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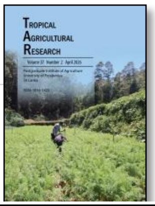

RESEARCH

Bio-accumulation of Potentially Toxic Trace Elements in Vegetables in Sri Lanka

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ABSTRACT

Potentially toxic trace elements (PTEs) from natural and anthropogenic sources, particularly in agriculture, may accumulate in soils and enter the food chain, posing health risks. Only a portion of these elements is bioavailable for plant uptake, which is strongly influenced by soil properties. This study quantified bioaccumulation factors (BAFs) to assess the uptake of Cd, Pb, As, Cu, and Zn by different vegetables, identified the soil properties influencing the bioavailability and accumulation, and evaluated whether Mehlich 3 extractable PTEs concentrations could serve as indicators of plant-available PTEs. Surface soil (0-15 cm) and corresponding vegetables were collected from two different cropping systems and soil types: vegetable-only Ultisol (Nuwara Eliya) and coarse-textured Entisol (Kalpitiya), and vegetable paddy rotation Ultisol (Badulla). PTE concentrations in soil and vegetables were measured using an Inductively Coupled Plasma Optical Emission Spectrometer. Total concentrations (mg/kg) of Cd (0.88), Pb (15), As (14.6), Cu (53.5), and Zn (136.7), Mehlich 3 extractable Cd (0.245), Pb (3.6), Cu (5.55), and Zn (19.1) were higher in Ultisol in Nuwara Eliya, while the highest As (0.245) concentration was observed in the Entisol of Kalpitiya. Elevated BAF values were observed for Cd (0.53) in carrots, Zn (0.64) in beetroot from Nuwara Eliya, and Zn in carrots (0.75), beetroot (1.69), cabbages (0.67), beans (0.97), and red onions (0.68) in Badulla, and Zn in beetroots (2.7) and red onions (4.22), Cu in beetroots (0.50), and red onions (1.13), and Cd in red onions (0.79), from Kalpitiya showing the highest accumulation. BAFs of Pb (0.01-0.06) and As (0.01 - 0.08) relative to low across three locations. Soils in Kalpitiya contained very low organic carbon (<2%) and clay (<3%), while soils from Nuwara Eliya and Badulla had higher organic carbon (>2%) and clay (>20%). Higher organic carbon and clay levels reduced the mobility of potentially toxic elements (PTEs).

INTRODUCTION

Potentially Toxic Trace Elements (PTEs) such as Cu and Zn are essential for plants, animals, and humans in small quantities, as they play critical roles in metabolic functions and enzymatic activities (Antoine *et al.,* 2012). However, these elements can become toxic to humans when their concentrations in vegetables exceed safe limits, established by the WHO/FAO (1999). In contrast, elements like As, Cd, and Pb are nonessential, providing no known benefits to living organisms (Chang, 2000), but can be toxic to humans even at low concentrations (Nies., 1999). Both essential and non-essential trace elements, including Pb, Cd, Cr, and As, can originate naturally from the bedrock or be introduced into the soil through anthropogenic activities such as soil management, pest and disease management through chemical fertilizers, herbicides, and pesticides, and agricultural amendments such as organic manure and liming materials. Road traffic pollution can also contribute to soil contamination, with these trace elements eventually entering the living beings through the food chain, particularly in humans, posing some health risks (Premarathna *et al*., 2005).

The upcountry wet and intermediate zones, as well as the Kalpitiya area in the low-country dry zone, are major hubs for intensive, commercial vegetable cultivation in Sri Lanka. Farmers in these areas typically grow 2 to 3 crops yearly on the same land, often using large amounts of fertilizers, manures, and other agrochemicals. It has been documented that these practices could lead to soil contamination with PTEs (Wijewardena and Yapa, 1999). Among the various types of vegetables grown in the upcountry regions, carrots (*Daucus carota*), beets (Beta vulgaris), potatoes (*Solanum tuberosum*), leeks (*Allium ampeloprasum*), and cabbage (*Brassica oleracea*) are the most widely consumed (AgStat, Sri Lanka, 2015) vegetables. cabbage, beets, and red onion (*Allium cepa*) as vegetables are intensively grown in the Kalpitiya area as well. Additionally, several samples of root and tuber crops of carrot, beet, and potato, collected from the upcountry wet and intermediate zone in Sri Lanka, exceeded the maximum permissible limit of Pb and Cr imposed by FAO/WHO Joint Codex (Silva *et al*., 2018).

The bioavailable fraction of these PTEs is the readily mobilizable fraction, which is accessible to plants. Total metal concentrations in soil do not necessarily correspond with trace element bioavailability. Absorption of PTEs by plants depends on soil properties, such as pH, organic matter, cation exchange capacity, texture, and clay content in soil (Adamo *et al.,* 2018). Bioaccumulation of PTEs in plants refers to the process by which plants absorb and accumulate PTEs in their tissues from the soil over time. This process is quantified by the bioaccumulation factor (BAF), which is the ratio of the PTE concentration in a plant to its concentration in soil (Yeasmin *et al.,* 2013).

The uptake and bioaccumulation of PTEs by plants are influenced by the bioavailability of PTE in soils, which depends on soil properties and plant physiological characteristics (Nepal, 2024). Additionally, factors other than soil characteristics, plant genotype, age, and their interactions play a significant role in determining trace element absorption or accumulation by plants (Ding *et al*., 2013). However, among all the factors that control bioavailability and bioaccumulation of trace elements, soil factors are crucial in regulating the bioavailability of PTEs in the soil-plant system because they control chemical form and solubility of the elements, which directly impacts how readily plants can absorb them.

Various extractions can be used to measure and estimate the bioavailability of potentially toxic trace elements. Such extractions can mobilize and isolate certain trace elements that reflect their mobile pool in soil. Extractable trace elements are often called exchangeable, mobile, plant-available, or bioavailable trace elements. However, the Mehlich 3 extraction solution was widely used because it is a multi-nutrient extractant that effectively dissolves the soil fractions most closely associated with the plant – available forms of PTE (Mehlich, 1984; Houba *et al.*, 1996). Its combination of weak acids, fluoride, and chelating agents allows it to extract metals bound to easily exchangeable, carbonate, and weakly adsorbed soil phases (Simard, 1993; Griggs and Cooperband, 2003). As a result, Mehlich 3 provides a reliable estimate of the bioavailable and environmentally mobile fractions of PTEs, making it suitable for risk assessment, monitoring contaminated soils, and comparing soil fertility across different soil types (Miller and Kissel, 2010).

However, limited research has been conducted on the bioavailability and bioaccumulation of potentially toxic trace elements in soil-vegetable systems across different soil types and agro ecological zones in Sri Lanka. Therefore, this study aimed to: (1) quantified the BAF to assess the extent of PTE of Cd, Pb, As, Cu and Zn uptake by different vegetables crops grown in intensive vegetable-growing areas across three different agro-climatic zones of upcountry wet zone (Nuwara Eliya), upcountry intermediate zone (Badulla), and low country dry zone (Kalpitiya) area; (2) identify the soil properties affecting the bioavailability and bioaccumulation of PTEs in vegetables, and (3) evaluate whether Mehlich 3 extractable PTEs concentrations could use as a measure of potential plant available PTEs.

