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Research Article:

Accumulation of potentially toxic trace elements in vegetables collected from selected vegetable-based cropping systems in Sri Lanka, and estimation of their dietary intakes

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Abstract

Contamination of vegetables with potentially toxic trace elements (PTEs) is a globally recognized environmental issue that poses a risk to human health. This study assessed PTE concentrations in edible parts of beetroot (*Beta vulgaris*), carrot (*Daucus carota*), potato (*Solanum tuberosum*), cabbage (*Brassica Oleracea*), red onion (*Allium cepa*), and bean (*Phaseolus vulgaris*) collected from selected vegetable-based cropping systems in Sri Lanka (Nuwara Eliya, Badulla, and Kalpitiya). A total of 265 samples were analyzed using microwave digestion and ICP-OES, and dietary exposure was estimated. Among the PTEs, Zn showed the highest concentrations across all vegetable types, followed by Cu, while As and Cd were present in the lowest concentrations. The highest concentrations (mg/kg) of Cd (0.002-.037) and Pb (0.01-0.111) were in carrot, and As in red onion (0.008 – 0.042) and cabbage (0.02-0.014). However, mean concentrations of all PTEs in every vegetable type remained well below the maximum permissible limits established by FAO/WHO. Multivariate analysis demonstrated that Cd and Zn dominate PTE variability in vegetables, whereas Pb and As exhibit distinct source-related behaviour, influenced by crop type and sampling location. Estimated weekly dietary intakes of As, Cd, Pb, Cu, and Zn for adults were far below the Provisional Tolerable Weekly Intakes recommended by FAO/WHO, indicating minimal health risk from vegetable consumption in these regions. The study suggests the necessity of periodic monitoring of PTE accumulation in vegetables and the importance of revisiting the current Codex maximum limits of As for leafy vegetables and Cd for leafy vegetables and root and tuber crops for the Sri Lankan context.

Keywords: Trace elements. Vegetables, Human health, Dietary exposure, Weekly intake.

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1. Introduction

Potentially toxic trace elements (PTEs) are environmental pollutants that pose significant threats to human health and the ecological system. Some trace elements, such as copper (Cu) and zinc (Zn), play crucial roles in the metabolic pathways of plants, animals, and humans when presenting the required quantities; however, excessive concentration can have detrimental effects on living organisms. Certain elements, such as cadmium (Cd), lead (Pb), arsenic (As), and mercury (Hg), have no known beneficial biological function, and their accumulation over time can lead to severe health and environmental issues.

Chemical fertilizers, herbicides, pesticides, and some agricultural amendments such as organic manure, lime, and dolomite. etc., may contain toxic trace element contaminants as impurities, leading to soil contamination and subsequently transferring to humans through the food chain (Premarathna et al., 2005). The overuse of organic manures and chemical fertilizers beyond the recommended doses is a common practice in intensively vegetable-growing areas in Sri Lanka. Many of these areas have been under continuous intensive cultivation for more than 10 to 20 years, making the soil's potential long-term sinks for toxic trace elements. The accumulation of these metals in the soil may result in their excessive uptake by plants. Consumption of vegetables contaminated with PTEs is considered one of the main dietary pathways for exposure to PTEs (Zafarzadeh et al., 2018).

Vegetables are highly recommended for human consumption, and Sri Lankan people consume large quantities of vegetables in their daily diets. Hence, safety assessment of the edible parts of commonly consumed vegetables is required. Similar studies have been conducted in many countries to ensure food safety. Among the vegetables consumed in Sri Lanka, upcountry vegetables are in high demand, with carrots, beetroot, potatoes, leeks, and cabbage being the most consumed types (AgStat, 2015). Upcountry wet and upcountry intermediate zones, and the Kalpitiya area in the low-country dry zone, are intensive and highly commercialized regions in Sri Lanka. In these areas, farmers typically grow two to three crops per year on the same land and apply high doses of fertilizers, manures, and other agro-chemicals. These intensive agricultural practices may lead to the accumulation of PTEs in the soil (Wijewardena and Yapa, 1999; Premarathna et al., 2011). The transfer of PTEs from soil to plants is considered the primary pathway through which humans are exposed to trace metal contamination

Therefore, a detailed risk assessment of PTE accumulation in vegetables is required for safe and healthy human beings in Sri Lanka. Although a few studies have shown the PTE contamination of fruits and vegetables in Sri Lanka (Kananke et al., 2014; Premarathna et al., 2011; Silva et al., 2016; Wickramaratne et al., 2016), there is no evidence of any research conducted to assess the daily dietary intakes of potentially toxic trace elements in humans due to vegetables contaminated with trace elements. Therefore, this study was conducted to determine the contamination levels of PTEs (As, Cd, Pb, Cu, and Zn) in edible parts of vegetables and to estimate the daily dietary intakes of the trace elements through the consumption of vegetables grown in intensive vegetable growing areas in Sri Lanka.

2. Materials and Methods

2.1. Study area and collection of samples

The collection of different types of vegetable crops, such as root and tuber crops (carrot, beetroot, and potato), fruit crops (bean), leafy vegetables (cabbage), and bulb crops (red onion), was selected for this study. Different types of vegetable samples were collected from intensive vegetable growing areas in Nuwara Eliya, Badulla, and Kalpitiya. Cropping systems and cultivation practices are different in the three locations. Year-round vegetable cultivation (vegetable-vegetable) and 2-3 cropping cycles were observed in the Nuwara Eliya and Kalpitiya areas. The rice–vegetable cropping system was observed in the Badulla area, where the rice is grown in the wet (rainy) season from October to March, and vegetables are grown in the dry season from April to September. These areas belong to different Agro-climatic zones: up-country wet zone (Nuwara Eliya), upcountry intermediate zone (Badulla), and low-country dry zone (Kalpitiya). Major soil groups are Red Yellow Podzolic (Ultisols) in Nuwara Eliya and Badulla, and Sandy Regosol (Entisols) in Kalpitiya (Mapa, 2020).

Random sampling was done during the period from December 2018 to March 2020. Samples were collected from 265 sampling sites, resulting in an approximate sampling density of two sampling sites per 1000 m^2. The locations of the vegetable samples collected, and the number of samples collected from each location, are shown in Table 1.

Table 1. Number of vegetable samples collected from each location

Agro Climatic Zone	Vegetable Growing Area	Vegetable Crops	No of Samples
Up Country Wet Zone	Nuwara Eliya	Carrot	31
		Potato	16
		Beetroot	12
		Cabbage	16
Up-Country Intermediate Zone	Badulla	Carrot	26
		Beetroot	09
		Potato	22
		Cabbage	20
		Bean	25
		Red Onion	08
Low Country Dry Zone		Cabbage	15
		Red Onion	25
		Beetroot	22

2.2 Preparation of vegetable samples for analysis

Collected vegetable samples were brought to the laboratory on the same day, and the following day, they were thoroughly rinsed with tap water, followed by washing with 0.5% sodium lauryl sulfate. Finally rinsed with distilled water. Root crops (beetroot, carrot, and potato) were scrubbed with tap water using a brush to remove attached soil particles, followed by sodium lauryl sulfate. They were peeled off after washing using a stainless-steel knife. Peeled samples were again washed with distilled water. Washed samples were left in an open area free from dust for a few hours until the excess water on the surface of the samples had dried. Then the fresh weight of the whole sample was recorded after removing any remaining moisture left on the surface using a soft tissue. All samples were cut into small pieces (5-10cm) using a stainless-steel knife, and the cut pieces were oven-dried at 60 °C until a constant weight was reached, and dry weights were recorded. Moisture contents of the samples were determined gravimetrically, and the oven-dried samples were ground using a stainless-steel grinder and passed through a 0.5mm sieve. The ground samples were then placed in polythene bags and stored in a refrigerator until analysis.

