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Health risk assessment of heavy metals in Cassava cultivated on leachate-contaminated soil during the early transition from landfilling to co-landfilling with incineration

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Abstract
This study aimed to investigate heavy metal contamination in soil and cassava in the area of the Khon Kaen Municipality landfill during the transition period of waste management (December 2015), focusing on non-carcinogenic and carcinogenic health risks from consuming cassava tubers. Soil (0-30 cm) and cassava samples were collected from agricultural areas most affected by leachate leakage. Soil and cassava samples were digested for heavy metal analysis using microwave-assisted acid digestion (USEPA 3052), followed by heavy metal analysis with ICP-AES (USEPA 6010D). The analysis revealed that the concentration of heavy metals in soil did not exceed the WHO/FAO permissible limits, but contamination levels in cassava tubers for Cd, Cr, and Pb exceeded the permissible limits. Cassava demonstrated the ability to accumulate heavy metals in its tubers, with Ni showing the highest bioaccumulation potential (BCF = 5.837). Once accumulated in tubers, heavy metals translocated to leaves (Cd, Cr, Fe, Mn, Pb, Zn) and stems (Cr, Fe, Mn, Pb, Zn), with Mn exhibiting the highest translocation potential (TF tuber to leave = 10.670, TF tuber to stem = 7.094). Health risk assessments showed that both non-carcinogenic and carcinogenic health risks for both children and adults were unacceptable (HI >1, TCR >10^{-4}). These findings highlight that, during the initial phase of waste management improvements, contamination persists in the soil and cassava, posing health risks to consumers. Therefore, enhancing leachate management systems is essential, and the results should serve as a reference for future waste management.

Keywords: *health risk assessment, heavy metal, soil, cassava, landfill*

Introduction

Asia is experiencing a continuous increase in municipal solid waste generation. In 2016, the global population generated approximately 1.2 billion tons of waste, with projections indicating an increase to 1.5 billion tons by 2030 and further rising to 1.9 billion tons by 2050 (World Bank, 2018; World Bank, 2012). This increasing waste generation is closely linked to economic development (UNEP, 2024). Thailand is one of the countries that has experienced significant economic development, particularly between 1985 and 2014 (Asian Development Bank, 2015). Consequently, the country is also facing the challenge of increasing waste generation. A comparison of waste generation between 2008 and 2015 reveals an increase from 23.93 million tons to 26.85 million tons per year (Local Administration Department of Thailand, 2015). Moreover, between 2020 and 2022, waste generation increased from 25.37 million tons to 25.7 million tons per year (Pollution Control Department of Thailand, 2022). The waste generation rate in Thailand varies between urban and rural areas. In ur-

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ban areas, the waste generation rate is 1.5 kg per person per day, while in rural areas, it is 0.4 kg per person per day (Pollution Control Department of Thailand, 2011). This indicates that economically developed urban areas tend to generate more waste than rural areas. In the case of Khon Kaen, a study conducted by the Pollution Control Department found that the city's waste generation rate is 1.59 kg/person/day (Sustainable Environment Research Institute, 2023). This elevated rate is attributed to Khon Kaen's status as the fastest-growing economic hub in Northeastern Thailand, leading to increased waste generation per capita. Given the increasing waste generation rate, government agencies must adopt effective waste management strategies. In the past, Thailand primarily utilized controlled dumping, later transitioning to open dumping, and subsequently developing sanitary landfill methods to mitigate the contamination of pollutants from landfills into the environment (Local Administration Department of Thailand, 2015). However, with the continuous rise in waste generation, sanitary landfill management has led to environmental challenges. A major issue stems from the excessive accumulation of waste in landfill sites, which results in a significant increase in leachate production. The leakage of leachate into the environment poses a serious concern, as it contains toxic organic compounds and toxic inorganic compounds (Pranav and Deblina, 2024), particularly heavy metals. Consequently, landfill operations contribute to environmental contamination and facilitate bioaccumulation in soil, water, and plants surrounding landfill areas. The process of bioaccumulation in living organisms and the environment subsequently affects the food chain, leading to potential health risks. These risks include both non-carcinogenic and carcinogenic effects, ultimately impacting human health as the final consumers in the chain (Sumona et al., 2015). The Khon Kaen municipal landfill is one of the waste management sites that frequently faces environmental challenges, particularly concerning soil, water, and agricultural crops surrounding the landfill. Additionally, frequent landfill fires have been reported, primarily caused by the anaerobic decomposition of waste, which generates methane gas and leads to fire incidents, resulting in significant air pollution. Thus, it can be concluded that this landfill has environmental impacts on multiple dimensions, including soil, water, air, and surrounding ecosystems. The primary cause of these environmental issues is the excessive accumulation of waste in the landfill. To address this challenge, the Thai government has allocated funding for the development of waste management systems aimed at treating both newly generated and accumulated waste through incineration technology. This initiative commenced in 2015, and the co-disposal approach, which combines landfilling and incineration, has significantly reduced the volume of accumulated waste. Specifically, in 2017, the total waste accumulation in the landfill was 548,328 tons, and by 2023, this amount had decreased to 288,244 tons (Khon Kaen Provincial Statistical Office, 2020). This substantial reduction suggests that improvements in waste management practices have been effective in reducing waste accumulation. However, continuous environmental monitoring remains essential, particularly for soil, water, and agricultural resources, especially cassava (Manihot esculenta). Cassava is a key economic crop in Thailand (Land Development Department of Thailand, 2021) and is widely cultivated in the northeastern region, including areas surrounding landfill sites. As a result, cassava grown near landfills may contain hazardous pollutants, particularly heavy metals, due to the absorption of contaminants from soil affected by leachate leakage. The accumulation of heavy metals in cassava can lead to their transfer and bioaccumulation through the food chain (Arivalagan et al., 2024; Nouri et al., 2009) posing potential health risks to humans. This study investigates the contamination of heavy metals, including Arsenic (As), Cadmium (Cd), Chromium (Cr), Iron (Fe), Manganese (Mn), Nickel (Ni), Lead (Pb), and Zinc (Zn), in soil and different components of cassava plants at high-risk sites surrounding the Khon Kaen municipal landfill during the initial phase of waste management system development. Furthermore, this research identifies the sources of heavy metal contamination in soil using statistical methods and assesses the health risks associated with heavy metal contamination in cassava tubers through non-carcinogenic and carcinogenic health risk assessment models.