METHODOLOGY

Study area and collection of samples

Soil and highly consumed, corresponding vegetable samples were collected from intensive vegetable growing areas in Nuwara Eliya (Up Country Wet Zone, WU1), Badulla (Up Country Intermediate Zone, IU1), and Kalpitiya (Low Country Dry Zone, DL3). Soils collected from Nuwara Eliya mainly belong to the Nuwara Eliya and Kandapola soil series, while soils from Badulla mainly belong to the Hali Ela *and* Badulla soil series, all of which are classified under Ultisol (Red Yellow Podzolic soils). Soils in Kalpitiya mainly belong to the Kalpitiya soil series and are classified under the order Entisol (Regosols). The cropping systems and cultivation practices differ across these three regions. Nuwara Eliya and Kalpitiya practice year-round vegetable cultivation with multiple cropping cycles, whereas in Badulla, a rice-vegetable rotation is employed, with one or two vegetable crops grown per year. In Badulla, rice is grown during the "Maha" season (October to March), and vegetables are cultivated during the "Yala" season (April to September). Sampling was carried out between December 2018 and March 2020. Soil samples were randomly collected from farmer fields at a depth of 0–15 cm using a soil auger. A random sampling strategy was adopted, and multiple sub-samples (3-5) within each field were collected to form a composite sample representing the specific sampling point to reduce the field variability. About 500g of soil samples were brought to the laboratory. In total, 265 soil samples were collected, with an approximate sampling density of two samples per 1000 m^2. The number of samples and locations is detailed in Table 1.

Analysis of soil samples for basic soil properties

Soil samples were air-dried at room temperature and passed through a 2-mm sieve. Soil properties, including pH, electrical conductivity (EC), available phosphorus (P), exchangeable potassium (K), and organic matter (OM) content, were analyzed. pH was determined by a 1:1 soil-to-water extraction and measured using a calomel glass electrode (McLean, 1982). Electrical conductivity was determined using a 1:5 soil-to-water extraction and measured with a conductivity meter (Rhoades, 1982). Available phosphorus was extracted using sodium bicarbonate (Olsen, 1954) and quantified by UV-Visible spectrophotometer (Hach DR 3900) after developing a blue color with ammonium molybdate and ascorbic acid (Murphy and Riley, 1962). Exchangeable potassium was extracted using ammonium acetate (Knudsen *et al*., 1982), and K concentration was measured with a Flame Photometer (Sherwood M 410). Soil organic carbon was determined using the dichromate oxidation method, and organic matter content was estimated (Nelson and Sommers, 1982). The hydrometer method was used to determine the texture (Clay, sand, and silt contents) of soil (Gee and Or, 2002).

Table 1. Number of soil and vegetable samples collected from each location

Agro - Climatic Zone	Vegetable Growing Area	Cropping system/Soil type	Vegetable Crops	No of soil and Vegetable samples
Up Country Wet Zone	Nuwara Eliya	Vegetable-only Ultisol	Carrot	31
			Potato	18
			Beet	15
			Cabbage	21
Up-Country Intermediate Zone	Badulla	Vegetable –Paddy-vegetable- Ultisol	Carrot	26
			Beet	09
			Potato	23
			Cabbage	20
			Bean	26
			Red Onion	09
Low Country Dry Zone	Kalpitiya	Vegetable only Entisol	Cabbage	18
			Red Onion	25
			Beet	24

Analysis of soil samples for total concentration of Cu, Zn, Cd, Pb, Cr, and As

Air-dried and sieved (2 mm sieve) soil samples (0.5 g) were digested in a microwave digester (Model No. MARS 6) at 1400 W with a mixture of 8.0 mL concentrated. HNO_3 (69 %, trace metal grade) and 2.0 mL of 30%. H_2O_2. (Analytical Grade). The digestion process involved heating the samples to 180°C for about 20 minutes, followed by maintaining the same temperature for an additional 15 minutes to complete the digestion (USEPA 3051, 1994). After the digestion, the samples were filtered through Whatman No. 42 filter paper into a 50 ml volumetric flask and diluted to volume with deionized water. The concentrations of Cu, Zn, Mn, Cd, Pb, and As were determined using ICP-OES (Thermo Scientific iCAP 7000 Series, Model iCAP 7400 Duo). To validate the results, Certified Reference Material (CRM) Montana Soil 2710, issued by the National Institute of Standards and Technology (NIST), USA, was digested along with the samples, and the concentrations of Cu, Zn, Mn, Cd, Pb, and As were determined in all the digested samples. The percentage recoveries were calculated, showing satisfactory results for Cd (105%), Pb (96%), As (100.7%), Cu (98.9%), and Zn (100%). A strong, significant correlation was observed between certified and measured values for the standard reference materials (r^2 = 0.99), confirming the accuracy of the analysis. To further ensure accuracy, duplicate samples were digested and analyzed, and blank samples were included in each batch to eliminate any interference from chemicals used during the analysis.

Analysis of soil samples for extractable (Mehlich 3) concentration of PTEs Cu, Zn, Cd, Pb, and As

Mehlich 3 extraction solution was prepared by mixing 20.0125 g of ammonium nitrate, 4.0 mL of 3.75 M ammonium fluoride and 0.25M EDTA stock solution, 11.5 mL of glacial acetic acid, and 0.825 mL of concentrated nitric acid in 1 L of deionized water. Analytical grade chemicals were used for the preparation of the extract. pH of the solution was adjusted to 2.5±0.05 (Mehlich, A., 1984). A 2.0 g air-dried, sieved (2 mm sieve) soil sample was weighed into a 50 ml polypropylene bottle, and 20.0 ml of Mehlich 3 extracting solution was added to each polypropylene bottle. Samples were shaken for 5 minutes, shaking immediately filtered the soil suspension through a Whatman No. 42 filter paper. Trace element concentrations were determined using an ICP-OES (Thermo Scientific iCAP 7000 Series, Model iCAP 7400 Duo). Blank samples were also subjected to analysis for each batch of extraction.

Analysis of vegetable samples for PTE concentrations

Vegetable samples (approximately 500g) were brought to the laboratory and thoroughly rinsed with tap water, followed by a wash with 0.5M sodium lauryl sulfate, and finally rinsed with distilled water. Root crops such as beet, carrot, and potato were scrubbed with a brush under tap water to remove soil particles before washing with 0,5M sodium lauryl sulfate and distilled water, and then peeled using a stainless-steel knife. The peeled samples were rinsed again with distilled water. After washing, the samples were air-dried for a few hours to let surface moisture to evaporate. The fresh weight of each sample was recorded after removing any remaining moisture using a tissue. The samples were then cut into small pieces with a stainless-steel knife, oven-dried at 60°C for a few days until reaching a constant weight, and their dry weights were measured. Moisture contents of vegetables were determined gravimetrically. The oven-dried samples were ground using a stainless-steel grinder and passed through a 0.5 mm sieve. Samples were analysed for PTEs of Pb, Cd, As, Cu, and Zn.

Dried finely ground vegetable samples (0.5000 g) were digested in a microwave digester (MARS 6, CEM Corporation) at 1400 W using a mixture of 8.0 ml of concentrated HNO_3 (69%, trace metal grade) and 2.0 ml of H_2O_2 (30%, analytical grade). The digestion process took 20 minutes to reach 180°C, and this temperature was maintained for 15 minutes to complete the digestion process (Briscoe *et al*., 2015). A blank digestion was also carried out using the same digestion mixture without a sample with each batch of samples. The digested samples were then filtered through Whatman No. 42 filter paper into 50 mL volumetric flasks and diluted to volume with distilled water. The concentrations of Pb, Cd, Cr, As, Cu, and Zn were determined using ICP-OES (Thermo Scientific iCAP 7000 Series, Model iCAP 7400 Duo). To validate the results, Certified Reference Material (CRM) of tomato leaves 1573a, issued by the National Institute of Standards and Technology (NIST), USA, was digested alongside the samples. The concentrations of Pb, Cd, Cr, As, Cu, and Zn were measured, and percentage recoveries were calculated. Trace element concentrations in the plant samples were expressed on both dry and fresh weight bases. According to Pearson correlation analysis, a strong, significant correlation (r^2 = 0.999) existed between the certified and measured values for the standard reference materials. Satisfactory recoveries were obtained for Cd (82%), As (84%), Cu (85%), and Zn (90%) in the CRM samples.