2.3 Analysis of vegetable samples

Finely ground vegetable samples (0.5000 g) were digested with a mixture of 8.0 mL of conc. HNO_3 (69 %, trace metal– grade) and 2.0 mL of 30% H_2O_2 (Analytical Grade) in a microwave digester (Model: MARS 6, CEM Corporation), power at 1400 W. The digester took 20 minutes to reach 180 °C, and this temperature was maintained for another 15 minutes until the digestion was complete (Briscoe et al., 2015). Blank digestion was also performed using the digestion mixture without a sample. Digested samples were filtered through Whatman No. 42 filter paper into a 50 mL volumetric flask and made up to volume with de-ionized water. Pb, Cd, As, Cu, and Zn were determined by ICP- OES (Thermo Scientific iCAP 7000 Series, Model iCAP 7400 Duo). Certified Reference Material (CRM) of tomato leaves 1573a issued by the National Institute of Standards and Technology (NIST), USA, was digested along with the sample, and As, Cd, Pb, Cu, and Zn concentrations and percentage recoveries were calculated to validate the results.

According to the Pearson correlation, there was a significant correlation between the certified and measured values for standard reference materials for plants ($r^2 = 0.999$). Satisfactory recoveries were found for Cd (82%), As (84%), Cu (85% and Zn (90%) in CRM. Further duplicate samples were digested and measured to test the accuracy of the results in each batch. Blank samples were also included in each batch of analysis to eliminate the interference of chemicals used in the analysis. The concentration of trace elements in vegetable samples was expressed on a fresh weight basis.

2.4 Estimation of daily dietary intake of PTEs

Exposure to contaminants is usually expressed as the provisional tolerable daily intake, a reference value based on body weight for an average adult (70kg body weight) established by the FAO/WHO (1999). The number of vegetables consumed per day is calculated as the serving size of vegetables multiplied by the number of servings per day (Attanayake et al., 2021).

2.5 Statistical analysis

Results were expressed as mean ± standard deviation. A descriptive analysis of trace element concentrations in different vegetable crops was done using Microsoft Excel (2013). A p-value ≤ 0.05 was considered statistically significant. Principal Component Analysis of vegetables grown in three locations.

3. Results and Discussion

3.1 Total concentration of PTE (As, Cd, Cu, Pb, and Zn) in edible parts of the vegetables (Fresh weight basis)

In this study, the moisture contents in vegetables were determined to calculate the PTE contents on a fresh weight basis, because vegetables are consumed by humans as fresh. Moisture contents in all tested vegetables ranged from 85-93% on a fresh weight basis (Bean, 93 %±0.54, Beetroot, 90% ±0.54, Carrot, 91% ±0.61, Potato, 85%±0.54, Cabbage, 92%±0.46, Red onion 92%±0.89).

The mean concentrations of As, Cd, Pb, Cu, and Zn on a fresh weight basis found in edible portions of all different types of vegetables (carrot, potato, beetroot, cabbage, red onion, and bean) collected from intensive vegetable growing areas are shown in Figures 1a, 1b, 1c, 1d, and 1e, respectively. Tested trace element concentrations differed considerably from one plant species to another, as has been reported by Garg et al. (2014); Khan et al. (2015); Hamian et al. (2015).

These vegetable crops accumulate different concentrations of different trace elements. The highest mean concentration of potentially toxic trace elements found in all types of vegetables was Zn, followed by Cu. Comparison of mean concentrations of potentially toxic trace elements in tested vegetables, root and tuber crops such as carrot, potato, and beet were in the order of Zn>Cu>Pb>Cd>As, while cabbage, red onion, and bean were in the order of Zn> Cu>Pb>As>Cd. A similar trend in root and tuber crops has been reported by Afshin et al. (2008) in Iran and Amin et al. (2013), Saglam (2013) in Turkey, and Silva et al. (2018) in Sri Lanka.

Significantly ($p<0.01$), the highest As concentration (0.009±0.001mg/kg) was observed in red onion, followed by cabbage (0.008±0.0006 mg//kg). Other vegetable crops tested showed significantly similar As concentrations.

Significantly higher Cd concentration was observed in carrots (0.015±0.002 mg/kg), and the lowest was observed in beans (0.004±0.00008 mg/kg), followed by cabbage (0.005 ± 0.003 mg/kg). All other vegetable crops, potato (0.008±0.002 mg/kg), beetroot (0.007±0.001 mg/kg), and red onion (0.007±0.002 mg/kg) showed similar concentrations of Cd with insignificant ($p>0.05$). Carrot showed significantly ($p<0.05$) the highest Pb concentration (0.0345±0.003 mg/kg) while the lowest was observed in cabbage (0.0124±0.001 mg/kg). There was no significant difference in Cu concentrations among all tested vegetable crops. Among all tested trace elements, Zn showed the highest concentrations in the edible parts of all tested vegetables. Significantly ($p<0.05$), the highest Zn concentration was observed in beetroot (4.96±0.536 mg/kg), and there was no significant difference in Zn concentrations among the other tested vegetable crops.

3.2 Total concentrations of PTE in different types of vegetables across locations

Figures 2a, 2b, 2c, 2d, and 2e show the concentrations of As, Cd, Pb, Cu, and Zn, respectively, in the edible parts of vegetables collected from three different locations. The concentrations of PTEs in vegetables varied with both crop type and geographical location. This suggests the influence of soil geochemistry, agricultural practices, and plant species and their uptake mechanisms on PTE uptake. Overall, vegetable crops in Badulla showed the highest accumulation of most PTEs, followed by Nuwara Eliya, while Kalpitiya generally showed comparatively lower concentrations, particularly for Cd and Cu.

3.2.1 As concentrations in vegetables in different locations

Arsenic accumulation showed a location and crop-specific pattern, and the highest concentrations were observed in red onion from Badulla. Root, tuber, and bulb crops (carrot, beet, potato, and red onion) from Badulla consistently showed elevated As levels compared to the same crops from Nuwara Eliya and Kalpitiya, indicating a higher As bioavailability in soil from Badulla, possibly related to parent material or agrochemical inputs. Interestingly, leafy vegetables (red onion and cabbage) from Kalpitiya contained higher As concentrations than beetroot (a root crop) from the same area, indicating that soil–plant transfer is governed by soil chemistry and As speciation. Similar observations have been reported in previous studies, where As uptake varied significantly depending on soil redox conditions and phosphate competition (Smith et al., 2008; Zhao et al., 2010).

3.2.2 Cd concentrations in vegetables in different locations

Cadmium concentrations were highest in carrot samples from Badulla, followed by beetroot from Nuwara Eliya, showing the trend of root and tuber crops to accumulate Cd more efficiently than leafy or fruit vegetables. Except for beetroot from Kalpitiya, root crops from Badulla and Nuwara Eliya consistently showed higher Cd levels than leafy vegetables (cabbage and red onion). Among vegetables grown in Badulla, beans (fruit crops) showed the lowest Cd concentration, highlighting the limited translocation of Cd to pods or fruits. Alloway (2013) and Clemens et al. (2013) reported that these findings indicate that Cd is preferentially retained in roots due to strong binding with cell wall components and limited phloem mobility.