Materials and Methods

Study area

The study area is located within the Khon Kaen municipal landfill. Sampling sites are in agricultural fields used for cassava cultivation, identified as high-risk areas due to leachate migration from the landfill. This contamination is caused by the lower elevation

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of the fields compared to the landfill, as well as the proximity of the agricultural area to the landfill site. Sampling locations and coordinates are shown in Figure 1. The sampling was conducted in December 2015, during the landfill's transition from landfilling to a co-disposal approach, combining landfilling and incineration to manage both new and accumulated waste.

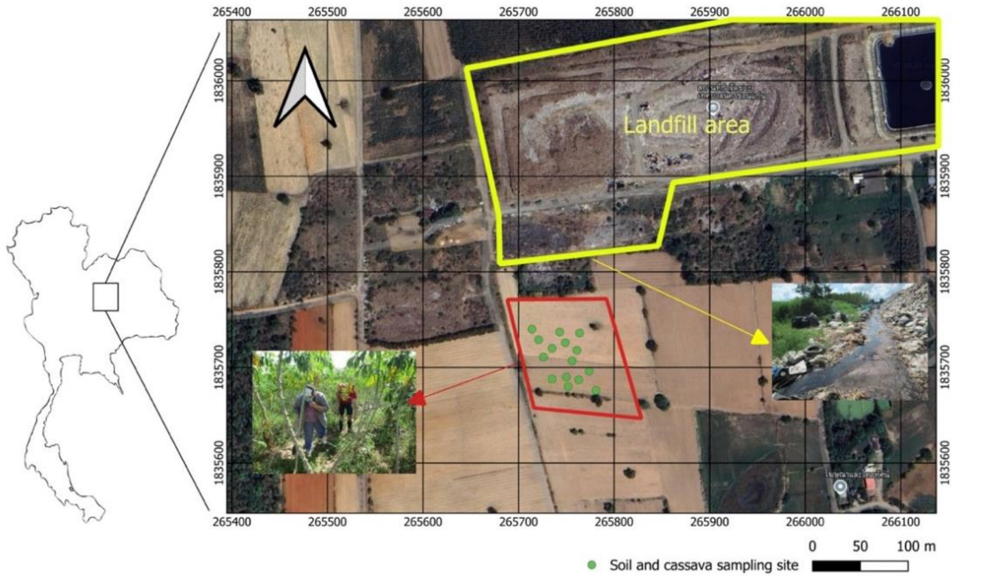

Figure 1.
Geographic coordinates of soil and cassava sampling sites in the Khon Kaen Municipality landfill area

Soil and cassava sampling

Cassava samples were collected using a grid sampling method, in which the cultivation area was divided into 3 × 3 m² grids, totaling 15 grids, to ensure comprehensive coverage of the entire area. Samples were taken from the central aligned square grid following the standard research methodology of USEPA (USEPA, 2002a). Cassava was sampled before harvest, or 10 months after planting. The cassava samples were divided into three parts: leaves, stems, and tubers. Soil samples were taken from the area around the cassava plants, near the base, at a depth of 0-30 cm using a composite sampling method with a hand auger (CSIRO, 2021), collecting 1 kilogram of soil per sample. To preserve the samples during transportation, cassava and soil were stored in polyethylene bags before being transported to the laboratory.

Sample preparation, digestion, and analysis

Cassava samples (tubers, stems, and leaves; n = 15) were washed with deionized water, then oven-dried at 45°C for 48 hours (Bortey-Sam et al., 2015) and ground into smaller particles using a clean porcelain mortar. Soil samples (n = 15) were oven-dried at 50°C (Olusegun et al., 2023). After preparation, both cassava and soil samples were sieved (pore size = 200 micrometers), and 0.5 grams of each were subjected to acid digestion using the USEPA 3052 standard method with microwave-assisted acid digestion (USEPA, 1996). A mixture of concentrated nitric acid (Merck, Germany), 30% hydrogen peroxide (Chem supply, Australia), deionized water, and concentrated hydrofluoric acid (QReC, New Zealand) in a 3.5:2:2:0.1 ml ratio was u-sed, and the samples were digested in a microwave dige-ster (PerkinElmer, USA) at 180°C for 5 minutes, then held at 180°C for 10 minutes, followed by cooling for 30 minu-tes. The digested samples were filtered using filter paper No. 42 (Whatman, USA) and adjusted to a final volume of 25 mL (Yong et al., 2023). The samples were stored at temperatu-res below 4°C in a dark space until analysis. Heavy metal contamination was analyzed using the USEPA 6010D D standard method by ICP-AES (PeklinElmer Optima 8300, USA) at wavelengths of 193.696, 226.502, 267.716, 259.940, 257.610, 231.604, 220.353, and 213.856 nm for the determination of As, Cd, Cr, Fe, Mn, Ni, Pb, and Zn, respectively (USEPA, 2018).

Bioaccumulation Factor

Bioaccumulation Factor (BCF) is a tool used to study the accumulation of heavy metals from soil to plants (Kamal et al., 2019), which can be calculated using the following equation [1]

$$BCF = \frac{Ctuber}{Csoil} \qquad [1]$$

where, C refers to the concentration of metals in the tuber (Ctuber) and soil (Csoil). When the BCF value is >1, it indicates that the plant can efficiently accu-mulate heavy metals and is classified as a hyperac-cumulator, whereas a BCF value <1 suggests that the plant lacks the ability to accumulate the metal.

Transfer Factor

Transfer Factor (TF) is a tool used to study the trans-

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location of substances from the tuber to the upper parts of the plant (Kim et al., 2003), as shown in equation [2].

$$TF = \frac{Cleave, Cstem}{Ctuber} \quad [2]$$

where C represents the concentration of heavy metals in the leave (Cleave), stem (Cstem), and tuber (Ctuber). When the TF value is greater than 1, it indicates that the plant has a strong ability to translocate metals from the tuber to the shoots (leave and stem). However, when the TF value is less than 1, it suggests that the plant's ability to translocate heavy metals is inefficient (Kovacs et al., 2021).