Calculation of Bioaccumulation (BAF)

PTE concentrations in the extracts of soils and plants were expressed on a dry weight basis. The bioaccumulation factor (BAF) is the ratio of the trace element concentration in the edible part of the vegetable to total PTEs in the soil sample (Ma *et al*., 2001; Cluis, 2004; Yeasmin *et al,* 2013; Basma *et al*, 2023).

$$BAF = C_{veg} / C_{soil\ (total)} \qquad (1)$$

C veg- PTE concentration in vegetables and C soil – total trace element concentration

Statistical Analysis

The descriptive statistics were conducted using Microsoft Excel (2016). Principal component analysis (PCA) was performed to investigate the variation of PTE contamination in soil (total and Mehlich 3 extractable and vegetables across the three locations. In PCA, differences in observation scales of different locations were accounted for by using their correlation matrix. The optimal number of PCs for each trace element was determined using the plot of eigenvalues against their corresponding PCs, the Scree Plot (Cattell, 1966). Spearman correlation analysis was performed to assess the relationship of soil properties, total PTE concentration in soil and vegetables, with Mehlich 3 extractable PTE concentration. PCA and Spearman correlation analysis were conducted using SAS Studio (version 9.4).

RESULTS AND DISCUSSION

Table 2 shows selected physicochemical properties of the soils collected from three locations, namely Nuwara Eliya, Badulla, and

Kalpitiya. Soil from Kalpitiya was sandy in texture, with a high sand content (95% sand) and a much lower clay content (<3% clay). The texture of soil from Badulla and Nuwara Eliya was similar and was sandy loam to sandy clay loam. The sand content and clay content in Badulla were 67% and 18.7 %, respectively, while in Nuwara Eliya, they were 69.1%. and 19.7%. Soil pH in Nuwara Eliya, Badulla, and Kalpitiya ranged between 5.0 – 8.3, 4.1- 7.4, and 4.1 -7.9, respectively. Soil pH in three locations showed a wide variation; however, most of the soil collected from the Nuwara Eliya and Badulla areas displays acidic pH, while the soil in the Kalpitiya exhibits slightly acidic to neutral pH.

The electrical conductivity (EC) of the soils of Nuwara Eliya was 0.16 dS/m, indicating low soil salinity. With a range from 0.06 to 0.56 dS/m, showing a comparatively high variability of EC, while the EC value in soil from Badulla was slightly higher at 0.174 dS/m compared to soil from Nuwara Eliya with a range from 0.027 to 0.660 dS/m, which indicates some locations have relatively higher salinity levels. The EC of the soil in Kalpitiya was 0.14 dS/m, similar to Nuwara Eliya. The range from 0.035 to 0.60 also shows higher variability.

The organic matter (OM) content in soils of Nuwara Eliya was 4.7%, with values ranging from 0.31 % to 10.4%, while the organic matter content was 4.0%, and ranged from 0.19% to 14.0% in soils of Badulla. In the case of Kalpitiya, the organic matter content is 2.7%, which was lower than the other two locations, and the range was 0.12% to 9.9%. However, the ranges of organic matter contents in all three locations show substantial variation, with some areas having higher OM.

Total and extractable PTE concentrations in soil

The total concentrations of all individual PTE concentrations in the soils collected from the three cropping systems were significantly different ($p<0.05$) (Table 3). Soil collected from Nuwara Eliya had the highest concentration of all PTE concentrations, followed by soils from Badulla, except for As., which was higher in soil from Kalpitiya compared to those in Badulla. The variation in soil texture among the sites, particularly the high sand content in Kalpitiya soils, may explain the higher As levels there, as sandy soils generally exhibit lower adsorption capacity, potentially allowing for greater mobility and accumulation of As compared to the finer-textured soils in Badulla. In addition to soil texture, several other factors may also cause higher As concentrations in soil in Kalpitiya. Farmers in this area frequently apply agrochemicals, which can introduce arsenic into the soil over time. The region also relies heavily on groundwater for irrigation, and any As present in the water whether from natural geochemical sources or seawater intrusion, can accumulate in the soil with prolonged use. Due to low organic matter contents and low cation exchange capacity in these soils influence the retention, movement, and accumulation of As in soil in Kalpitiya.

The total concentrations of Pb, Cd, Cu, and Zn in the soil from three different locations were within the maximum permissible level (MPL) stipulated by the European community set standards (McGrath and McCormack, 1999). Additionally, the total Arsenic (As) concentration in soil was compared with the maximum allowable limit set by the USEPA (1999*)*, and the results showed that the As levels in all three locations were below the maximum permissible limit set by the USEPA (1999).

The concentrations of the Mehlich 3 extractable all tested PTEs were different ($p<0.001$) among the three different locations. The highest concentrations of Mehlich 3 extractable PTEs of Cd, Pb, Cu, and Zn were observed in soil collected from Nuwara Eliya, and the lowest was in Badulla. In contrast, the highest Mehlich 3 extractable As concentration was observed in Kalpitiya, and the lowest was in Badulla.

Table 2: Selected physicochemical properties of the soil (Mean ±*SE)

Location		Soil Properties					
		pH	Electrical Conductivity (dS/m)	OM	Texture		
					Clay%	Sand %	Loam %
Nuwara Eliya	Mean	6.3±0.06	0.16±0.0.01	4.7±0.0.2	17.9±0.9	69.1±1.1	13.1±1.2
	Range	5.0-8.3	0.058-0.564	0.31- 10.4	13.0-26.2	60.0-79.0	5.2-23.6
Badulla	Mean	5.7±0.07	0.174±0.0.01	4.0±0.0.2	19.3±0.7	65.8±0.9	14.9±0.7
	Range	4.1-7.4	0.027-0.66	0.19-14.0	1.0-31.0	41.6-97.0	2.0-44.7
Kalpitiya	Mean	6.0±0.08	0.14±0.0.01	2.7±0.0.3	2.6±0.3	95.2±0.4	2.2±0.2
	Range	4.1-7.9	0.035-0.60	0.162-9.9	1.0-7.0	189.9-98.0	0.0-7.0

*SE- Standard Error

Table 3: Total and Mehlich 3 extractable concentration of PTEs in soil (Mean ±SE)

PTEs	Total PTE concentration in soil (mg/kg)				Mehlich 3 extractable concentrations of PTE in Soil (mg/kg)		
	Nuwara Eliya	Badulla	Kalpitiya	Maximum Allowable Limits for total PTEs	Nuwara Eliya	Badulla	Kalpitiya
Cd	0.88 ±0.03 [a]	0.57 ±0.02[b]	0.12 ± 0.01[c]	**1-3	0.245 ±0.15[a]	0.045 ±0.003[b]	0.025 ±0.001[c]
Pb	15.0 ±1.5 [a]	13.8 ±0.8[a]	5.4 ± 0.5[b]	**50-140	3.6 ±0.10[a]	2.5 ±0.30[b]	1.3 ±0.105[c]
As	14.6 ±1.6 [a]	2.3 ±0.1[c]	4.8 ±0.56[b]	***50	0.115 ±0.003[b]	0.100 ±0.003[c]	0.245 ±0.01[a]
Cu	53.5 ±2.7 [a]	43.4 ±1.4[a]	12.6 ±1.5[b]	**50-300	5.55 ±0.382[a]	3.52±0.225[b]	1.77 ±0.176[c]
Zn	136.7 ± 6.6 [a]	74.9 ±3.0[b]	18.6 ± 2.5[b]	**150-300	19.1± 1.49[a]	9.47 ±0.718[b]	6.89± 0.352[c]