3.2.3 Pb Concentration in vegetables in different locations

Similar to Cd, accumulation of Pb in carrots and potatoes from Badulla showed the highest concentrations. Beetroot from Nuwara Eliya also showed elevated Pb levels compared to the same crop, supporting earlier reports that Pb uptake and accumulation in crops are strongly governed by soil physicochemical properties and plant species differences (McLaughlin et al., 2010; Singh et al., 2010; Grant et al., 2008) from other locations. Across all sites, cabbage consistently showed the lowest Pb concentration, reflecting the limited mobility of Pb from soil to

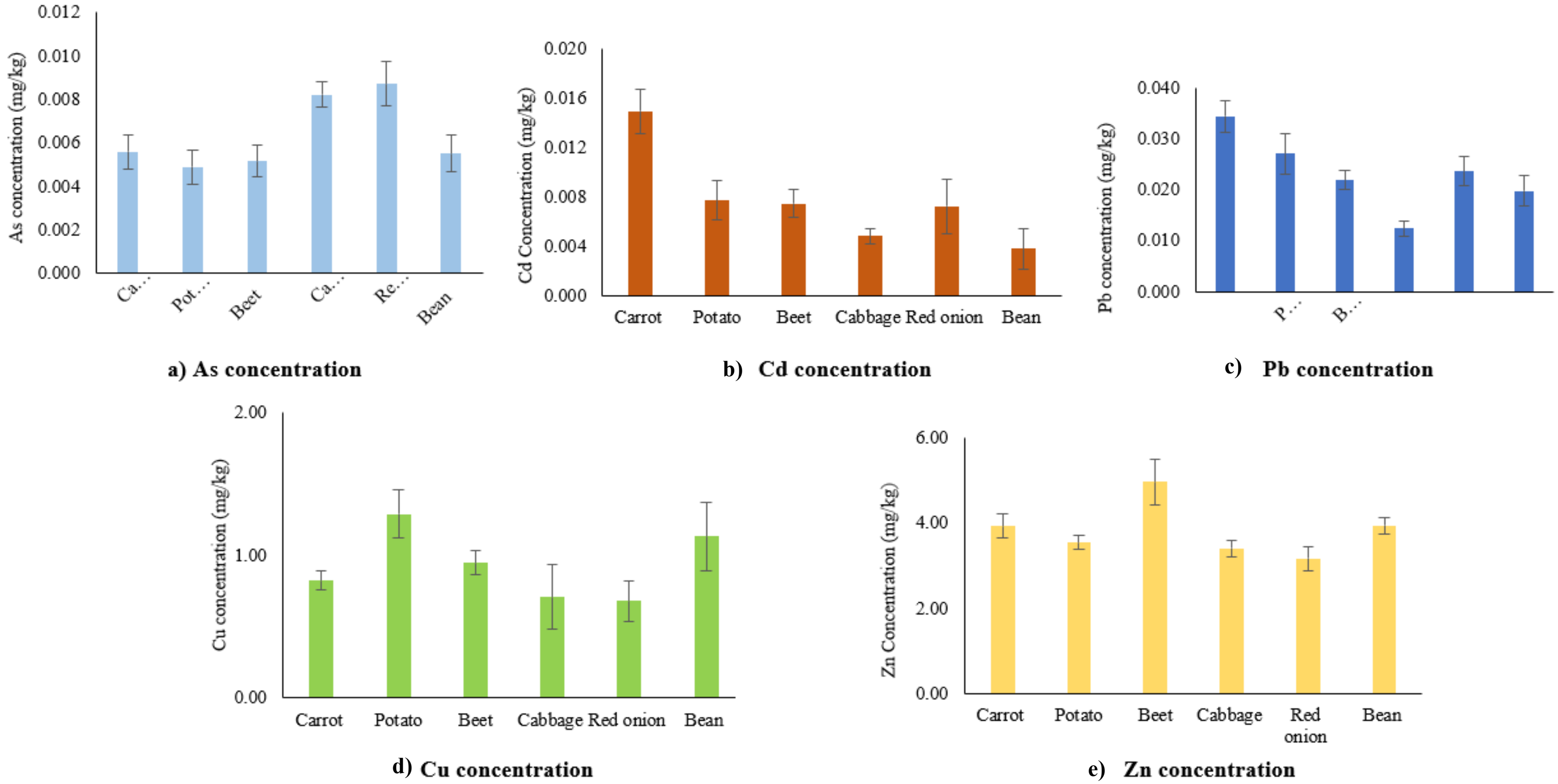

Figure 1: Mean concentrations of PTE (As, Cd, Pb, Cu, and Zn) in the edible parts of different vegetable types (fresh weight basis)