Statistical Analysis

The results of the descriptive statistical analysis are presented as the mean, median, and standard deviation (SD). Reference statistics are calculated using One-way ANOVA, Pearson's correlation, and Principal Component Analysis (PCA). One-way ANOVA was conducted, followed by a post-hoc test using Tukey's HSD method, to analyze differences in heavy metal contamination in soil and various parts of the plant at a significance level of 0.05. Pearson's correlation and PCA analysis, also at a significance level of 0.05, are used to identify sources of contamination between pairs of heavy metals (Dragovic et al., 2008) and to group the metals accordingly (Yan et al., 2023). All statistical calculations are performed using the SPSS software.

Quality analysis (QA)/Quality control (QC)

Quality control for the analysis will be ensured through instrument and chemical quality control. Specifically, glassware used in the analysis must be soaked in 10% nitric acid for 48 hours before use. All chemicals used for the analysis will be of AR grade. The quality control of the analytical results will be managed by conducting triplicate determinations, with the %RSD set to be less than 5%. The concentration of heavy metals will be calculated using a standard solution graph, with a Certified Reference Material from PeklinElmer (Lot No.: 3-18MKBY1). The linearity test results showed an r^2 value ranging from 0.996 to 0.999, which meets the acceptable standard ($r^2 > 0.995$). The % recovery values were between 97% and 117%, which fall within the AOAC acceptable range of 80% to 120%. (Abdullah et al., 2020; AOAC, 2002; Jiang, 2013)

Health Risk Assessment

The health risk assessment is a mathematical model used to evaluate the risk of heavy metal exposure to the human body through exposure assessment. This assessment includes both non-carcinogenic risk assessment and carcinogenic risk assessment. The model is designed by the USEPA (1989) and adapted from Onyedikachi et al. (2018).

Exposure assessment

Exposure assessment is a tool used to evaluate the intake of heavy metals into the body through ingestion, which can be calculated using Equation [3].

$$\text{EDI (mg/kg.day)} = \frac{Ctuber \times CF \times DFI}{BW} \quad [3]$$

where, EDI represent Estimated daily intake (mg/kg/day); Ctuber represents the concentration of heavy metals in cassava tuber (mg/kg); CF is the conversion factor from fresh to dry weight (0.085) (Avila et al., 2017); DFI is the daily food intake for cassava tuber (0.418 kg for adults, 0.209 kg for children) (Onyedikachi et al. ,2018); and BW is the body weight (70 kg for adults, 15 kg for children) (USEPA, 1989).

Non-carcinogenic health risk assessment

Non-carcinogenic health risk assessment evaluates the potential risk of non-cancerous diseases resulting from the ingestion of cassava tuber contaminated with heavy metals. The non-carcinogenic risk from the ingestion of a single heavy metal element is calculated using the Target Hazard Quotient (THQ) (USEPA, 2012). For multiple heavy metal elements, the risk is assessed by calculating the Hazard Index (HI) (USEPA, 1989), as shown in equations [4] and [5], respectively.

$$THQ = \frac{EDI}{RefD} \quad [4] \qquad HI = \sum_{i=1}^{n} THQi \quad [5]$$

where, THQ is the Target Hazard Quotient; HI is the Hazard Index; EDI is the Estimated Daily Intake (mg/kg/day); i represents the type of heavy metal; and RefD is the reference dose for ingestion, with the following values for As, Cd, Cr, Fe, Mn, Ni, Pb, and Zn as 0.0003, 0.001, 1.5, 0.7, 0.033, 0.02, 0.0037, and 0.3 mg/kg/day, respectively. (USEPA, 2013; Lalifn et al., 2018; IRIS, 2006). When the calculated THQ value is greater than 1, it indicates a potential health risk for non-cancerous diseases. Conversely, when the THQ or HI is less than 1, it suggests no significant health risk for non-cancerous diseases (USEPA, 1989).

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Carcinogenic health risk assessment

Carcinogenic health risk assessment is a process used to evaluate the potential health risk of developing cancer from the ingestion of carcinogenic substances (USEPA, 1989). The cancer risk is assessed by calculating the Cancer Risk (CR) for single heavy metal elements and the Total Cancer Risk (TCR) for multiple heavy metal elements, as shown in equations [6] and [7], respectively.

$$CR = EDI \times SF \quad [6] \qquad HI = \sum_{i=1}^{n} THQi \quad [7]$$

where, CR is carcinogenic risk; TCR is total carcinogenic risk; EDI is estimated daily intake (mg/kg /day); i represents the type of heavy metal; and SF is slope factor. The slope factors for As, Cd, Cr, Ni, and Pb are 1.5, 0.38, 0.5, 0.84, and 8.5×10^{-3}, respectively (USEPA, 2002b; USEPA, 2011). When CR or TCR is greater than 10^{-6}, it indicates a potential health risk for cancer. If CR or TCR falls between 10^{-6} and 10^{-4}, the risk is considered acceptable. However, if CR or TCR exceeds 10^{-4}, the risk is considered unacceptable. If CR or TCR is less than 10^{-6}, it indicates no risk of cancer (USEPA, 2005).

Results and Discussion

Concentration of heavy metals in soil and cassava

The contamination of heavy metals in soil and various parts of cassava, including leaves, stems, and tubers (mg/kg), is presented in Table 1. The study found that the average heavy metal contamination in the soil of agricultural areas was ranked as follows: Fe (2665.062) > Mn (58.981) > Cr (18.631) > Zn (17.273) > Ni (4.935) > Pb (2.263) > As (1.003) > Cd (0.194). The average contamination in cassava tubers was ranked as: Fe (123.536) > Ni (28.806) > Cr (22.669) > Zn (19.307) > Mn (15.544) > Pb (1.467) > As (1.088) > Cd (0.083). For cassava leaves, the average contamination was: Fe (160.017) > Mn (110.270) > Zn (38.594) > Cr (27.443) > Ni (26.990) > Pb (1.598) > As (0.596) > Cd (0.071). The average

Table 1. *Heavy metal concentrations in soil and cassava (mg/kg) and statistical analysis results using One-way ANOVA.*