*SE- Standard Error, No. of samples Badulla=107, Nuwara Eliya=85, Kalpitiya=73
The different letters indicate significant differences in PTEs among the different locations at $p<0.05$, separately for total and Mehlich extractable PTE
**EU: The European Union set standards for the total concentration of trace elements in sewage sludge-amended soils (McGrath and McCormack, 1999), ***USEPA (McGrath et al., 1999

Table 4: Rotated component matrix for the variation of total PTE concentrations in soil across the three locations

Location	As		Cd		Pb		Cu		Zn	
	PC1	PC2	PC1	PC2	PC1	PC2	PC1	PC2	PC1	PC2
Nuwara Eliya	0.284	0.956	0.635	0.471	0.137	0.947	0.465	0.766	0.661	0.277
Badulla	0.672	-0.242	0.731	-0.113	0.716	0.108	0.698	-0.009	-0.333	0.941
Kalpitiya	-0.683	0.161	-0.247	0.874	-0.684	0.303	-0.544	0.643	0.673	0.277

Table 5: Rotated component matrix for the variation of Mehlich 3 extractable PTE concentrations in soil across the three locations

Location	As		Cd		Pb		Cu		Zn	
	PC1	PC2	PC1	PC2	PC1	PC2	PC1	PC2	PC1	PC2
Nuwara Eliya	0.577	0.577	0.689	0.189	0.714	0.016	0.273	0.845	0.572	-0.587
Badulla	-0.493	0.810	0.698	0.086	0.382	0.828	0.742	0.119	0.403	0.809
Kalpitiya	0.651	0.102	-0.195	0.978	-.586	0.560	0.612	-0.521	-0.714	-.0139

Variability of total concentrations of PTE in different locations

The rotated component matrix for the variation of total and Mehlich 3 extractable PTE concentrations in soil across the three locations is shown in Tables 4 and 5, respectively.

Locations with common factors cluster into a single principal component (PC). The PCA reduced the dimensionality of locations into two PCs for each element, while accounting for 72-86% variability. Table 4 shows the component matrices for the five PTEs.

The PCA results for all elements (As, Cu, Zn, Pb, Cd) consistently showed two distinct components, each capturing a different dimension of spatial variability. PC1 generally represented the dominant contrast between Kalpitiya and Badulla. However, between Kalpitiya and Badulla, there are opposite trends in As, Pb, and Cu concentrations. PC2 of these elements was commonly dominated by Nuwara Eliya, reflecting its unique environmental factors and distinct trace element behavior compared to the other sites. Nuwara Eliya is the most heterogeneous with the highest concentrations and distinct behavior along secondary components. PCA for Cd reveals that Kalpitiya exhibits unique characteristics along PC2, while Badulla and Nuwara Eliya largely contribute to the primary variability along PC1, emphasizing the need for region-specific assessment in monitoring and managing this parameter in soils. Zinc displayed clear spatial patterns across the regions. Kalpitiya and Nuwara Eliya showed similar Zn behavior, supported by moderate positive correlation, while Badulla acted independently. PCA revealed that PC1 (55.1%) contrasted Kalpitiya and Nuwara Eliya with Badulla, and PC2 (30.7%) was dominated by Badulla. Together, these findings confirm that trace element distributions and soil conditions vary independently across regions, strongly influenced by localized environmental factors such as parent material, climate, land-use intensity, and agricultural practices.

Correlation analysis across all parameters demonstrated weak inter-regional relationships, indicating that metal concentrations in one region did not predict those in others and reaffirming the independence of regional geochemical behavior. This independence likely arises from differences in parent material, fertilizer regimes, irrigation practices, and climatic conditions among the regions.

Variability of Mehlich 3 extractable concentrations of PTE in different locations

Across all Mehlich 3 extractable PTEs, the correlation matrix reveals very weak relationships among the three locations, indicating that each location exhibits largely independent behavior in terms of Mehlich 3 extractable PTE concentrations. This suggests that Mehlich 3 extractable PTE concentrations depend on site-specific environmental conditions, local anthropogenic activities, and varied geochemical characteristics rather than a single regional source.

The PCA reduced the dimensionality of locations into two PCs for each element, while accounting for 71-80% variability. Table 5 shows the component matrices for the five PTEs.

PC1 is defined primarily by opposing contributions from Kalpitiya (−0.683) and Badulla (+0.673) for Mehlich 3 extractable As. This indicates a strong contrast between these two locations. PC2 is dominated almost entirely by the Nuwara Eliya, which has a very high loading of 0.957. highlighting that Nuwara Eliya behaves independently of the other two variables. In Mehlich 3 extractable Pb in three locations, PC1 explains a strong contrast between Nuwara Eliya and Kalpitiya, as indicated by the opposite signs and magnitudes of their loadings. Pb in Nuwara Eliya loads strongly and positively on PC1, whereas Pb in Kalpitiya loads moderately and negatively. In the case of Mehlich 3 extractable Cd, PC1 is defined primarily by strong positive loadings from Badulla and Nuwara Eliya, with the clustering together along PC1, suggesting that Mehlich 3 extractable Cd concentrations at Badulla and Nuwara Eliya follow similar trends and may be influenced by related environmental or anthropogenic sources. The separation of Cd in Kalpitiya in PC2 confirms its statistical independence from other locations.

According to the PCA analysis of Mehlich 3 extractable Zn, PC1 shows a con trast between Kalpitiya (-0.714) and Nuwara Eliya (0.572). PC2 is almost entirely defined by Badulla (0.809) and Nuwara Eliya (-0.587) in opposite directions. PCA analysis of Mehlich 3 extractable Cu in three locations shows samples from Badulla and Kalpitiya cluster together along PC1, highlighting Mehlich 3 extractable Cu concentrations at Badulla and Kalpitiya follow similar trends, while samples from Nuwara Eliya appear separated along PC2.

Relationship between soil properties and Mehlich 3 extractable PTEs

Mehlich 3 extractable Pb and Zn only showed a significant ($p<0.05$) positive correlation with soil pH, while there was no observed correlation between EC and all extractable trace elements. Several studies have reported that a pH range between 6 and 7 is more suitable for trace metal mobility, as this range enhances metal complexation with organic matter, making metals more soluble and increasing the mobility of trace elements (Genc-Fuhrman *et al.,* 2016; Matong *et al.,* 2016; Moreno-Jimenez *et al.,* 2017). In most of the soils tested in this study, the pH was around 6.0 (weakly acidic). Correlation analysis revealed that Mehlich 3 extractable trace elements of Pb, Cd, As, Cu, and Zn were positively correlated with organic matter contents, and correlations were significant ($p<0.05$). Organic matter could have a mixed effect in the availability and mobility of trace elements in soil organic matter. Organic matter could reduce the bioavailability of trace elements in soil by absorption or forming stable complexes with humic substances (Li *et al*., 2009). and involved in which may increase some trace elements' availability to plants by serving as a chelate (Zeng et al, 2011). As indicated by the positive correlation between Mehlich extractable PTEs and OC in this study, the organic C may increase the solubility of PTE in these soils. Replenishing soluble organic C pool in soils with frequent manure addition (Bolan et al, 2003, Gonçalves et al., 2020) could be a reason for this observation. The trace elements of Cd, Pb, Cu, and Zn positively correlated with clay contents, while Arsenic (As) negatively correlated. suggesting that the surface soil's texture affects the bioavailability of the trace elements in soil.