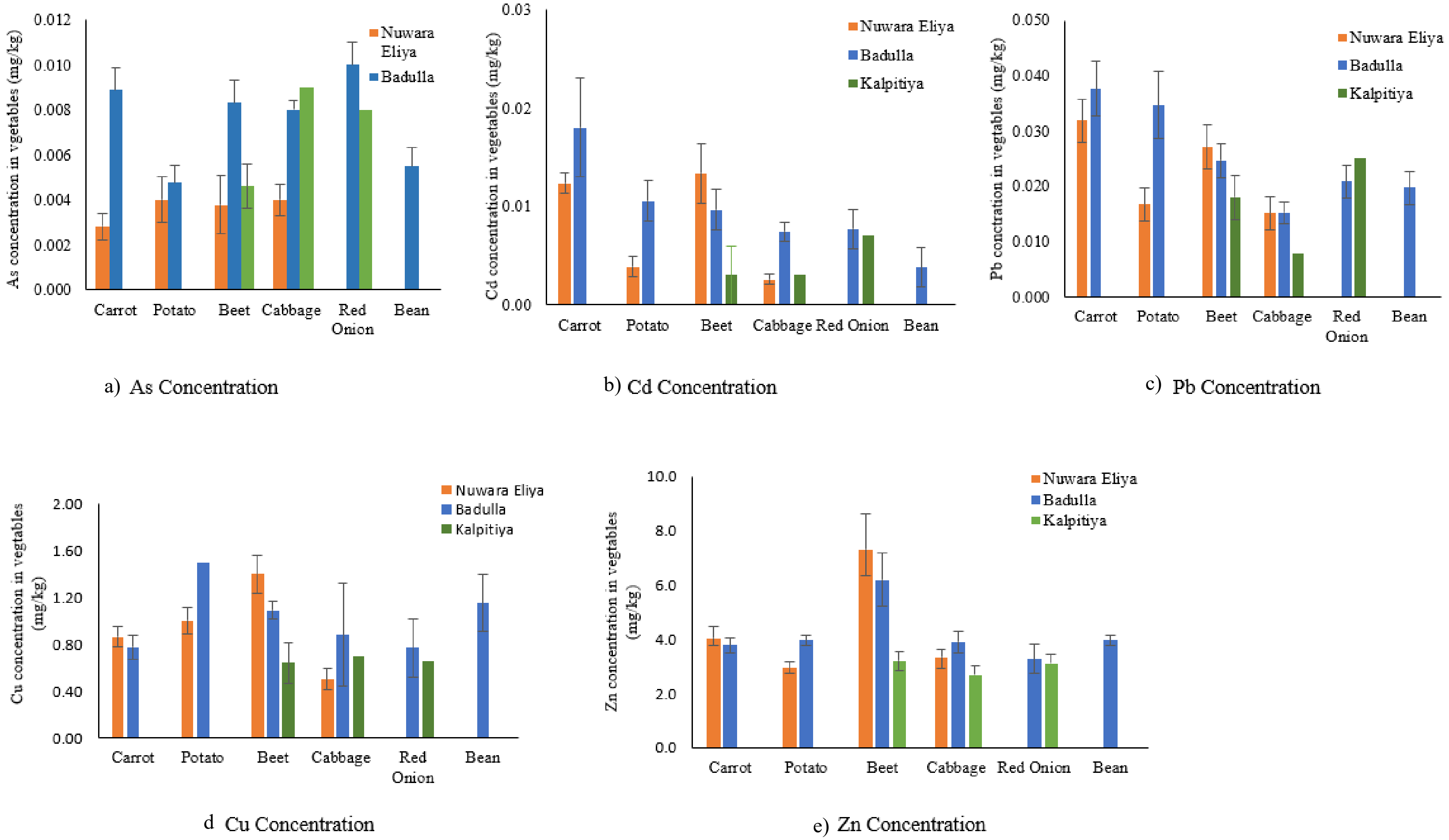

Figure 2: Spatial variation of PTE concentrations (As, Cd, Pb, Cu, and Zn) in edible parts of different vegetable types (Fresh weight Basis) collected from three different locations

aerial plant parts. These findings are consistent with reports by Attanayake et al. (2021) and Bonanno (2013), who highlighted that Pb predominantly accumulates in roots due to its strong adsorption to soil particles and low translocation efficiency within plants.

3.2.4 Cu Concentration in vegetables in different locations

Copper concentrations varied moderately across crops and locations. Potato from Badulla showed the highest Cu concentration, followed by beetroot from Nuwara Eliya, while cabbage from Nuwara Eliya recorded the lowest levels. Carrot samples from Badulla and Nuwara Eliya exhibited comparable Cu concentrations, suggesting similar Cu availability or uptake efficiency in these soils. All vegetables from Kalpitiya contained lower Cu concentrations, possibly reflecting sandy soil conditions with lower organic matter and micronutrient retention capacity. Since Cu is an essential micronutrient, its concentration is often regulated within a narrow physiological range unless soils are contaminated or heavily fertilized (Kabata-Pendias, 2011).

3.2.5 Zn Concentration in vegetables in different locations

Overall, Zn concentrations varied more by crop type than by location, except for beetroot, which showed location-specific differences. Most vegetables showed relatively uniform Zn availability or uptake across three locations.

This study clearly showed that root, tuber, and bulb crops grown in Badulla are more prone to accumulation of PTE, compared to leafy and fruiting vegetables, particularly As, Cd, and Pb. The results of this study showed that within the same location, different vegetable crops have different accumulations of trace elements. This may be due to many plant factors, as well as soil properties of pH, organic matter, and phosphate concentration affecting the uptake of trace elements (Wan, 2024). Muller (1969) reported that absorption and accumulation of trace elements in plant tissue depend not only on total trace element concentrations in soil but also on various other factors, which include temperature, moisture, soil pH, organic matter, cation exchange capacity of soil and nutrient availability of soil and Aktaruzzaman et al., (2013) stated that the accumulation of trace elements also depends on plant factors such as plant age, plant species, etc. Therefore, site-specific soil and crop monitoring is needed to minimize the human dietary exposure to PTE.

However, the mean concentrations of tested trace elements in all tested vegetables (fresh weight basis) were lower than the maximum permissible limit imposed by WHO/FAO Joint Codex Alimentarius Commission (2019, 1991and 1985) for Cd and Pb and FAO/WHO, 2011 for As cited by Yang et al (2018) and FAO/WHO (2007) cited by Odujebe et al. (2020) for Cu and Zn. Arsenic concentrations in all tested vegetable crops were 5 to 10 times lower than the maximum permissible limit established by FAO/WHO. According to the FAO/WHO, the maximum Permissible limits of Cd are 0.2mg/kg for leafy vegetables and 0.1 mg/kg for root and tuber crops and legume crops. In this study, we tested cabbage and red onion, which are considered leafy vegetables. The Cd concentrations in cabbage and red onion were 70 and 30 times lower than the maximum permissible limits, respectively. In the case of Cd concentration in root and tuber crops, which were 10 to 15 times lower than the maximum permissible limits.

Lead concentrations in cabbage and red onion samples were respectively 30 and 15 times lower than the maximum permissible limit for leafy vegetables. Among the root and tuber crops tested, carrot and potato showed about 3 times lower concentrations of Pb than the maximum permissible limit for root and tuber crops, while beetroot showed 10 times lower concentrations. Pb concentration in bean samples was 10 times lower than the maximum permissible limit for legumes. However, these results suggested that all the vegetables tested were not contaminated by potentially toxic trace elements of As, Cd, Pb, Cu and Zn.

3.3 Principal Component Analysis (PCA) of PTE in vegetables grown in three different areas.

The PCA was applied to evaluate the relationship between PTE concentrations and vegetable crops collected from Nuwara Eliya (NE), Badulla (Bad), and Kalpitiya (Kal). The Eigenvalues of the correlation matrix and scree plot show a clear decrease in eigenvalues after the fifth principal component, supporting the retention of five components, which together explain 71.2% of the total variance in PTE concentrations in vegetables (Figure 3 and Table 2).

High positive loadings on PC1 are mainly associated with Cd, Pb, Zn, and As**,** indicating elevated metal accumulation, while negative loadings represent comparatively lower contamination levels.PC1 showed the strong positive loadings for Cd and Zn across most vegetables, particularly carrot, beetroot, cabbage, and red onion. Carrot and beet samples, particularly from Nuwara Eliya and Badulla**,** and cabbage from Nuwara Eliya showed strong positive loadings on PC1 and PC3, closely associated with Cd, Zn, and Pb**.** This pattern reflects the high trace element uptake capacity of root vegetables due to direct and prolonged contact with contaminated soils. The strong association with cadmium suggests intensive fertilizer application and increased metal bioavailability in cultivated soils. The PC2 highlighted the high loadings from PTE in leafy vegetables (cabbage) and contrasting behavior in root and tuber crops (potato, carrot). This component exhibits crop–specific elemental uptake and accumulation patterns, indicating the influence of plant physiology and trace element absorption. PC3 indicated distinct contamination sources, particularly separating Pb-As-dominated variables from Cd-Zn-dominated variables (Figure 5), suggesting that the samples were driven by metal-specific uptake mechanisms and crop–location interactions**.** Pb contamination in vegetables is often controlled by different pathways. Unlike Cd and Zn, Pb is relatively immobile in soil, and translocation from roots to edible plant parts is less. Several studies have reported that Pb contamination in vegetables is frequently associated with atmospheric deposition from traffic emissions, industrial activities, and dust fallout rather than direct root uptake alone (Sharma et al., 2009; Tóth et al., 2016). PC4 reflected a strong influence from Cu and Pb in some vegetables, particularly red onion and cabbage, suggesting the site-specific contamination. PC5 was mainly contributed to by As-related variables, and As showed distinct geochemical behaviour and may originate from geogenic or irrigation practices. Meharg and Zhao (2012), and Smedley and Kinniburgh (2002) reported that arsenic accumulation in vegetables is strongly influenced by geogenic sources, soil mineralogy, and irrigation water chemistry, particularly in regions affected by arsenic-rich groundwater.

