followed by the same letter within each PTE and plant compartment do not differ according to Tukey's test ($p < 0.05$).

Rice accumulated Ba and Ni in proportions similar to those observed in lettuce; however, Ni showed greater internal mobility, with relatively higher accumulation in grains (Figure 2). In contrast, Cd exhibited strong retention in roots, resulting in extremely low concentrations in grains. In several treatments, Cd concentrations in rice grains remained below the analytical quantification limit reported for the ICP-OES analyses.

This behavior indicates that, despite considerable root uptake, Cd translocation to rice grains was limited (Table 4). The low BCF_{Fruits} and TF values observed for Cd are consistent with the restricted mobility of this element within rice plants and with previous reports describing preferential Cd retention in vegetative tissues [25,32].

Zn presented the highest TF values among the evaluated PTEs, indicating greater mobility from roots to aerial tissues and grains. Grain Zn concentrations ranged from 43.8 to 60.9 mg kg^{-1}, demonstrating substantial translocation capacity under the evaluated conditions.

Table 4. Bioconcentration factors [1] (BCF) and transfer factor [1] (TF) of barium (Ba), cadmium (Cd), copper (Cu), nickel (Ni) and zinc (Zn) applied to two soils cultivated with rice under two base saturation levels (V).

Soil	V (%)	BCF_{Roots}	$BCF_{Stem+Leaves}$	BCF_{Fruits}	TF
			Ba		
Entisol	30	7.6 a ± 2.0	1.4 a ± 0.3	0.0 b ± 0.0	0.1 c ± 0.0
	50	6.7 a ± 2.3	1.2 a ± 0.1	0.1 a ± 0.0	0.1 c ± 0.0
Oxisol	30	1.4 b ± 0.6	0.4 b ± 0.2	0.0 b ± 0.0	0.2 b ± 0.0
	50	0.5 c ± 0.2	0.4 b ± 0.2	0.0 b ± 0.0	0.5 a ± 0.1
			Cd		
Entisol	30	11.9 a ± 2.9	1.7 a ± 0.4	0.0 b ± 0.0	0.1 b ± 0.0
	50	12.5 a ± 3.0	1.6 a ± 0.4	0.0 b ± 0.0	0.1 b ± 0.0
Oxisol	30	3.3 b ± 0.9	0.8 b ± 0.2	0.1 a ± 0.1	0.2 a ± 0.0
	50	3.2 b ± 1.0	0.5 b ± 0.0	0.0 b ± 0.0	0.1 b ± 0.1
			Cu		
Entisol	30	1.8 a ± 0.4	0.2 a ± 0.1	0.1 a ± 0.1	0.1 a ± 0.0
	50	pnd	pnd	Pnd	pnd
Oxisol	30	0.9 b ± 0.0	0.1 b ± 0.0	0.1 a ± 0.0	0.1 a ± 0.0
	50	1.1 b ± 0.0	0.1 b ± 0.0	0.1 a ± 0.0	0.1 a ± 0.0
			Ni		
Entisol	30	7.8 a ± 1.3	0.6 a ± 0.1	0.5 a ± 0.1	0.1 a ± 0.0
	50	6.3 a ± 0.4	0.5 a ± 0.0	0.4 a ± 0.0	0.1 a ± 0.0
Oxisol	30	2.1 b ± 0.5	0.2 b ± 0.1	0.3 a ± 0.2	0.1 a ± 0.0
	50	2.3 b ± 1.2	0.1 b ± 0.0	0.4 a ± 0.1	0.1 a ± 0.0
			Zn		
Entisol	30	8.3 a ± 0.3	5.0 a ± 0.7	0.5 a ± 0.1	0.4 a ± 0.0
	50	6.8 b ± 0.5	5.3 a ± 1.9	0.5 a ± 0.2	0.4 a ± 0.1
Oxisol	30	3.0 c ± 0.4	2.2 c ± 0.4	0.4 a ± 0.1	0.6 a ± 0.0
	50	5.0 b ± 0.0	2.5 c ± 0.3	0.6 a ± 0.1	0.5 a ± 0.1