The results of this study indicated that the relationship between extractable trace element concentrations and soil properties varied across different cropping systems. This finding aligns with previous studies, such as Lopes et al. (2012), which demonstrated that the influence of soil properties on extractable trace element concentrations can differ depending on the context. Similarly, Xu *et al.* (2022) reported that the extraction method influenced the correlation between extractable trace elements and soil properties. Furthermore, Fang et al. (2007) and Wang et al. (2004) emphasized that the content of soil organic matter plays a crucial role in determining the concentrations of trace metals extractable by DTPA or EDTA. However, in this study, potentially toxic trace elements were extracted using the Mehlich 3 method, and a positive correlation was observed between soil organic matter and extractable trace elements

PTE concentrations in the edible parts of vegetable crops collected from three locations

Table 7 summarizes the mean concentrations of PTE found in edible portions of all vegetables collected from three locations on a dry weight basis. Carrots accumulated the highest concentration of Cd in both Nuwara-Eliya (0.136±0.01 mg/kg) and Badulla (0.20±0.04 mg/kg) (Table 7).

The concentration of Cd in carrots was 6 and 4 fold higher compared to potatoes and cabbage grown in Nuwara-Eliya, respectively. In Badulla, Cd concentration in carrot was about 2-fold higher than all the other vegetables (beetroot, potato, cabbage, red onion, and bean). In Kalpitiya, carrot was not included in the study because it is not a common vegetable in the region, and the concentration of Cd was similar in all the vegetables (beet root, cabbage, and red onion) in Kalpitiya. Concentration of Pb was also the highest (0.41±0.01mg/kg; and 2-fold) in carrot compared to all the other vegetables (beetroot, potato, cabbage, red onion, and bean) grown in Badulla. Both carrot and beetroot had similar Pb concentrations in Nuwara-Eliya, and they were 3-fold higher than potato and 20-fold higher than cabbage. In Kalpitiya the highest Pb concentration was found in red onion (0.324 ± 0.05 mg/kg), which was 2-fold higher than in beetroot and 4-fold higher than in cabbage.

Table 6: Spearman correlation coefficients between extractable trace element concentrations in the soil and selected physicochemical properties of the soil across three different locations

Soil property	Cd	Pb	As	Cu	Zn
pH	0.107	0.273*	0.118	0.120	0.149*
EC	-0.041	0.054	0.029	0.069	0.027
Organic matter	0.226*	0.249*	0.199*	0.211*	0.216*
Clay content	0.342*	0.213*	-0.543*	0.328*	0.245*

*indicates a significant correlation at the probability level p<0.05

Table 7 : PTE concentrations (Cd, Pb, As, Cu, and Zn) in edible parts of vegetables (Dry weight basis)[1]

Location	Crops	Cd	Pb	As	Cu	Zn
		mg/kg				
Nuwara Eliya	Carrot	$0.136±0.01^{a}$	$0.35±0.042^{a}$	$0.031±0.01^{a}$	$9.48±0.9^{b}$	$44.3±7.0^{b}$
	Beetroot	$0.132±0.03^{c}$	$0.268±0.04^{a}$	$0.037±0.13^{a}$	$13.8±1.6^{a}$	$72.5±13^{a}$
	Potato	$0.02±0.01^{b}$	$0.114±0.02^{b}$	$0.026±0.01^{a}$	$6.8±0.7^{c}$	$19.9±1.3^{c}$
	Cabbage	$0.035±0.01^{b}$	$0.015±0.06^{b}$	$0.042±0.01^{a}$	$5.6±0.8^{c}$	$40.1±3.9^{b}$
Badulla	Carrot	$0.20±0.04^{a}$	$0.41±0.01^{a}$	$0.10±0.01^{ab}$	$8.5±1.1^{a}$	$41.5±3.2^{c}$
	Beetroot	$0.10±0.02^{b}$	$0.24±0.03^{b}$	$0.08±0.01^{ab}$	$10.8±0.8^{a}$	$61.4±9.9^{a}$
	Potato	$0.07±0.01^{b}$	$0.22±0.04^{b}$	$0.03±0.01^{c}$	$9.5±1.7^{a}$	$25.5±1.1^{d}$
	Cabbage	$0.11±0.02^{b}$	$0.19±0.03^{b}$	$0.08±0.01^{b}$	$8.6±3.8.0^{a}$	$42.4±3.5^{c}$
	Red Onion	$0.10±0.02^{b}$	$0.28±0.04^{b}$	$0.13±0.02^{a}$	$10.2±3.4^{a}$	$42.9±7.1b^{c}$
	Bean	$0.05±0.02^{b}$	$0.26±0.04^{b}$	$0.07±0.01^{b}$	$15.3±3.2^{a}$	$53.1±2.6^{ab}$
Kalpitiya	Beetroot	$0.035±0.01^{a}$	$0.174±0.02^{b}$	$0.043±0.01^{b}$	$6.1±0.09^{a}$	$31.0±3.6^{ab}$
	Cabbage	$0.035±0.01^{a}$	$0.085±0.01^{b}$	$0.095±0.01^{a}$	$8.4±5.6^{a}$	$29.9±1.6^{b}$
	Red Onion	$0.037±0.09^{a}$	$0.324±0.05^{a}$	$0.110±0.02^{a}$	$8.6±3.2^{a}$	$42.1±4.5^{a}$

[1] indicates a significant correlation at the probability level p<0.05
The same letters are not significantly different among the vegetables in each location at p<0.05 level.

Bioaccumulation of the PTEs in vegetables and estimation of the BAF

The bioaccumulation or transfer route of PTEs from soil to the edible parts of vegetables represents the main means of entrance of trace elements to the food chain (Ashraf, 2021). Calculated BAFs for three different study sites, Nuwara Eliya, Badula, and Kalpitiya, are summarized in Figure 1 and it shows the variation of BAF values of vegetable crops in different locations.

Carrots showed the highest BAF for Cd in both Nuwara Eliya (0.534) and Badulla (0.388). It was 20-fold higher compared to potato, and 16-fold higher than cabbage grown in Nuwara-Eliya. In Badulla, the BAF of carrot was about 2-fold higher than all the other vegetables (beet root, potato, cabbage, red onion) except bean. In Kalpitiya, red onion showed the highest BAF of Cd (0.505), which was about 2-fold higher than all the other vegetables (beet root, cabbage). The highest BAF of Pb (0.064) and Cu (1.13) was observed in red onion grown in Kalpitiya, and all other vegetables showed almost similar BAFs of Pb and Cu. The vegetables (beetroot, cabbage, and red onion) grown in Kalpitiya showed the highest BAF of Zn compared to those grown in the other two locations. The trends in the transfer of PTEs to the edible parts of carrots, beets, potatoes, and cabbages collected from Nuwara Eliya were as follows: for carrots, Cd > Zn > Cu > Pb > As; for beetroots, Zn > Cu > Cd > Pb > As; for potatoes, Cu > Zn > Cd > As > Pb; and for cabbages, Zn > Cu > Cd > Pb > As.