The location-wise loading patterns of PCA summarize the samples from Nuwara Eliya, which mostly cluster on positive PC1 with strong loadings of Cd, Zn, and Pb due to intensive fertilizer use, increasing trace element bioavailability due to low pH, and high rainfall. Samples from Badulla associated with Pb and As due to mixed land use (rice – vegetable cropping system), or possible roadside or atmospheric Pb contamination. Many vegetable samples from Kalpitiya showed negative PC1 with lower PTE load. This may be due to sandy soil with lower trace element retention in the Kalpitiya area.

Overall, the PCA analysis results revealed that PTE accumulation in vegetables is influenced by a combination of trace element properties, vegetable species, and crop location-specific contamination sources.

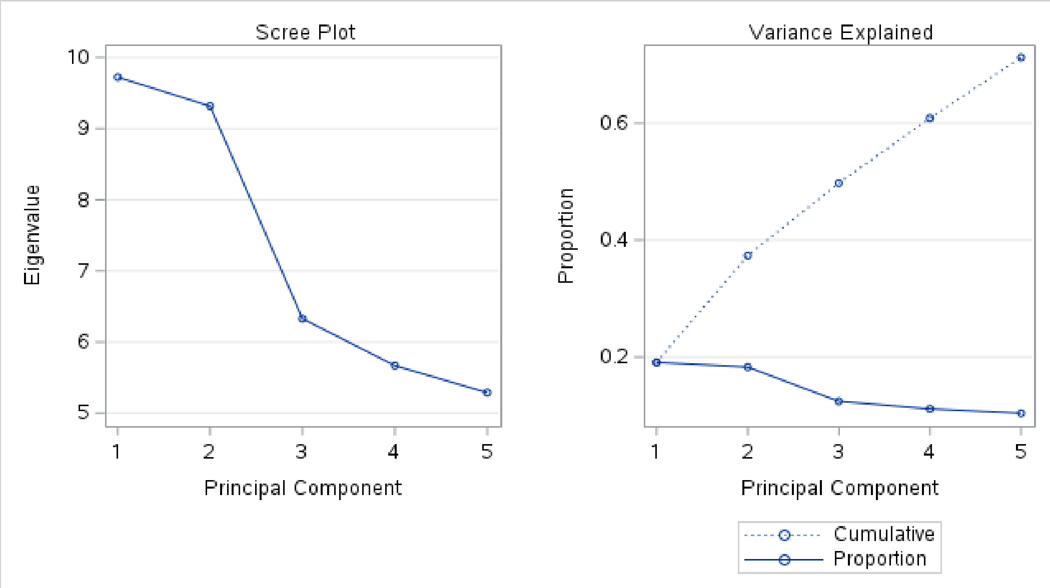

Figure 3: Scree plot of eigenvalues obtained from principal component analysis (PCA)

Table 2: Eigenvalues of the Correlation Matrix

Component	Eigen Values	Variance (%)	Cumulative (%)
PC1	9.72	19.1	19.1
PC2	9.32	18.3	37.3
PC3	6.33	12.4	49.7
PC4	5.67	11.1	60.9
PC5	5.23	10.4	71.2

Liu et al. (2013), and Wei & Yang (2010) confirmed similar findings, which emphasize the importance of considering both anthropogenic and natural inputs when assessing food safety risks.
Score plot: PC2 Vs PC1 (Figure 6) shows the samples cluster primarily according to sampling location, with greater dispersion observed in Badulla, indicating heterogeneous contamination sources.

3.4 Dietary exposure to potentially toxic trace elements via vegetables

There are several possible pathways of exposure to PTE in humans; among them, the food chain is the main pathway. Exposure to contaminants is usually expressed as a provisional tolerable daily or weekly intake, a reference value based on body weight for an average adult (60kg body weight) established by the Joint FAO/WHO Expert Committee for Food Additives (FAO/WHO, 2018). Daily Intake of trace elements from the soil through vegetables was calculated as Daily Intake of trace elements = daily vegetable consumption x Mean trace element concentration of vegetable (mg/day/ fresh weight). The number of vegetables consumed per day is calculated as the serving size of vegetables x the number of servings per day (Attanayake et al.1 2021). The recommended no of servings of vegetables for Sri Lankan people is 3-5 servings per day (Food-based Dietary Guidelines of Sri Lanka, 2011).