Element	Sample (n=15)	Concentration (mg/kg)				Anova	
		Range	Median	Mean	SD	F	P value
As	Soil	0.357 - 4.020	0.777	1.003	0.909	4.284	0.009*
	Cassava tuber	0.470 - 1.650	1.070	1.088	0.303		
	Cassava stem	0.021-1.112	0.573	0.596	0.257		
	Cassava leave	0.300-1.062	0.525	0.562	0.227		
Cd	Soil	0.138 - 0.550	0.163	0.194	0.105	12.376	0.000*
	Cassava tuber	0.050 - 0.102	0.08	0.083	0.017		
	Cassava leave	ND - 0.100	0.081	0.071	0.034		
	Cassava stem	0.041 - 0.250	0.180	0.158	0.069		
Cr	Soil	5.965 - 58.176	10.328	18.631	17.831	1.036	0.384
	Cassava tuber	2.390 - 40.756	24.200	22.669	9.520		
	Cassava leave	2.362 - 61.601	27.464	27.443	15.190		
	Cassava stem	4.135 - 48.907	21.961	25.395	14.182		
Fe	Soil	1763.387-5272.549	2307.498	2665.062	1095.94	59.981	0.000*
	Cassava tuber	22.59 - 203.831	123.895	123.536	51.187		
	Cassava leave	30.151 - 356.052	157.18	160.017	83.227		
	Cassava stem	27.4 - 1638.35	859.08	756.871	466.569		
Mn	Soil	39.242 - 106.400	56.086	58.981	17.231	13.030	0.000*
	Cassava tuber	1.850 - 165.640	4.511	15.544	41.551		
	Cassava leave	35.133 - 224.174	88.650	110.270	67.059		
	Cassava stem	1.450 - 363.250	180.450	165.851	113.554		
Ni	Soil	3.075-10.350	3.913	4.935	2.176	12.384	0.000*
	Cassava tuber	11.98-64.600	24.38	28.806	12.908		
	Cassava leave	1.460-54.881	23.93	26.99	14.472		
	Cassava stem	3.66-53.352	28.05	28.194	15.901		
Pb	Soil	1.384-7.524	1.831	2.263	1.565	1.918	0.137
	Cassava tuber	0.63-3.282	1.35	1.467	0.621		
	Cassava leave	0.62-4.510	1.31	1.598	0.932		
	Cassava stem	0.48-5.022	2.11	2.195	1.215		
Zn	Soil	7.697-25.447	18.099	17.276	5.181	14.360	0.000*
	Cassava tuber	8.96-55.801	15.12	19.307	12.435		
	Cassava leave	7.25-56.512	42.46	38.594	15.509		
	Cassava stem	3.08-114.420	70.36	62.56	37.849		

*, significant at the level of 0.05

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average contamination was: Fe (160.017) > Mn (110.270) > Zn (38.594) > Cr (27.443) > Ni (26.990) > Pb (1.598) > As (0.596) > Cd (0.071). The average heavy metal contamination in cassava stems was: Fe (756.871) > Mn (165.851) > Zn (62.560) > Ni (28.194) > Cr (25.395) > Pb (2.195) > As (0.562) > Cd (0.158). The comparison of mean heavy metal concentrations in soil, cassava leaves, stems, and tubers using One-way ANOVA (Table 1) revealed significant differences at the 0.05 level for As (F = 4.289, p-value = 0.009), Cd (F = 12.376, p-value = 0.000), Fe (F = 59.981, p-value = 0.000), Mn (F = 13.030, p-value = 0.000), Ni (F = 12.884, p-value = 0.000), and Zn (F = 14.360, p-value = 0.000). A comparison of the concentration of heavy metals in cassava tubers and soil with the permissible limits of WHO/FAO (Table 2) showed that the average concentrations of Cd, Cr, and Pb in cassava tubers exceeded the permissible food limits. However, the average concentration of all heavy metals in the soil was within the permissible limits for agricultural soil. This indicates that the consumption of cassava may pose health risks from exposure to Cd, Cr, and Pb. A comparison of heavy metal contamination in cassava tubers from the Khon Kaen municipal landfill area with those from other areas with potential sources of contamination indicated that the average levels of contamination in cassava tubers from the Khon Kaen landfill area were higher, with the exception of Pb (3.97) and Zn (21.83) in rural areas of Enugu State, Nigeria, As (5.14) and Pb (9.71) in Beluluane Industrial Park, Mozambique, Fe (127) and Pb (5.70) in Benin dumping site, and Cd (3.24) and Pb (2.08) in an automobile waste dumping site in Abia State, as shown in Table 3. The comparison highlights that despite the shift in waste management to a combined landfill and incineration method, the accumulation of waste and the leakage of leachate into agricultural areas still results in high levels of contamination in cassava, higher than in other comparison areas.

Table 2. *Permissible limit values for agricultural soil and food according to WHO/FAO.*

WHO/FOA Standard	Concentration (mg/kg)								Reference
	As	Cd	Cr	Fe	Mn	Ni	Pb	Zn	
Maximum permissible limit in food	2.0	0.02	1.30	425	500	67	0.03	99.4	(WHO/FOA, 2002; WHO/FOA, 2007; WHO/FOA, 2011)
Maximum permissible limit in agricultural soil	5.0	1.0	100	50000	2000	50	60	200	

Table 3. *Heavy metal contamination in cassava tubers from other studies***.**

Study area	Concentration (mg/kg)								Reference
	As	Cd	Cr	Fe	Mn	Ni	Pb	Zn	
Urban area Bodo City, Nigeria	-	0.01	0.84	118.6	5.04	0.01	0.02	-	(Dikioye et al., 2018)
Rural area in Enugu State, Nigeria	0.0012	0.0015	0.0067	41.79	7.30	1.79	3.97	21.83	(Orish et al., 2019)
Beluluane Industrial Park, Mozambique	5.14	0.04	0.43	-	-	0.57	9.71	5.4	(Mario et al., 2024)
Asphalt Quarry Company, Nigeria	-	0.02	0.39	0.00	0.16	0.05	0.09	-	(Chincdu et al., 2021)
Tarkwa, Ghana	0.009	0.007	0.05	-	-	3.7	0.18	7.6	(Bortey-Sam et al., 2015)
Benin dumping site, Nigeria	-	0.00	2.00	127	-	20	5.70	-	(Omorogieva and Tonjoh, 2020)
Automobile waste dumping site in Abia State, Nigeria	-	3.24	0.051	-	-	-	2.08	-	(Ogbonna et al., 2020)

Identify source of heavy metal in soil

The analysis of the correlation coefficients using the Pearson method to identify the sources of heavy metal contamination in the soil is shown in Table 4.