[1] Arithmetic mean (n = 3) ± standard deviation; BCF: PTE concentration in a specific plant compartment/corresponding pseudo-total PTE concentration in soil; TF: PTE concentration in shoot/PTE concentration in roots; pnd = plants did not develop sufficiently for BCF or TF determination. Means followed by the same letter within each PTE and plant compartment do not differ according to Tukey's test ($p < 0.05$).

The overall sequence of BCF values followed the order $BCF_{Roots} > BCF_{Stems+Leaves} > BCF_{Fruits}$, indicating progressive restriction of PTE transfer from roots to edible tissues. Nevertheless, the magnitude of accumulation varied markedly according to soil type. In the Entisol, BCF values were consistently higher, reinforcing the role of lower CEC and organic carbon in increasing PTE availability and uptake.

Although TF values remained below one for most elements, the substantial differences between soils demonstrate that environmental risk cannot be inferred solely from total concentrations in soil. Instead, the interaction between soil properties and plant physiology strongly controlled contaminant mobility and transfer to grains.

3.5. PTEs in Sunflower

Sunflower exhibited substantial accumulation and translocation of Cd, Ni, and Zn, particularly to reproductive tissues (Figure 3). Among the evaluated crops, sunflower

presented some of the highest BCF_{Fruits} values for Cd, indicating considerable transfer of this element to grains under specific soil conditions.

Ba was absorbed in appreciable quantities, especially in the Entisol, although its mobility within the plant remained relatively low. The higher accumulation observed under increased base saturation may be associated with improved plant growth and greater nutrient uptake under more favorable fertility conditions. Similar responses were observed by [39], who reported increased Ba uptake in limed soils cultivated with sunflower.

The strong influence of soil properties on PTE behavior was evident in the contrasting responses between the Entisol and Oxisol. The influence of soil type on PTE transfer was particularly evident for Cu, Ni, and Zn, for which the Entisol and Oxisol showed contrasting accumulation patterns. These differences are consistent with the contrasting physicochemical properties of the two soils and their potential effects on PTE retention and accessibility to plants.

The observed toxicity is environmentally relevant because the nominal PTE additions were based on prevention values established by CETESB [64]. Under the evaluated conditions, Cu, Ni, and Zn were sufficient to impair plant establishment and development, demonstrating that the biological response to regulatory-based additions depends strongly on soil physicochemical properties.

Cadmium presented the highest BCF_{Fruits} values and TFs among the evaluated elements, particularly in the Entisol (Table 5). These results indicate substantial internal translocation from roots to grains and highlight the potential for transfer to edible plant structures.

The overall pattern of accumulation followed the order roots > shoots > fruits, indicating partial restriction of PTE transfer to reproductive tissues. Nevertheless, Cd, Zn, and Ni showed comparatively greater internal translocation than Ba and Cu, reinforcing their environmental relevance regarding transfer to edible structures.

3.6. PTEs in Tomato

Tomato plants showed substantial uptake of PTEs, particularly in roots and shoots (Figure 4). In the Entisol, lower base saturation increased PTE availability and resulted in higher BCF values in shoots and leaves.

Although plants cultivated under lower base saturation accumulated high concentrations of PTEs, plant development was restricted under these conditions. Differences between BCF and total PTE accumulation indicate that concentration-based and total-accumulation metrics may provide complementary information on PTE transfer among treatments. This demonstrates that accumulation patterns were influenced not only by bioavailability, but also by plant growth responses under contrasting fertility and toxicity conditions.

Tomato fruits accumulated lower concentrations of PTEs than roots and shoots for most evaluated elements. Ba exhibited particularly low TF values, indicating restricted translocation to fruits. In contrast, Cd showed substantial mobility within the plant, with TF values ranging from 0.8 to 2.3 and BCF_{Fruits} reaching values up to 2.0 (Table 6).