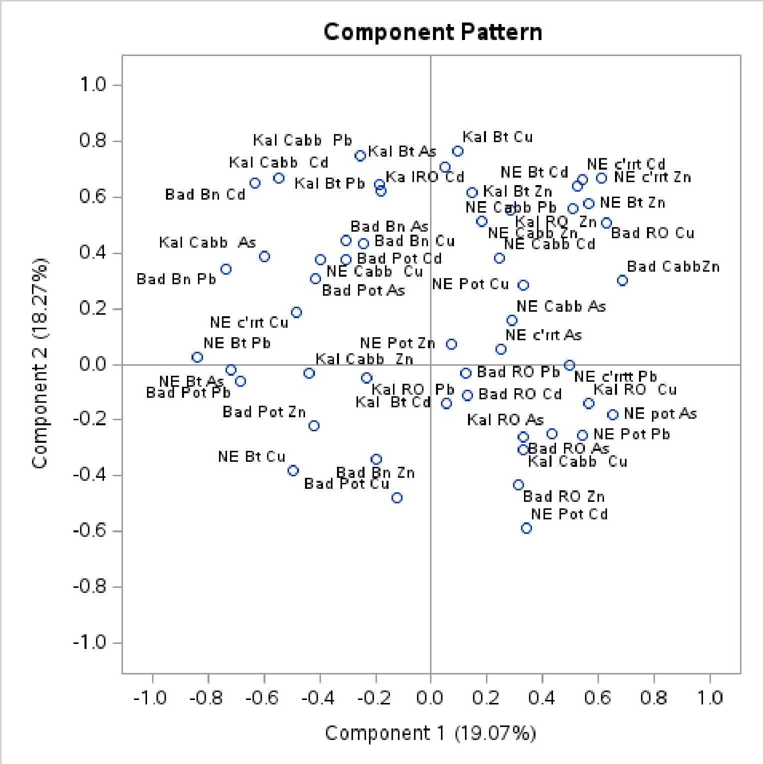

Figure 4: Loading (pattern) plot of principal components 1 and 2

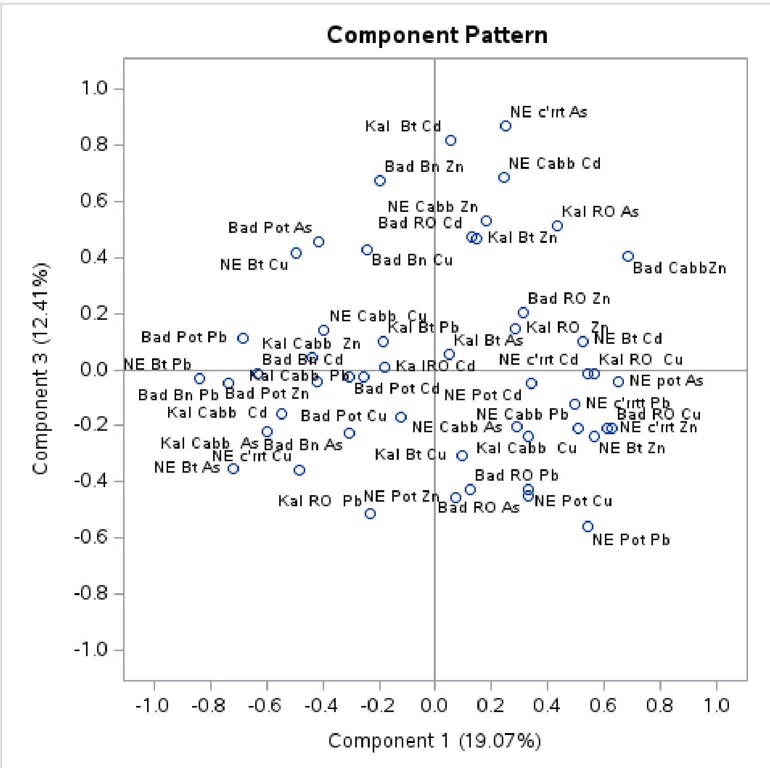

Figure 5: Loading (pattern) plot of principal components 1 and 3

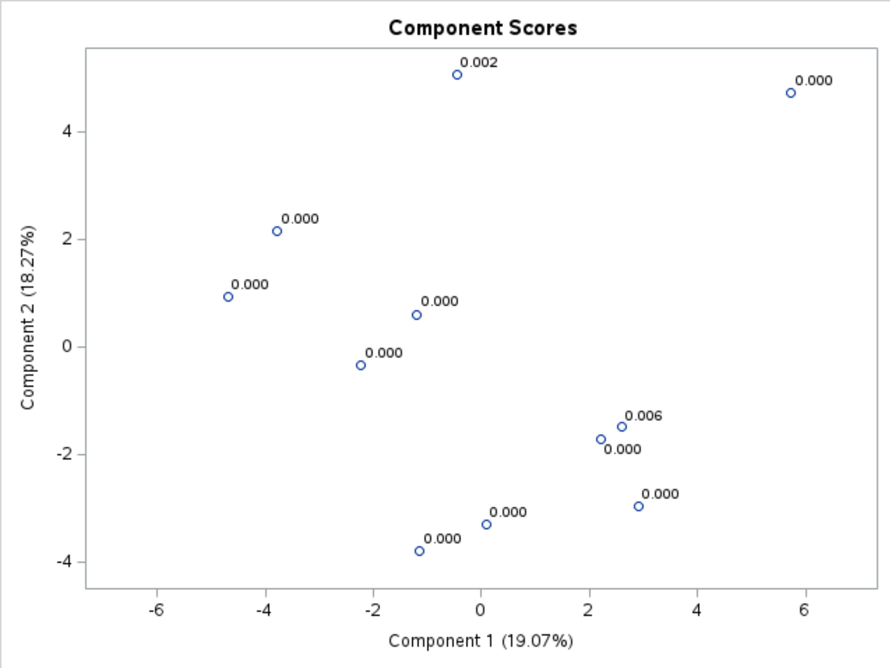

Figure 6: Score plot of principal components 1 and 2

Therefore, none of the servings for this was considered 4 servings of vegetables per day. The serving size of the vegetable was considered according to the serving size of the U.S. Food and Drug Administration (2008) (Table 3). The body weight of the person (adult) was assumed to be 60kg. The estimated weekly tolerable dietary intakes of the potentially toxic trace element are presented in Table 4.

The estimated weekly dietary intakes per person via these vegetable crops did not exceed the Provisional Tolerable Weekly Intake (PTWI) levels per person stipulated by the Joint FAO/WHO Expert Committee for Food Additives (FAO/WHO, 2018) Estimated dietary intakes for root and tuber crops in order of decrease were Zn>Cu>Pb>Cd>As while fruiting crops (bean) and leafy vegetables (cabbage and onion) showed in the order of Zn>Cu>Pb>As>Cd. However, to assess the risk of consumption of tested vegetable crops, estimated weekly dietary intakes per person were compared with Provisional Tolerable Weekly Intakes (PTWI) per person for trace elements established by the Joint FAO/WHO Expert Committee on Food Additives (JECFA). Estimated Dietary intakes of all five trace elements of As, Cd, Pb, Cu, and Zn in edible parts of all tested vegetable crops were far below the Provisional Tolerable Weekly Intakes recommended by FAO/WHO, showing that little intake of tested trace elements is associated with the consumption of vegetables in this study. In this study, weekly dietary intakes of trace elements in edible parts of vegetables were estimated based on the national recommended no of servings reported in the Food-based dietary guidelines of Sri Lanka (2011).

Table 3: Serving size of the different vegetable crops

Vegetable crop	Serving Size (g)
Bean	83
Carrot	78
Potato	148
Beet	78
Cabbage	84
Red onion	148

Table 4: Estimated Weekly Dietary Intake of PTEs from vegetables (mg/week/person)

Vegetable Crop	**Tolerable Weekly Intake for adults (Body weight assumed to be 60kg)**				
	mg/week /person				
	As	Cd	Pb	Cu	Zn
Bean	0.0116	0.0093	0.046	2.62	9.13
Carrot	0.0131	0.0328	0.075	1.80	8.56
Potato	0.021	0.0332	0.112	5.34	14.67
Beet	0.011	0.0153	0.048	2.06	10.83
Cabbage	0.019	0.0118	0.029	1,66	8.00
Red Onion	0.037	0.0290	0.098	2.81	13.09
Codex MPL					
Leafy Vegetables	1.19	0.476	0.714	95.2	142.8
Root crops /legumes	1.09	0.218	0.218	87.4	131.0
Brassica/Bulb veg		0.117	0.235	94.1	141.1
PTWI (mg /week/person)	0.9*	0.42*	1.5*	210**	420**

** CODEX GENERAL STANDARD FOR CONTAMINANTS AND TOXINS IN FOOD AND FEED CXS 193-1995 Adopted in 1995 Revised in 1997, 2006, 2008, 2009 Amended in 2010, 2012, 2013, 2014, 2015, 2016, 2017, ** Provisional tolerable weekly intake recommended by the FAO/WHO (2018)*

However, it is impossible to obtain a recommended number of servings or recommended amounts of vegetables by most Sri Lankan people. Because the serving size varies greatly depending on people's knowledge, food habits, availability of specific vegetables and availability of vegetables and economic condition of the people (Khan et al., 2015). Jayawardena et al. (2012) reported that the actual average dietary intake of vegetables (no of servings of vegetable consumption) of Sri Lankan adults was 1.7. Therefore, the estimated dietary intake values of trace elements in this study may be further decreased.

Furthermore, Provisional Tolerable Weekly Intervals and CODEX limits maximum permissible levels were mainly established based on the food habits of European peoples. They consumed more vegetables than the people in Sri Lanka. Therefore, when considering the Sri Lankan context, FAO/WHO maximum permissible limits may be high. In addition, PTWI of potentially toxic trace elements by FAO/WHO had been established not only from vegetable consumption but also considering exposure to trace elements from all sources, such as other foods, water, air, dust, etc. Therefore, human exposure to tested trace elements from the vegetables tested in this study was further declined.