According to Howladar (2017), the correlation coefficient has four levels: 1) 0-0.4 indicates weak correlation, 2) 0.4-0.6 indicates moderate correlation, 3) 0.6-0.8 indicates strong correlation, and 4) 0.8-1 indicates very strong correlation.

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Table 4
Pearson correlation coefficient matrix of heavy metals contamination in contaminated agricultural soil

	As	Cd	Cr	Fe	Mn	Ni	Pb	Zn
As	1	0.082	0.236	0.145	-0.184	0.370	0.076	0.143
Cd		1	0.456	0.871^{**}	0.262	0.801^{**}	0.987^{**}	0.485
Cr			1	0.730^{**}	0.543^{*}	0.742^{**}	0.484	0.542^{*}
Fe				1	0.433	0.822^{**}	0.862^{**}	0.651^{**}
Mn					1	0.464	0.361	0.293
Ni						1	0.848^{**}	0.444
Pb							1	0.445
Zn								1

*** Correlation significant at the level of 0.05 (2-tailed), ** Correlation significant at the level of 0.01 (2-tailed)**

The pairwise correlation analysis at a significance level of 0.05 showed that the correlation between Ni-Cd, Ni-Fe, Fe-Cd, Ni-Pb, and Pb-Fe had a very strong correlation, Fe-Zn, Ni-Cr, and Fe-Cr had a strong correlation, and Mn-Cr and Zn-Cr had a moderate correlation. This indicates that the pairs of heavy metals are likely to originate from the same source of contamination (Polash et al., 2020), such as waste types releasing heavy metals into leachate that contaminates the soil.

Table 5. *Varimax rotated component matrix of heavy metal contamination in soil by PCA*

Parameter	Component 1	Component 2
As	0.239	0.892
Ni	0.929	0.135
Cd	0.883	-0.007
Mn	0.514	-0.603
Fe	0.954	-0.044
Zn	0.662	-0.002
Pb	0.899	-0.056
Cr	0.781	-0.032
Eigenvalue	4.733	1.182
% total of variance	59.167	14.777
Cumulative %	59.167	73.944

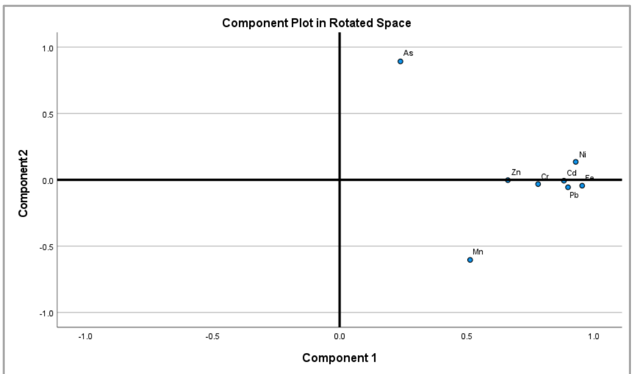

Figure 2. *Loading plot of PCA analysis of heavy metals in soil.*

The PCA analysis results of heavy metals in contaminated soil showed that the Kaiser Meyer Olkin (KMO) value and p-value were 0.630 and 0.000, respectively. This indicates that the data on heavy metal contamination in the soil can be analyzed for components to identify the sources of contamination using PCA analysis (KMO>0.6, p-value<0.05). The PCA results with the rotated component matrix are shown in Table 5 and Figure 2. The 1st component (PC1) consists of Mn, Ni, Cd, Cr, Fe, Pb, and Zn (59.167% of the total variance), while the 2nd component (PC2) consists of As (14.777% of the total variance). The PCA analysis combined with the field survey found that PC1 was caused by human activities, particularly the leakage of leachate from landfills into agricultural areas. In contrast, As in PC2 also results from human activities but originates from both leachate leakage and agricultural chemical use, especially pesticides (Chopra et al., 2007). This aligns with the findings of Banyam (2017), which showed contamination of Cd, Cr, Mn, Ni, Pb, and Zn in leachate, while As contamination was not detected in the leachate.

Transferring Factor and Bioaccumulation Factor

The analysis of the BCF and TF value of heavy metals in cassava was shown in Table 6. The results of the heavy metal accumulation in cassava tubers, as calculated by BCF, indicate that the trend in BCF values is as follows: Ni (5.837) > Zn (1.118) > Cr (1.217) > As (1.084) > Pb (0.648) > Cd (0.426) > Mn (0.264) > Fe (0.046). The heavy metals that were most effectively accumulated in the cassava tubers were Ni, Zn, Cr, and As (BCF>1), suggesting that cassava is a potential hyperaccumulator plant for Ni, Zn, Cr, and As. Regarding the translocation of metals from the tubers to the leaves and stems, the TF values demonstrated that Cd, Cr, Fe, Mn, Pb, and Zn exhibited the ability to translocate from the tuber to

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Table 6. *BCF and TF values of heavy metals in cassava plants.*

Indicator		As	Cd	Cr	Fe	Mn	Ni	Pb	Zn
Bioaccumulation factor		1.084	0.426	1.217	0.046	0.264	5.837	0.648	1.118
Transferring factor	tuber to leave	0.517	1.911	1.120	6.127	10.670	0.979	1.497	3.240
	tuber to stem	0.548	0.855	1.211	1.295	7.094	0.937	1.090	1.999

the leaves (TF tuber to leave > 1). Similarly, the metals that were effectively transported from the tuber to the stem (TF tuber to stem > 1) included Cr, Fe, Mn, Pb, and Zn. Based on accumulation and translocation in cassava through BCF and TF values, three groups of heavy metals can be identified. Group 1 consists of As and Ni, which are metals that accumulate well in the tuber but do not effectively translocate from the tuber to the leaves and stems. Group 2 consists of Cr and Zn, which accumulate well in the tuber and are also able to translocate to the leaves and stems. Group 3 consists of Cd, Mn, Fe, and Pb, which either accumulate minimally in the tuber or do not accumulate significantly at all, but the metals that do accumulate can effectively move to the shoots. Therefore, in agricultural areas where As and Ni contamination in the soil is present, cassava should not be cultivated in these areas. Doing so would result in the accumulation of As and Ni in the tubers, with little to no translocation of these metals to other parts of the plant (such as the leaves and stems), potentially posing health risks to humans through the consumption of the tubers.