The elevated Cd transfer to fruits is environmentally important because tomato is a widely consumed crop, with potential implications for dietary exposure. The lower Cd accumulation observed in the Oxisol indicates that higher clay content, organic carbon, and adsorption capacity substantially reduced Cd bioavailability and transfer to edible tissues.

Ni and Zn also exhibited relatively high TF values, particularly in the Entisol under low base saturation, confirming enhanced mobility under conditions of lower retention capacity. In contrast, Cu remained predominantly retained in roots, resulting in low TF values and limited accumulation in fruits.

Table 5. Bioconcentration factors [1] (BCF) and transfer factor [1] (TF) of barium (Ba), cadmium (Cd), copper (Cu), nickel (Ni) and zinc (Zn) applied to two soils cultivated with sunflower under two base saturation levels (V).

Soil	V (%)	BCF_{Roots}	$BCF_{Stem+Leaves}$	BCF_{Fruits}	TF
			Ba		
Entisol	30	13.0 b ± 2.8	4.4 b ± 1.2	0.3 a ± 0.0	0.3 a ± 0.1
	70	24.7 a ± 5.0	6.4 a ± 1.5	0.3 a ± 0.1	0.2 a ± 0.1
Oxisol	30	7.7 b ± 4.5	1.5 c ± 0.6	0.1 b ± 0.0	0.2 a ± 0.1
	70	4.6 c ± 1.1	1.2 c ± 0.4	0.1 b ± 0.1	0.2 a ± 0.0
			Cd		
Entisol	30	17.4 b ± 5.2	18.7 a ± 5.8	5.7 a ± 4.1	1.1 a ± 0.6
	70	22.1 a ± 6.1	8.8 b ± 2.8	4.6 a ± 1.1	0.4 b ± 0.1
Oxisol	30	2.8 c ± 0.5	1.0 c ± 0.2	1.1 b ± 0.1	0.4 b ± 0.1
	70	2.1 c ± 0.7	0.7 c ± 0.1	0.9 b ± 0.1	0.4 b ± 0.2
			Cu		
Entisol	30	5.5 b ± 0.1	0.6 a ± 0.1	0.3 a ± 0.1	0.1 a ± 0.0
	70	6.9 a ± 2.1	0.4 a ± 0.0	0.4 a ± 0.1	0.1 a ± 0.0
Oxisol	30	1.4 c ± 0.3	0.2 b ± 0.0	0.2 b ± 0.0	0.1 a ± 0.0
	70	0.8 c ± 0.1	0.1 b ± 0.0	0.2 b ± 0.0	0.1 a ± 0.0
			Ni		
Entisol	30	pnd	pnd	pnd	pnd
	70	8.9 a ± 3.4	2.1 a ± 0.2	2.1 a ± 0.4	0.3 a ± 0.1
Oxisol	30	2.0 b ± 1.1	0.5 b ± 0.1	0.8 b ± 0.1	0.4 a ± 0.1
	70	2.6 b ± 1.5	0.3 b ± 0.1	0.9 b ± 0.3	0.2 a ± 0.0
			Zn		
Entisol	30	28.7 a ± 1.1	13.8 a ± 1.9	2.2 a ± 1.0	0.4 b ± 1.7
	70	21.0 a ± 1.5	8.7 b ± 1.0	1.2 b ± 0.2	0.3 c ± 0.0
Oxisol	30	3.9 b ± 0.9	2.9 c ± 0.6	0.7 c ± 0.1	0.6 a ± 0.1
	70	5.4 b ± 1.0	3.0 c ± 1.0	1.1 c ± 0.3	0.5 b ± 0.1

[1] Arithmetic mean ($n = 3$) ± Standard deviation; BCF: metal concentration in a specific part of the plant (total digestion)/concentration of the metal in the soil; TF: metal concentration in the shoot/metal concentration in the roots; pnd = plants did not develop sufficiently for BCF/TF determination. Means followed by the same letter within each PTE and plant compartment do not differ according to Tukey's test ($p < 0.05$).