The trend of bioaccumulation of PTEs in vegetables collected from Badulla was as follows: Zn > Cd > Cu > As > Pb for carrots, Zn > Cu > Cd > As > Pb for beets, cabbage, and beans, and Zn > Cu > Cd > Pb > As for potatoes and red onions. All vegetable crops in Badulla exhibited the highest BAF for Zn, followed by Cu, except for carrots, which showed the highest Cd BAF value. However, considering the BAF of carrots in both locations, they exhibit higher absorption of Cd among all other trace elements. The mean BAFs of trace elements in the edible parts of vegetables from Kalpitiya, including beets, cabbage, and red onions, decreased in the order of Zn > Cu > Cd > Pb > As. Similar results were observed by Alhogbi *et al.* (2023). As shown in Figure 1, the BAF values for Zn, Cu, Cd, Pb, and As for various vegetable crops varied greatly between plant species, location, and soil contamination level. Mihali *et al* (2012 reported that the highest BAF of trace elements is known for its high mobility, reflecting its relatively poor sorption in soil.

This study's BAF values show that Zn, Cu, and Cd have higher BAF values, and Pb and As had the lowest accumulation with lower BAF values for most of the vegetable crops tested. Mihali *et al*. (2012) reported that the highest BAF or transfer factors for Cd were found in carrots, and similar results were also found in this study. The highest BAF for trace elements indicates a strong accumulation of these elements in plant tissues. Sajjad *et al*. (2000) reported that if the transfer factor of a metal exceeds 0.5, the plant is at a higher risk of metal contamination due to anthropogenic activities. In this study, BAF values for Cd (0.534) in carrots from Nuwara Eliya, Zn (0.645) in beetroots from Nuwara Eliya, and BAF values for Zn in carrots (0.755), beets (1.69), cabbages (0.677), beans (0.974), and red onions (0.687) in Badulla were observed. Additionally, for vegetables from Kalpitiya, the BAF values were Zn in beetroots (2.7) and red onions (4.22), Cu in beetroots (0.503) and red onions (1.13), and Cd in red onions (0.79). Therefore, the accumulation of Zn, Cu, and Cd in most vegetable crops may be attributed to anthropogenic activities.

Furthermore, the bioaccumulation factors (BAF) of Zn in beetroots from Badulla, beets, cabbage, and red onions from Kalpitiya, and Cu in red onions from Kalpitiya were higher than 1, indicating that these vegetables have accumulated Zn and Cu. The BAF values for other trace elements in all vegetable crops were below 1, suggesting that these vegetables do not accumulate significant levels of the different trace elements Ma *et al*., 2001; Cluis, 2004; Yeasmin *et al,* 2013). Higher BAF (2-3) for Zn was reported by Mirecki *et al* (2015) and Xiong *et al* (1998). Zinc (Zn) is not considered highly phytotoxic, and the toxicity limit for Zn (300-400 mg/kg) varies depending on the plant species and its growth stage (Kloke *et al.,* 1984).

This study focused on the accumulation of trace elements in the edible parts of vegetables. However, other parts of the vegetable crops, such as the peels of tuber crops, roots, stems, and leaves, were not considered. If all parts of the vegetables were included, the correlation may have been different.

PCA analysis was conducted to explore patterns of bioaccumulation factors (BAF) of PTE among different vegetables grown in different locations. Tables 8, 9, and 10 present the rotated component matrix for the variation of BAF of PTE in vegetables grown in Nuwara Eliya, Badulla, and Kalpitiya. Principal component analysis of PTE bioaccumulation factors in vegetables grown in Nuwara Eliya, and Badulla revealed three dominant components for each element, explaining 86-98% of the total variance. Kalpitiya showed that two dominant components accounted for 78-93% of the total variance.

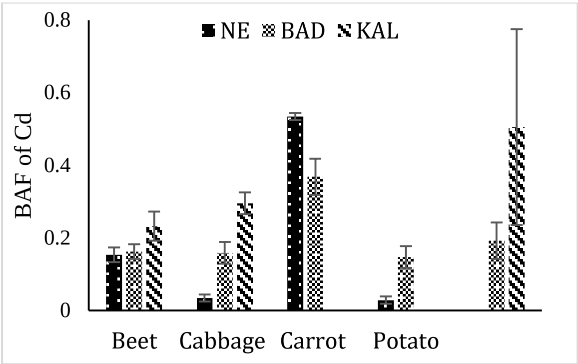
Across the elements of As, Cd, Pb, Cu, Zn, PCA showed elemental-specific clustering patterns among vegetables grown in Nuwara Eliya. Beetroot and cabbage frequently showed similar accumulation behaviors, particularly for Cd, Pb, and Cu, whereas carrot and potato often formed clusters for As and Pb. Zn displayed more uniform uptake across vegetables. Multivariate analysis of As, Cd, Pb, Cu, and Zn bioaccumulation factors in six vegetables from Badulla demonstrated strong structure in PTE uptake patterns. Carrot, bean, and beet consistently formed a high-accumulation cluster. Red onion and potato showed highly elemental-specific behaviors, often separating independently in PCA space, with red onion accumulating Pb and Zn strongly but excluding As and Cd, and potato displaying unique uptake mechanisms across all elements. Cabbage emerged as a low accumulator of Pb, Zn, and Cu, though it accumulated Cd strongly.

According to the PCA of PTE bioaccumulation in vegetables from Kalpitiya, As and Pb showed uniform accumulation patterns across all vegetables, indicating strong environmental influence from soil and irrigation water. In contrast, Cd, Cu, and Zn exhibited distinct crop-dependent behaviors, with Beet and Red Onion consistently acting as high accumulators, while Cabbage displayed unique uptake patterns.

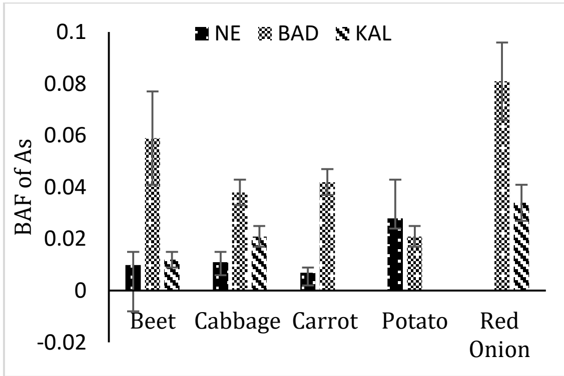
Relationship between BAF and Soil properties

Table 11 presents a correlation analysis of the Bio Accumulation Factor (BAF) of PTE in vegetable crops and soil properties from samples collected from Nuwara Eliya. The results revealed that the BAF of Cd, Pb, As, and Zn in carrots did not correlate with soil properties, suggesting that other factors beyond soil characteristics may influence bioaccumulation. However, the BAF of copper (Cu) in carrots exhibited a positive correlation with electrical conductivity (EC) and available phosphorus (P), indicating that these soil properties might facilitate Cu uptake. In beetroots, phosphorus was positively correlated with the BAF of Cd and Zn, while Pb's BAF was negatively correlated with organic matter and phosphorus. This suggests that available P and organic matter can influence trace element uptake, with organic matter possibly limiting Pb accumulation. Mendis *et al.* (2006) reported that lead uptake of velvet bean was not changed with applied P fertilizer, while Cd uptake was significantly increased with the addition of the P fertilizer. Table 12 exhibits the correlation coefficients between the BAF of PTE of the vegetables and soil properties in samples collected from Badulla. Results indicate that the BAF of Cd in root, tuber, and bulb crops (such as carrots, beets, potatoes, and red onions) showed a negative correlation with soil pH, indicating that lower pH may enhance Cd accumulation in these crops. The stronger correlation was observed between the BAF of Cd and soil pH in vegetables from the Badulla area, where the pH differences (low, moderate, slightly acidic, and neutral) in the soil from Badulla are higher than in Nuwara Eliya, which supports this conclusion. Additionally, organic matter (OM) content was negatively correlated with the BAF of Pb and Cu, suggesting that OM may restrict their accumulation in root crops. The positive correlation between the BAF of available phosphorus (P) and the accumulation of As and Cu in red onions from

Badulla highlights the role of phosphorus in promoting trace element bioaccumulation.