Exposure assessment

The calculation of EDI for heavy metals through cassava tuber consumption is shown in Table 7. The trend in EDI values for both children and adults was

Table 7. *Estimated Daily Intake (EDI) of heavy metals through cassava tuber consumption*

Element	Estimated Daily Intake (mg/kg/day)	
	Children	Adult
As	1.288×10^{-3}	5.555×10^{-4}
Cd	9.791×10^{-5}	4.196×10^{-5}
Cr	2.685×10^{-2}	1.151×10^{-2}
Fe	1.463×10^{-1}	6.270×10^{-2}
Mn	1.841×10^{-2}	7.890×10^{-3}
Ni	3.412×10^{-2}	1.462×10^{-2}
Pb	1.737×10^{-3}	7.444×10^{-4}
Zn	2.287×10^{-2}	9.799×10^{-3}

as follows: Fe > Ni > Cr > Zn > Mn > Pb > Cd. Heavy metals were more readily absorbed in children compared to adults, primarily due to their lower body weight. As a result, children's EDI values are higher, with metals accumulating at a greater rate in their bodies. This finding is consistent with Qing et al. (2022), which observed that children's EDI values are 1.25 to 2.8 times higher than those of adults, largely due to body weight differences.

Non-carcinogenic health risk assessment

The results of the Non-Carcinogenic Health Risk Assessment, based on THQ and HI calculations, are shown in Table 8.

Table 8. *The values of THQ and HI for non-carcinogenic health risk, and the values of CR and TCR for carcinogenic health risk assessment through cassava tuber ingestion.*

Element	Target Hazard Quotient		Carcinogenic Risk	
	Children	Adult	Children	Adult
As	4.195	1.841	1.933×10^{-3}	8.283×10^{-4}
Cd	9.790×10^{-2}	4.196×10^{-2}	3.720×10^{-5}	1.595×10^{-5}
Cr	1.790×10^{-2}	7.671×10^{-3}	1.342×10^{-2}	5.753×10^{-3}
Fe	2.090×10^{-1}	8.958×10^{-2}	Not calculated	Not calculated
Mn	5.579×10^{-1}	2.391×10^{-1}	Not calculated	Not calculated
Ni	1.706	7.311×10^{-1}	2.866×10^{-2}	1.228×10^{-2}
Pb	1.241	5.317×10^{-1}	1.477×10^{-5}	6.328×10^{-6}
Zn	7.622×10^{-2}	3.267×10^{-2}	Not calculated	Not calculated
Total	HI = 8.200	HI = 3.514	TCR = 4.407×10^{-2}	TCR = 1.889×10^{-2}

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The THQ values for children from single metal exposure indicate the following trend: As > Ni > Pb > Mn > Fe > Cd > Zn > Cr. A similar trend is observed for adults. Specifically, the THQ values for As (4.195 for children, 1.841 for adults), Ni (1.706 for children), and Pb (1.241 for children) exceed the acceptable risk level (THQ > 1), indicating unacceptable health risk levels. The potential health effects include liver damage from Ni, kidney dysfunction, and neurological issues from Pb, and organ impairment from As (Ugonna et al., 2020; Prabhat et al., 2019; Shetty et al., 2025). Children exhibit higher THQ values than adults due to their lower body weight, resulting in higher EDI values. Interestingly, the THQ of As is high despite lower exposure, likely due to its low reference dose (RefD), which indicates higher toxicity even at low concentrations. Conversely, metals with higher RefD, such as Fe, show lower THQ, suggesting lower health risks. The Multi element exposure health risk, assessed using the HI, indicates a significant risk (HI > 1) for both children (8.200) and adults (3.514), with children at a greater risk. While some metals have acceptable THQ values individually, the combined effect of multiple metal exposures through cassava consumption leads to an unacceptable risk level. To mitigate this, waste management strategies should focus on enhancing landfill leachate containment to prevent continued contamination. Agricultural practices should also address the reduction of heavy metal contamination in cassava. Farmers, waste management operators, and industrial stakeholders should collaborate to employ technologies like nanotechnology, advanced washing technologies, and ion-exchange to minimize metal contamination in cassava before industrial processing (Seo et al., 2023). Additionally, cultivating crops with a low BCF, such as maize (Aladesanmi et al., 2019), near landfill sites could mitigate the accumulation of heavy metals in plant parts consumed by humans.

Carcinogenic health risk assessment

The results of the Carcinogenic Health Risk Assessment, based on the calculation of CR and TCR values for heavy metals such as As, Cd, Cr, Ni, and Pb through ingestion, are shown in Table 8. The analysis reveals that the trend of CR values for heavy metals in children is Ni > Cr > As > Cd > Pb, which is consistent with the trend for adults. For both groups, the assessment of carcinogenic risk from single metal exposure indicates unacceptable risk levels (CR > 10^{-4}) for As, Cr, and Ni in both children and adults. Cd and Pb fall into the acceptable risk category for both groups. No metals were found to have a risk level below the threshold for carcinogenic health impacts. The carcinogenic risks associated with the exposure to As, Cr, and Ni, which exceed the acceptable limits, could lead to various cancers, including: 1) Cd exposure leading to renal and kidney cancer (Rapisarda et al., 2018); 2) As exposure leading to urinary and bladder cancer (Jomova et al., 2024); 3) Cr exposure leading to gastrointestinal cancer (NTP, 2008); 4) Ni exposure causing respiratory system cancer and affecting carcinogenic processes (Mcgregon et al., 2000; Seikop and Oller, 2003); and 5) Long-term Pb exposure causing stomach and bladder cancer (Garcia et al., 2010; WHO, 2023). The multiple-element exposure assessment shows that the total carcinogenic risk, with TCR values exceeding the acceptable limit (TCR > 10^{-4}), is unacceptable for both children and adults. Specifically, the TCR for adults is 1.889×10^{-2}, while for children it is 4.407×10^{-2}, indicating a higher cancer risk for children. These findings highlight the unsuitability of cassava from the study area for consumption, as prolonged ingestion may lead to an increased risk of cancer, as also shown in the non-carcinogenic health risk assessment.