Weekly Dietary Intakes per person for potentially toxic trace elements for maximum permissible limits established by FAO/WHO-CODEX were estimated and compared with Provisional Tolerable Weekly Dietary Intakes (PTWI) per person, assuming that the body weight of the person was 60 kg. The As and Cd intakes associated with CODEX maximum limits in leafy vegetables were a little higher than the PTWI per person imposed by JECFA. The CODEX-FAO/WHO Food Standards program established Maximum Permissible limits that apply to contaminants (trace elements) contained in foods intended for safe human consumption, as well as to promote international trade. Therefore, Maximum Permissible Limits (MPL) and Provisional Tolerable Weekly intakes of trace elements through the consumption of vegetables should be revisited for the corresponding region or country based on the food habits, availability of vegetables, and economy of each country.

4. Conclusions

This study demonstrates that commonly consumed vegetables grown in intensive agricultural areas accumulate varying levels of PTEs (As, Cd, Pb, Cu, and Zn) in their edible parts, and zinc exhibited the highest concentrations in all vegetables, followed by copper, reflecting their essential roles in plant growth. Root and tuber crops (carrot, potato, and beetroot) accumulated PTEs in the order of Zn > Cu > Pb > Cd > As, while cabbage, red onion, and bean followed the order Zn > Cu > Pb > As > Cd. Carrot showed significantly higher concentrations of Cd and Pb, red onion exhibited the highest As concentration, and beetroot accumulated the highest Zn concentration. Copper concentrations did not differ significantly among vegetable types.

The PCA results demonstrate that PTE accumulation in vegetables is controlled by a combination of elemental properties, crop type, and location-specific contamination sources. High loadings of Cd and Zn on PC1 indicate strong soil-related contamination, particularly in root vegetables from Nuwara Eliya and Badulla, while Pb and As showed distinct behaviour linked to atmospheric deposition and geogenic or irrigation sources. The clear clustering of samples by location highlights the influence of intensive fertilizer use, soil acidity, rainfall, and land-use patterns on the bioavailability of trace elements. Site-specific fertilizer management and soil pH regulation can be recommended to minimize the PTE contamination in vegetables.

The estimated weekly dietary intakes of As, Cd, Pb, Cu, and Zn through consumption of the studied vegetables were all below the Provisional Tolerable Weekly Intake (PTWI) values established by FAO/WHO, indicating a low health risk from vegetable consumption in the study area. Dietary intake followed the order Zn > Cu > Pb > Cd > As for root and tuber crops, and Zn > Cu > Pb > As > Cd for leafy and fruiting vegetables. Actual dietary exposure is lower, as average vegetable consumption in Sri Lanka (1.7 servings/day) is below national dietary recommendations. PTWI and CODEX limits are based largely on European dietary patterns and consider exposure from multiple sources (vegetables, rice, drinking water, air, and dust), suggesting that current international limits may overestimate risk in the Sri Lankan context and it is suggesting the need of country specific risk assessment model and revisiting of Codex maximum permissible limits and PTWI values at regional or national level considering the local food consumption patterns, and socioeconomic conditions. This study further emphasized the need for continuous monitoring of PTE contamination in vegetables and soils to investigate long-term trends in PTE accumulation under changing land – use and climatic conditions.

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Competing Interests:
The authors declare that they have no competing interests.

Author Contribution:
N. R. N. Silva: Writing original draft preparation, visualization, project administration, funding acquisition. P. Attanayake: Validation, supervision, writing, review & editing. W. A. U. Vitharana: Supervision, writing, review & editing. P. Weerasinghe: Writing review & editing. All authors have read and agreed to the published version of the manuscript

Data Availability Statement:
The datasets generated and/or analysed during the current study are available from the authors upon reasonable request.

References

Afshin, M., & Zarasvand, M. A. (2008). Heavy metals in selected vegetables and estimation of their daily intake, Sanandaj, Iran. *Southeast Asian Journal of Tropical Medicine and Public Health, 39*(2). 335-340

AgStat. (2015). *Pocket Book of Agricultural Statistics* (Vol.XII.). Socio-Economics and Planning Center, Department of Agriculture.

Aktaruzzaman, M., Fakhruddin, A. N. M., Chowdhury, M. A. Z., Fardous, Z., & Alam, M. K. (2013). Accumulation of heavy metals in soil and their leafy vegetables in the region of Dhaka–Aricha Highway, Savar, Bangladesh. *Pakistan Journal of Biological Sciences, 16*(7), 332–338. https://doi.org/10.3923/pjbs.2013.332.338

Alloway, B. J. (2013). *Heavy metals in soils: Trace metals and metalloids in soils and their bioavailability* (3rd ed.). Springer. https://doi.org/10.1007/978-94-007-4470-7

Amin, O. I., Chibugo, H. A., & Charles, A. N. (2013). A survey of heavy metal (lead, cadmium and copper) contents of selected fruit and vegetable crops from Borno State of Nigeria. *International Journal of Engineering and Science, 2*(1). 1-4.

Attanayake, C. P., Hettiarachchi, G. M., Palomo, M., Pierzynski, G. M., & Calderon, B. (2021). Phytoavailability of lead for vegetables in urban garden soils. *ACS Agricultural Science & Technology, 1 (3)*, 173–181. https://doi.org/10.1021/acsagscitech.0c00068

Bonanno, G. (2013). Comparative performance of trace element bioaccumulation and biomonitoring in the plant species *Typha domingensis*, *Phragmites australis*, and *Arundo donax*. *Ecotoxicology and Environmental Safety, 97*, 124–130. https://doi.org/10.1016/j.ecoenv. 2013.07.017

Briscoe, M., Sullivan, D., Alewijn, M., Austad, J., Boison, J., Christiansen, S., Cook, J. M., De Vries, J., Indyk, H., Joseph, G., Konings, E., Krynitsky, A., Phillips, T., Popping, B., Reddy, M., & Wong, J. (2015). Determination of heavy metals in food by inductively coupled plasma–mass spectrometry: First Action 2015.01. *Journal of AOAC International, 98*(4), 1113–1120. https://doi.org/10.5740/jaoac.int.2015 .01

Clemens, S., Aarts, M. G. M., Thomine, S., & Verbruggen, N. (2013). Plant science: The key to preventing slow cadmium poisoning. *Journal of Experimental Botany, 64*(1), 407–419. https://doi.org/10.1093/jxb/ers315

Food and Agriculture Organization of the United Nations & World Health Organization. (2019). *General standard for contaminants and toxins in food and feed* (Codex Standard CXS 193-1995). Codex Alimentarius Commission.

Food and Agriculture Organization of the United Nations & World Health Organization. (2007). *Evaluation of certain food additives and contaminants: Sixty-seventh report of the Joint FAO/WHO Expert Committee on Food Additives* (WHO Technical Report Series No. 940). World Health Organization.

Food and Agriculture Organization of the United Nations & World Health Organization. (2018). *Joint FAO/WHO food standards programme: Codex committee on contaminants in foods (CF/12 INF/1).* Codex Alimentarius Commission.