The results obtained for tomato reinforce that soil properties strongly controlled PTE transfer and accumulation patterns. In sandy tropical soils with low CEC and reduced organic carbon, PTEs remained more available for plant uptake and translocation, increasing the potential for transfer to edible tissues following equivalent nominal PTE additions.

3.7. Environmental Implications and Future Perspectives

Across crops, the strongest determinant of PTE transfer was the interaction between element identity and soil properties. The sandy Entisol generally promoted greater bioconcentration, whereas the higher clay content, CEC, and organic carbon of the Oxisol favored PTE retention. Nevertheless, responses to base saturation were not uniform, demonstrating that PTE behavior cannot be inferred from a single soil attribute or management variable.

Table 6. Bioconcentration factors [1] (BCF) and transfer factor [1] (TF) of barium (Ba), cadmium (Cd), copper (Cu), nickel (Ni) and zinc (Zn) applied to two soils cultivated with tomato under two base saturation levels (V).

Soil	V (%)	BCF_{Roots}	$BCF_{Stem+Leaves}$	BCF_{Fruits}	TF
			Ba		
Entisol	30	55.0 a ± 28.1	5.1 a ± 2.0	0.1 a ± 0.0	0.1 a ± 0.0
	70	37.8 b ± 12.0	3.3 b ± 0.7	0.1 a ± 0.1	0.1 a ± 0.0
Oxisol	30	17.5 c ± 6.3	1.9 c ± 0.2	0.1 a ± 0.0	0.1 a ± 0.0
	70	5.6 d ± 2.6	1.5 c ± 0.4	0.1 a ± 0.0	0.2 a ± 0.1
			Cd		
Entisol	30	10.3 b ± 10.3	16.3 a ± 0.8	1.6 a ± 0.9	2.3 a ± 1.6
	70	15.9 a ± 5.5	14.6 b ± 3.1	2.0 a ± 0.6	0.8 b ± 0.2
Oxisol	30	1.3 c ± 0.2	2.0 c ± 0.6	0.2 c ± 0.1	1.2 b ± 0.4
	70	1.5 c ± 0.4	1.8 c ± 0.3	0.2 c ± 0.0	1.1 b ± 0.2
			Cu		
Entisol	30	6.4 a ± 1.8	0.5 a ± 0.2	0.2 a ± 0.0	0.1 a ± 0.1
	70	5.1 a ± 0.5	0.4 a ± 0.1	0.2 a ± 0.1	0.1 a ± 0.0
Oxisol	30	1.4 b ± 0.3	0.2 b ± 0.0	0.1 a ± 0.0	0.1 a ± 0.0
	70	1.1 b ± 0.4	0.2 b ± 0.0	0.2 a ± 0.1	0.2 a ± 0.1
			Ni		
Entisol	30	14.0 a ± 8.2	11.6 a ± 5.3	2.5 a ± 0.1	0.9 a ± 0.5
	70	13.1 a ± 0.7	5.1 b ± 1.0	1.7 b ± 0.2	0.3 b ± 0.1
Oxisol	30	4.5 b ± 3.0	1.4 c ± 0.2	0.9 c ± 0.3	0.4 b ± 0.2
	70	2.1 c ± 0.9	0.5 d ± 0.2	0.4 d ± 0.2	0.3 b ± 0.2
			Zn		
Entisol	30	26.7 a ± 25.9	13.7 a ± 5.1	0.5 b ± 0.3	0.8 a ± 0.7
	70	31.0 a ± 9.1	9.8 b ± 2.3	0.5 b ± 0.1	0.3 b ± 0.1
Oxisol	30	15.4 b ± 6.6	7.1 c ± 1.1	0.8 a ± 0.1	0.4 b ± 0.2
	70	10.6 c ± 2.1	3.7 d ± 0.6	0.4 b ± 0.0	0.3 b ± 0.1