A



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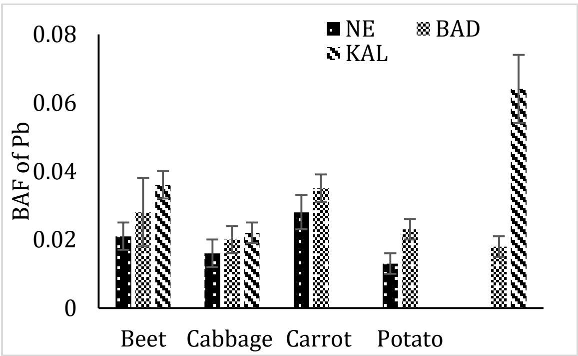
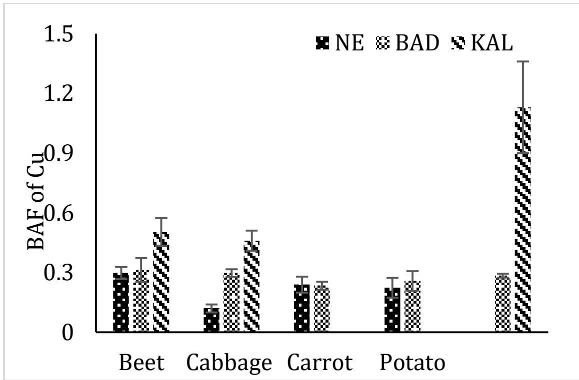


C



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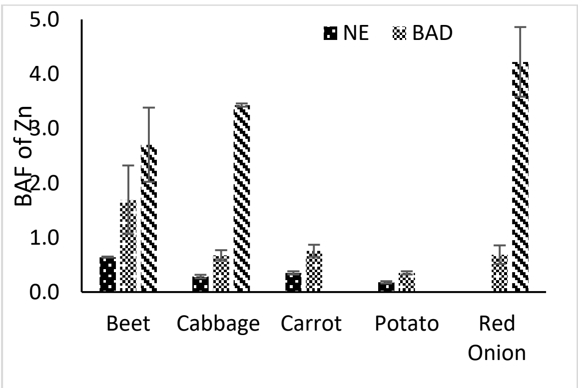

E

Figure 1: BAF of PTEs from edible parts of the different vegetable crops collected from 3 different locations. A-BAF of Cd, B-BAF of Pb, C-BAF of As, D- BAF of Cu and E- BAF of Zn. Variability of BAF of PTE in different vegetables according to the Principal Component Analysis (PCA)

Table 8: Rotated component matrix for the variation of BAF of PTE in vegetables in Nuwara Eliya

Crop	As			Cd			Pb			Cu			Zn		
	PC1	PC2	PC3	PC1	PC2	PC3	PC1	PC2	PC3	PC1	PC2	PC3	PC1	PC2	PC3
Carrot	0.514	0.342	-0.687	0.134	0.843	-0.472	0.614	0.354	0.239	-0.352	0.808	0.306	0.600	0.064	-0.186
Beet	-0.075	0.927	0.262	0.571	-0.440	-0.337	-0.330	0.625	-0.674	0.554	-0.222	0.604	0.551	-0.217	-0.588
Potato	0.567	-0.163	0.677	-0.678	-0.001	0.145	0.627	0.322	-0.223	0.518	0.317	-0.694	0.324	0.878	0.230
Cabbage	0.639	-0.152	-0.167	0.442	0.311	0.802	-0.346	0.616	0.662	0.548	0.444	0.243	0.480	-0.422	0.752

Table 9: Rotated component matrix for the variation of BAF of PTE in vegetables in Badulla

Crop	As			Cd			Pb			Cu			Zn		
	PC1	PC2	PC3	PC1	PC2	PC3	PC1	PC2	PC3	PC1	PC2	PC3	PC1	PC2	PC3
Carrot	0.507	-0.331	0.310	-0.098	0.848	0.269	0.555	-0.036	0.261	0.403	0.502	0.357	0.622	-0.290	0.086
Beet	-0.115	0.725	-0.210	0.459	0.085	-0.491	0.356	-0.405	-0.539	0.538	-0.709	-0.145	0.216	0.671	0.247
Potato	0.506	0.004	-0.503	0.459	-0.260	0.343	-0.787	0.787	0.72	-0.355	0.809	-0.140	-0.272	0.536	0.193
Cabbage	0.398	0.602	0.039	0.488	-0.106	-0.298	-0.258	-0.446	0.712	-0.102	-0.192	0.918	-0.123	-0.506	0.504
Red Onion	-0.721	0.247	0.751	-0.440	-0.438	0.324	0.477	0.081	0.318	0.559	-0.115	0.827	0.432	-0.286	-0.616
Bean	0.556	-0.221	0.201	0.370	0.061	0.680	0.513	0.105	0.166	0.473	-0.193	-0.391	0.539	-0.057	0.509

Table 10: Rotated component matrix for the variation BAF of PTE in vegetables in Kalpitiya

Crop	As		Cd		Pb		Cu		Zn	
	PC1	PC2	PC1	PC2	PC1	PC2	PC1	PC2	PC1	PC2
Beet	0.595	-0.138	-0.343	0.890	0.591	-0.559	0.663	0.136	0.710	-0.087
Red Onion	0.662	0.777	0.700	0.028	0.289	0.494	0.607	0.476	0.699	0.193
Cabbage	0.575	-0.616	0.626	0.455	0.753	-0.646	-0.437	0.868	-0.075	0.977

In Kalpitiya (Table 13), the BAF As and Cu in all vegetable crops and Zn in cabbage showed a negative correlation with soil pH, indicating that lower pH levels may increase bioaccumulation of these elements. The pH difference (4.1 to 7.9) of the soil in this area is also very high. The positive correlations between the BAF of As, and organic matter (OM) and available P further suggest that these factors enhance the uptake of As. The BAF of Pb in cabbage and Cu in Red onions also showed a positive correlation with OM and available P. The use of high doses of organic and mixed chemical fertilizers in Kalpitiya likely contributes to the high levels of available P and OM, which in turn explain the strong correlations between these factors and trace element accumulation in vegetables.