Conclusions

The contamination of heavy metals in soil and cassava, including tubers, leaves, and stems, showed the following trends: in the soil, the highest levels of contamination were Fe > Mn > Cr > Ni > Pb > As > Cd; in the cassava tubers, the highest levels were Fe > Ni > Cr > Zn > Mn > Pb > As > Cd; and in the cassava leaves, the highest levels were Fe > Mn > Zn > Ni > Cr > Pb > As. Significant differences in the contamination levels of As, Ni, Cd, Mn, Fe, and Zn were found between the soil and cassava at the 0.05 level. When comparing the levels of heavy metal contamination in the soil and cassava tubers to the permissible limits of WHO/FAO, the heavy metal contamination in the soil was found to be below the permissible limits. However, contamination levels of Cd, Cr, and Pb in the tubers exceeded the permissible limits. The source analysis of heavy metal contamination in the soil revealed that human activities contributed significantly to the contamination. PCA analysis identified 2 principal components: PC1 consisted of Ni, Cd, Mn, Fe, Zn, Pb, and Cr, which originated from leachate leakage into agricultural soil; PC2 consisted of As, which originated from both landfill

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operations and the use of chemicals in agriculture. The heavy metals that accumulated from the soil into cassava tubers were As, Cr, Ni, and Zn, while the metals that were capable of translocating from the tubers to the leaves were Cd, Cr, Fe, Mn, Pb, and Zn. The metals that were translocated from the tubers to the stems were Cr, Fe, Mn, Pb, and Zn. Health risk assessment analysis showed the trend of heavy metals entering the human body through ingestion, with the order being Fe > Ni > Cr > Zn > Mn > Pb > As > Cd in both children and adults. The non-carcinogenic health risk assessment revealed that the highest risks, based on THQ calculations, were from As, Ni, Pb, Mn, Fe, Cd, Zn, and Cr. Heavy metals exceeding acceptable levels for health risk were As in both children and adults, Ni and Pb in children. The multiple element exposure assessment revealed an unacceptable health risk (HI > 1) for both children and adults. The carcinogenic health risk assessment, based on multiple metal exposure, showed that the highest cancer risks were from Ni > Cr > As > Cd > Pb, with all heavy metals in children falling within the unacceptable health risk range (CR > 10^{-6}). Similarly, the carcinogenic health risk from multiple element exposure showed an unacceptable risk for both children and adults (TCR > 10^{-4}).

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References

ABDULLAH N.H., KEAN O.B., HIRMIZI N.M., YUSOFF N., MOHD A.R.N. (2020) Method Validation of Heavy Metals Determination in Traditional Herbal Tablet, Capsule and Liquid by Graphite Furnace Atomic Absorption Spectrometer and Flow Injec-tion for Atomic Spectroscopy Hydride System. Asian J. Pharmacogn, 4(3):37-45.

ALADESANMI O.T., OROBOADE J.G., OSISIOGU C.P., OSEWOLE A.O. (2019) Bioaccumulation Factor of Selected Heavy Metals in Zea mays. Journal of health & pollution, 9(24):191207. https://doi.org/10.5696/2156-9614-9.24.191207

AOAC (2002) AOAC Guidelines for Single Laboratory Validation of Chemical Methods for Dietary Supplements and Botanicals. AOAC, Washington, DC, USA.

ARIVALAGAN P., CHANDRAMOHAN G., ASHUTOSH S. (2024) Heavy metal accumulation in root and shoot tapioca plant biomass grown in agriculture land situated around the magnesite mine tailings. Environmental Research, 257:119287. https://doi.org/10.1016/j.envres.2024.119287

ASIAN DEVELOPMENT BANK (2015) THAILAND Industrialization and economic catch-up. ADB, Manila, Philippines.

AVILA P.F., FERREIRA S.E., CANDEIAS C. (2017) Health risk assessment through consumption of vegetables rich in heavy metals: the case study of the surrounding villages from Panasqueira mine, Central Portugal. Environmental Geochemistry and Health, 39:565–589.

BANYAM B. (2017) Contamination of Heavy Metals in Leachate, Groundwater and Soil at Khon Kaen Municipal Solid Waste Landfill, Khon Kaen Province. B.Sc. Thesis, Department of Earth Science, Faculty of Science, Kasetsart University, Thailand.

BORTEY-SAM N., NAKAYAMA S.M.M., AKOTO O., IKENAKA Y., FOBIL J.N., BAIDOO E., MIZUKAWA H., ISHIZUKA, M. (2015) Accumulation of Heavy Metals and Metalloid in Foodstuffs from Agricultural Soils around Tarkwa Area in Ghana, and Associated Human Health Risks. International Journal of Environmental Research and Public Health, 12(8):8811-8827. https://doi.org/10.3390/ijerph120808811

CHINEDU E.I., EVANS C.N., JOHN D.N., ENOS I.E., TOCHI E.E., ROSELINE F.N.T., ONYENONACHI C.I., EJEAGBA O.I., IKENNA N.N., ETIENNE C.C., CHIJIOKE N.U., CHINOMSO E.E., NWAOGWUGWU N.U. (2021) Heavy metal contamination of Cassava (Manihot esculenta Crantz) grown on quarry soils in Umunneochi Abia State and its health implications. EQA - International Journal of Environmental Quality, 45:1-9. https://doi.org/10.6092/issn.2281-4485/12563

CHOPRA B.K., BHAT S., MIKHEENKO I. P., XU Z., YANG Y., LUO X., CHEN H., ZWIETEN L., LILLEY R.M., ZHANG R. (2007) The characteristics of rhizosphere microbes associated with plants in arsenic-contaminated soils from cattle dip sites. Science of the Total Environment, 378(3):331–342.