[1] Arithmetic mean (n = 3) ± standard deviation; BCF: PTE concentration in a specific plant compartment/corresponding pseudo-total PTE concentration in soil; TF: PTE concentration in shoot/PTE concentration in roots. Means followed by the same letter within each PTE and plant compartment do not differ according to Tukey's test ($p < 0.05$).

The contrasting responses observed after equivalent nominal PTE additions are particularly relevant for environmental monitoring. The CETESB prevention values were used as a reference for defining the nominal PTE additions and not to reproduce aged field contamination or to validate the regulatory thresholds themselves. Because PTEs were applied as soluble nitrate salts and evaluated after a relatively short equilibration period, their behavior may differ from that of contaminants subjected to long-term aging and stabilization processes under field conditions. Therefore, the present results should be interpreted primarily in terms of the relative differences in soil-to-plant transfer between the contrasting soils under the experimental conditions.

Cadmium showed the greatest overall soil-to-plant transfer and translocation potential, particularly in lettuce and sunflower, whereas Ba and Cu generally remained more restricted in roots and vegetative tissues. Rice showed limited Cd transfer to grains, further demonstrating that crop-specific translocation behavior is a major component of environmental interpretation.

Increasing base saturation frequently reduced PTE uptake, although both the magnitude and direction of this response depended on the element, crop, soil type, and plant compartment. Soil correction may therefore reduce PTE bioavailability under some soil-crop combinations, but should not be interpreted as producing a uniform response across elements.

Future studies should integrate pseudo-total concentrations with reactive and available PTE fractions, soil-solution chemistry, and crop-specific physiological responses. Such approaches may improve prediction of PTE transfer and support more soil-sensitive environmental assessment frameworks for tropical agricultural systems.

The transfer of PTEs to edible tissues also requires consideration from a food-safety perspective. However, comparisons with maximum permissible concentrations should be restricted to element–food combinations for which specific regulatory limits are established. Brazilian and European regulations establish maximum levels for selected contaminants in specific food categories, including Cd [67,68] and Ni [69]. Therefore, the concentrations observed in edible tissues in the present study should be interpreted in relation to the corresponding food category and regulatory framework, rather than extrapolated across crops or elements for which no directly applicable limit is available.

4. Conclusions

Contrasting tropical soil properties strongly influenced the bioconcentration and transfer of Ba, Cd, Cu, Ni, and Zn to food crops. The sandy Entisol generally showed greater soil-to-plant transfer, whereas the clayey Oxisol, characterized by higher cation exchange capacity and organic carbon, restricted PTE accumulation in most soil–crop combinations. Cd showed the greatest overall transfer and translocation potential, particularly in lettuce, sunflower, and tomato, while Ba and Cu were generally more restricted in their transfer to aboveground tissues.

The effects of base saturation were not uniform and varied according to the element, crop, soil type, and plant compartment. Thus, liming-related changes in soil chemical conditions did not produce a consistent reduction or increase in PTE transfer across all soil–crop combinations. Equivalent nominal PTE additions also resulted in markedly different bioconcentration and translocation patterns between the two soils, reinforcing the importance of soil-specific characteristics in controlling soil-to-crop transfer.

These findings indicate that pseudo-total PTE concentrations should be interpreted together with soil properties and crop-specific responses when assessing the potential transfer of contaminants to edible tissues. Because the PTEs were applied as soluble nitrate salts under controlled greenhouse conditions, the results should not be directly extrapolated to aged field contamination. Nevertheless, the contrasting responses between soils demonstrate the importance of incorporating soil-specific information into environmental assessments and management strategies aimed at reducing PTE transfer to food crops.

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