Relationship between concentrations of PTE in vegetables and Mehlich 3 extractable PTEs

Table 9 presents the correlation between PTE concentrations in vegetables and Mehlich 3 extractable PTE concentrations in soils collected from Nuwara Eliya, Badulla, and Kalpitiya. Arsenic concentration in carrots collected from Nuwara Eliya significantly ($p<0.001$) correlated with its Mehlich 3 extractable concentration in soil ($r=0.570$). Furthermore, Pb concentration in carrots ($r=0.566$) and Zn concentration in potatoes ($r=0.605$) showed a significant correlation ($p < 0.001$) with their Mehlich 3 extractable concentrations in the respective soils collected from Badulla. A significant ($p<0.01$) correlation was observed between the As concentration in cabbage ($r=0.460$) and the Cu concentration in beetroot (0.444) collected from Badulla and its extractable concentration in soil. Ali *et al.* (2017) reported a significant ($p<0.0001$) correlation between Pb, Cd, and Zn concentrations in vegetables (Lady's Finger and Tomato) and the ammonium carbonate, DTPA extractable concentration of those elements in the soil. The relationship between extractable PTEs in soil and the concentration of these elements in vegetables is a critical aspect of understanding how soil chemistry influences plant uptake. Extractable trace elements in the soil are determined by different extraction methods, such as DTPA, EDTA, Mehlich 3, etc., that are considered available for plant absorption. PTEs in none of the vegetables from Kalpitiya correlate with Mehlich 3 extractable PTEs in the soil (Table 9). The soil in Kalpitiya is sandy, which distinguishes it from the soils at the other two locations. These results suggest that soil type also affects the uptake of PTEs by plants. However, the degree to which vegetables absorb these bioavailable elements depends on several factors, including soil pH, organic matter content, and the plant species itself. In general, higher concentrations of bioavailable PTE in soil can lead to higher levels of these elements in plant tissues, though plant mechanisms such as root absorption efficiency and translocation processes play a significant role in regulating uptake. Therefore, PTE concentration in some vegetable crops did not significantly correlate with extractable PTE concentrations in soil.

Table 11: Spearman correlation coefficients between BAF in each vegetable crop and basic soil properties in the respective soil from Nuwara Eliya [1]

Vegetable	PTE	pH	EC	OM	Ava. P
Carrots	As	0.026	-0.341	-0.102	0.138
	Cd	0.048	0.011	-0.230	0.262
	Pb	0.341	-0.118	-0.122	-0.210
	Cu	-0.086	-0.486**	0.177	0.477**
	Zn	0.246	-0.206	-0.370	0.205
Beet	As	-0.207	-0.333	-0.127	0.152
	Cd	-0.119	-0.224	0.189	0.788**
	Pb	0.179	-0.126	-0.496*	-0.550*
	Cu	0.063	-0.776**	-0.343	-0.059
	Zn	0.017	-0.364	-0.063	0.448*
Potato	As	-0.172	0.435	-0.340	0.383
	Cd	0.416	0.176	-0.152	-0.483*
	Pb	0.116	0.112	-0.193	-0.012
	Cu	-0.261	0.318	-0.015	0.437
	Zn	-0.145	0.478	-0.195	0.177
Cabbage	As	0.290	-0.217	0.174	-0.218
	Cd	-0.185	-0.332	-0.018	-0.193
	Pb	-0.157	-0.279	-0.243	-0.207
	Cu	-0.282	-0.055	0.032	-0.076
	Zn	-0.057	-0.169	0.037	-0.040

NE $p<0.05$*, $p<0.01$** $p<0.001$***

Table 12: Spearman correlation coefficients between BAF in each vegetable crop and basic soil properties in the respective soil from Badulla

Vegetable crop	BAF	pH	EC	OM	Ava. P
Carrot	As	0.353	0.014	-0.278	-0.120
	Cd	-0.540**	-0.168	-0.155	-0.161
	Pb	-0.130	-0.146	-0.499 **	-0.313
	Cu	0.078	-0.170	-0.443**	-0.437**
	Zn	0.078	0.007	-0.212	0.018
Beet	As	0.548*	0.238	-0.730**	-0.119
	Cd	-0.643*	0.119	-0.096	-0.190

	Pb	-0.333	0.762**	-0.551**	-0.524*
	Cu	0.071	0.238	-0.922****	-0.238
	Zn	-0.357	-0.524*	-0.323	0.428
Potato	As	0.147	0.066	-0.017	0.564**
	Cd	0.628***	-0.341	0.222	0.502**
	Pb	0.282	-0.578**	0.305	0.328
	Cu	-0.389	-0.083	0.015	-0.186
	Zn	-0.367	-0.426	-0.109	-0.061
Cabbage	As	0.396	0.199	0.230	0.342
	Cd	-0.216	0.411	0.176	-0.069
	Pb	-0.029	0.129	0.266	-0.123
	Cu	-0.149	0.232	-0.100	-0.209
	Zn	-0.123	0.372	0.496**	0.083
Bean	As	0.392	-0.143	-0.015	0.316
	Cd	0.192	-0.069	-0.171	0.336
	Pb	-0.263	0.257	0.036	0.239
	Cu	-0.368	0.362	-0.305	-0.138
	Zn	-0.423**	0.514**	-0.411*	0.117
Red Onion	As	0.142	0.239	0.174	0.540**
	Cd	-0.585**	0.124	0.107	0.301
	Pb	-0.248	0.266	0.201	0.505*
	Cu	-0.204	0.390	0.326	0.567**
	Zn	-0.248	0.186	0.134	0.540**

* p<0.05, **p<0.01, ***p<0.001

Table 14: Spearman correlation coefficients between the PTEs concentration in vegetables and Mehlich 3 extractable concentration in the respective soil collected from Nuwara Eliya, Badulla, and Kalpitiya

Vegetable crop	Spearman correlation coefficients														
	Nuwara Eliya					Badulla					Kalpitiya				
	Cd	Pb	As	Cu	Zn	Cd	Pb	As	Cu	Zn	Cd	Pb	As	Cu	Zn
Cabbage	0.102	0.027	0.057	-0.012	0.062	0.231	-0.283	*0.460	0.161	-0.138	0.004	0.046	0.087	-0.030	-0.082
Beet	0.154	0.333	-0.337	0.315	0.084	0.018	0.262	-0.169	*0.444	-0.030	0.354	0.314	-0.150	0.129	0.152
Carrot	0.035	0.148	**0.570	0.042	0.153	-0.198	**0.566	0.196	0.311	-0.333	-	-	-	-	-
Potato	0.176	-0.138	-0.477	0.365	0.106	0.191	0.392	-0.399	0.228	**0.605	-	-	-	-	-
Beans	-	-	-	-	-	0.443	0.142	0.376	-0.158	-0.041	-	-	-	-	-
Red Onion	-	-	-	-	-	0.227	0.300	-0.423	-0.166	0.055	0.060	0.315	-0.220	-0.059	0.291

[1] Significance of correlation is indicated as follows: * significant at a p-value <0.01; **significant at p-value ≤0.001

CONCLUSIONS

This study examined the bioavailability of PTEs in soil and their accumulation in vegetables in intensively vegetable-growing areas in Sri Lanka. Results revealed significant differences in the Mehlich 3 extractable concentrations of Cd, Pb, As, Cu, and Zn in soils from three locations, indicating that the bioavailability of PTEs is highly influenced by site-specific factors, such as soil characteristics and farming practices. This is further supported by the significant correlation between Mehlich 3 extractable PTEs and soil properties, as well as the total concentration of PTEs. Therefore, while bioavailability of PTEs is a key factor, the uptake of trace elements by vegetables is also governed by complex interactions between soil characteristics and other plant factors. The observed BAF provides valuable insight into the PTEs accumulation patterns in vegetables from different regions, with higher values suggesting a greater degree of bioaccumulation. The overall findings of the correlation analysis of the BAF of trace elements with selected soil properties emphasize the complex interactions between soil properties and PTE bioaccumulation in vegetables, highlighting the importance of factors such as soil pH, organic matter, and available phosphorus in regulating the uptake of potentially toxic trace elements by plants. These results underscore the need for careful management of soil conditions to minimize the risks associated with PTE accumulation in food crops, especially in regions with intensive agricultural practices.

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