Garg, V. K., Yadav, P., Mor, S., Singh, B., & Pulhani, V. (2014). Heavy metal bio concentration from soil to vegetables and assessment of health risk caused by their ingestion. *Biological Trace Element Research, 157*, 256–265. https://doi.org/10.1007/s12011-013-9860-6

Grant, C. A., Clarke, J. M., Duguid, S., & Chaney, R. L. (2008). Selection and breeding of plant cultivars to minimize cadmium accumulation. *Science of the Total Environment, 390*(2–3), 301–310. https://doi.org/10.1016/j.scitotenv.2007.10.038

Hamiani, O., El Khalil, H., Sirguey, C., Ouhammou, A., Bitton, G., Schwartz, C., & Boularbah, A. (2015). Metal concentrations in plants from mining areas in South Morocco: Health risks assessment of consumption of edible and aromatic plants. *Clean–Soil, Air, Water, 43*(3), 399–407. https://doi.org/10.1002/clen.201300200

Jayawardena, R., Byrne, N. M., Soares, M. J., Katulanda, P., & Hills, A. P. (2012). Food consumption of Sri Lankan adults: An appraisal of serving characteristics. *Public Health Nutrition, 16*(4), 633–658. https://doi.org/10.1017/S1368980012003314

Kabata-Pendias, A. (2011). *Trace elements in soils and plants* (4th ed.). CRC Press. https://doi.org/10.1201/b10158

Khan, A., Khan, S., Khan, M. A., Qumar, Z., & Waqas, M. (2015). The uptake and bioaccumulation of heavy metals by food plants, their effects on plant nutrients, and associated health risks: A review. *Environmental Science and Pollution Research, 22*(18), 13772–13799. https://doi.org/10.1007/s11356-015-488-0

Kananke, T., Wansapala, J., & Gunarathna, A. (2014). Heavy metal contamination in green leafy vegetables: Selected market sites of Piliyandala area, Colombo. *American Journal of Food Science and Technology, 2*(5), 139–144. https://doi.org/10.12691/ajfst-2-5-1

Liu, W., Zhao, J., Ouyang, Z., Söderlund, L., & Liu, G. (2013). Impacts of sewage irrigation on heavy metal distribution and contamination in Beijing, China. *Environment International, 31*(6), 805–812. https://doi.org/10.1016/j.evint.2005.05.042

Mapa, R. B. (2020). *The soils of Sri Lanka.* Springer Nature. https://doi.org/10.1007/978-3-030441 64-1

McLaughlin, M. J., Parker, D. R., & Clarke, J. M. (1999). Metals and micronutrients – food safety issues. *Field Crops Research, 60*(1–2), 143–163. https://doi.org/10.1016/S0378-4290(98)00137-3

Meharg, A. A., & Zhao, F. J. (2012). *Arsenic & rice*. Springer. https://doi.org/10.1007/978-94-007-2947-6

Muller, G. (1969). Index of geo-accumulation in sediments of the Rhine River. *GeoJournal, 2*, 108–118.

Nutrition Division, Ministry of Health, Sri Lanka, in collaboration with the World Health Organization. (2011). *Food-based dietary guidelines for Sri Lankans*. Ministry of Health, Sri Lanka.

Odujebe, O. F., Oyeyiola, O. A., Davidson, C. M., Olayinka, K. O., & Alo, B. I. (2020). Estimation of the dietary intake of potentially toxic elements in vegetables grown in the vicinity of dumpsites in a rapidly urbanizing tropical megacity. *Journal of Scientific Research and Development, 19*(2), 192–205.

Premarathna, H. M. P. L., Hettiarachchi, G. M., & Indrarathne, S. P. (2011). Trace metal concentration in crops and soils collected from intensively cultivated areas of Sri Lanka. *Pedologist*, 54(3).230–240.

Premarathna, H. M. P. L., Hettiarachchi, G. M., & Indrarathne, S. P. (2005). Accumulation of cadmium in intensive vegetable growing soils in the up-country. *Tropical Agricultural Research, 17*, 93–103.

Saglam, C. (2013). Heavy metal accumulation in the edible parts of some cultivated plants and media samples from a volcanic region in southern Turkey. *Journal of Ecology, 22*(86), 1–8.

Sharma, R. K., Agrawal, M., & Marshall, F. M. (2009). Heavy metals in vegetables collected from production and market sites of a tropical urban area of India. *Food and Chemical Toxicology, 47*(3), 583–591.https://doi.org/10.1016/j.fct.2008.12.016

Smedley, P. L., & Kinniburgh, D. G. (2002). A review of the source, behaviour and distribution of arsenic in natural waters. *Applied Geochemistry, 17*(5), 517–568. https://doi.org/10.1016/S08832927(02)00018-5

Smith, E., Naidu, R., & Alston, A. M. (2008). Arsenic in the soil environment: A review. *Environmental Pollution*, 156(2), 253–266. https://doi.org/10.1016/j.envpol.2008.02.019

Singh, A., Sharma, R. K., Agrawal, M., & Marshall, F. M. (2010). Risk assessment of heavy metal toxicity through contaminated vegetables from wastewater irrigated area of Varanasi, India. *Tropical Ecology, 51*(2), 375–387. https://doi.org/10.1016/j.ecoenv.2009.11.041

Silva, N. R. N., Weerasinghe, P., & Rathnapriya, H. D. K. (2016). Toxic trace elements in vegetables collected from markets in Kandy District. *Annals of the Sri Lanka Department of Agriculture, 18*, 19. https://doi.org/10.4038/aslda.v18i0.7286

Silva, N. R. N., Weerasinghe, P., Kodikara, K. M. S., & Wakwella, P. (2018). Toxic trace elements in soils and edible parts of root and tuber crops in the upcountry wet and intermediate zones of Sri Lanka. *Tropical Agriculturist, 166*(3),230-240. https://doi.org/10.4038/ta.v166i3.8120

Tóth, G., Hermann, T., Da Silva, M. R., & Montanarella, L. (2016). Heavy metals in agricultural soils of the European Union with implications for food safety. *Environment International, 88*, 299–309. https://doi.org/10.1016/j.evint.2015.12.017

U.S. Food & Drug Administration. (2008). *Vegetables: Nutrition facts.*Wan, Y. (2024). Heavy metals in agricultural soil: Soil components and their effects on heavy metal mobility and plant uptake. *Toxics, 12*(1), 63. https://doi.org/10.3390/toxics12010063

Wei, B., & Yang, L. (2010). A review of heavy metal contaminations in urban soils, urban road dusts and agricultural soils from China. *Microchemical Journal, 94*(2), 99–107. https://doi.org/10.1016/j.microc.2009.09.014

Wijewardena, J. D. H., & Yapa, U. W. S. P. (1999). Effect of the combined use of animal manure and chemical fertilizer on potato and vegetable cultivation in the up-country of Sri Lanka. *Sri Lankan Journal of Agricultural Sciences, 36*, 70–82.

Wickramarathna, N., Maduranga, T. M., & Chamara, L. L. S. (2016). Contamination of heavy metals in aquatic vegetables collected from cultivation sites in Sri Lanka. *IOSR Journal of Environmental Science, Toxicology and Food Technology, 10 (1)*, 76–82. https://doi.org/10.9790/2402-10117682

Yang, J., Ma, S., Zhou, J., Song, Y., & Li, F. (2018). Heavy metal contamination in soils and vegetables and health risk assessment of inhabitants in Daye, China. *Journal of International Medical Research, 46*(8), 3374–3387. https://doi.org/10.1177/030006051877 4931

Zafarzadeh, A., Rahimzadeh, H., & Mahvi, A. H. (2018). Health risk assessment of heavy metals in vegetables in an endemic esophageal cancer region in Iran. *Health Scope, 7*(3), e12340. https://doi.org/10.5812/jhealthscope.12340

Zhao, F. J., McGrath, S. P., & Meharg, A. A. (2010). Arsenic as a food chain contaminant: Mechanisms of plant uptake and metabolism and mitigation strategies. *New Phytologist*, 188(2), 328–341.https://doi.org/10.1111/j.14698137 .2010.03421.x