CSIRO - Commonwealth Scientific and Industrial Research Organization (2021) Soil sampling guidelines strenthening regional collaboration on soil analysis. https://research.csiro.au/pacsoils/wp-content/uploads/sites/404/2021/12/2-Soil-sampling-manual.pdf

DOI: 10.6092/issn.2281-4485/21307

DIKIOYE E.P., CHARITY E., KPOBARI W.N. (2018) Potential Human Health Risk Assessment of Heavy Metals via Consumption of Root Tubers from Ogoniland, Rivers State, Nigeria. Biological Trace Element Research, 186:568–578. https://doi.org/10.1007/s12011-018-1330-1

DRAGOVIĆ S., MIHAILOVIĆ N., GAJIĆ B. (2008) Heavy metals in soils: distribution, relationship with soil characteristics and radionuclides and multivariate assessment of contamination sources. Chemosphere, 72(3):491-495. https://doi.org/10.1016/j.chemosphere.2008.02.063

GARCÍA L.J., MÉNDEZ J., PÁSARO E., LAFFON B. (2010) Genotoxic effects of lead: an updated review. Environment international, 36(6):623–636. https://doi.org/10.1016/j.envint.2010.04.011

WHO (2023) Exposure to lead: a major public health concern. WHO, Geneva, Switzerland.

HOWLADAR M.F. (2017) An Assessment of surface water chemistry with its possible sources of pollution around the Barapukuria thermal power plant impacted area, Dinajpur, Bangladesh. Groundwater for sustainable development, 5:38−48.

IRIS (2006) Integrated Risk Information System 2006. https://iris.epa.gov/AtoZ/?list_type=alpha.

JIANG M., ZENG G., ZHANG C., MA X., CHEN M., ZHANG J., LU L., YU Q., HU L., LIU L. (2013) Assessment of Heavy Metal Contamination in the Surrounding Soils and Surface Sediments in Xia-wangang River, Qingshuitang District. PLoS ONE, 8(8):71176. https://doi.org/10.1371/journal.pone.0071176

JOMOVA K., ALOMAR S.Y., NEPOVIMOVA E., KUCA K., VALKO M. (2025) Heavy metals: toxicity and human health effects. Archives of toxicology, 99(1):153–209. https://doi.org/10.1007/s00204-024-03903-2

KAMAL U., MOHAMMAD A.A.G., MOHAMMED H.A.D. (2019) The assessment of cadmium, chromium, copper, and nickel tolerance and bioaccumulation by shrub plant Tetraena qataranse. Scientific Reports, 9:5658. https://doi.org/10.1038/s41598-019-42029-9

KHON KAEN PROVINCIAL STATISTICAL OFFICE (2020) Municipal Solid Waste Management Situation in Khon Kaen Province, 2019. Khon Kaen Provincial authority, Khon Kaen, Thailand. (In Thai)

KIM I.S., KANG K.H., GREEN J.P., LEE E.J. (2003) Investigation of heavy metal accumulation in Polygonum thunbergii for phytoextraction. Environmental Pollution, 126(2):235-243. https://doi.org/10.1016/S0269-7491(03)00190-8

KOVÁCS B.É., DOMOKOS E., BIRÓ B. (2021) Toxic metal phytoextraction potential and health-risk parameters of some cultivated plants when grown in metal-contaminated river sediment of Danube, near an industrial town. Environ Geochem Health, 43:2317–2330. https://doi.org/10.1007/s10653-021-00880-8

LAND DEVELOPMENT DEPARTMENT OF THAILAND (2021) Land Use Zone for Economic Crops: Cassava. Land Development Department of Thailand, Bangkok, Thailand. (In Thai)

LATIF A., BILAL M., ASGHAR W., AZEEM M., AHMAD M.I. (2018) Heavy metal accumulation in vegetables and assessment of their potential health risk. J. Environ. Anal. Chem, 5(1):1000234.

LOCAL ADMINISTRATION DEPARTMENT OF THAILAND (2016) The "Thailand Zero Waste" Action Plan 2016-2017. Local Administration Department of Thailand and Pollution Control Department of Thailand, Bangkok, Thailand. (In Thai)

MÁRIO M., SÓNIA V.G., RUI S.O., CÉLIA M.M., ORLANDO A.Q. (2024) Assessment of heavy metals and human health risk associated with the consumption of crops cultivated in industrial areas of Maputo, Mozambique. Journal of Environmental Science and Health, Part A, 59(4):200-211. https://doi.org/10.1080/10934529.2024.2349478

McGREGOR D.B., BAAN R.A., PARTENSKY C., RICE J.M., WILBOURN, J.D. (2000) Evaluation of the carcinogenic risks to humans associated with surgical implants and other foreign bodies - a report of an IARC Monographs Programme Meeting. International Agency for Research on Cancer. European journal of cancer (Oxford, England : 1990), 36(3):307–313. https://doi.org/10.1016/s0959-8049(99)00312-3

NOURI J., KHORASANI N., LORESTANI B., KARAMI M., HASSANI A.H., YOUSEFI N. (2009) Accumulation of heavy metals in soil and uptake by plant species with phytoremediation potential. Environ Earth Sci, 59:315–323. https://doi.org/10.1007/s12665-009-0028-2

NTP-National Toxicology Program (2008). Toxicology and carcinogenesis studies of sodium dichromate dihydrate (Cas No. 7789-12-0) in F344/N rats and B6C3F1 mice (drinking water studies). National Toxicology Program technical report series, 546:1–192.

OMOBOLAJI O.A., MAUREEN O.U., ALEX I.A.F., TOOCHUKWU T.U., OKECHUKWU N.N.O., SUNDAY O.J., AUGUSTINE O.W. (2024) Assessment of heavy metal contents in farm produce around Ewekoro and its health implications on consumers. SN Appl. Sci., 5:340. https://doi.org/10.1007/s42452-023-05550-1

OGBONNA P.C., OSIM O.O., BIOSE E. (2020) Determination of Heavy Metal Contamination in Soil and Accumulation in Cassava (Manihot Esculenta) in Automo-

DOI: 10.6092/issn.2281-4485/21307

bile Waste Dumpsite at Ohiya Mechanic Village. NIJEST, 4(1):54-69.

OMOROGIEVA O.M., TONJOH J.A. (2020) Bioavailability of heavy metal load in soil, groundwater, and food crops manihot esculenta and carica papaya in dumpsite environment. International Journal of Environmental Science and Technology, 17:4853-4864. https://doi.org/10.1007/s13762-020-02812-y

ONYEDIKACHI U.B., BELONWU D.C., WEGWU M.O. (2018) Human health risk assessment of heavy metals in soils and commonly consumed food crops from quarry sites located at Isiagwu, Ebonyi State. Ovidius University Annals of Chemistry, 29(1):8 - 24.

ORISH E.E., HARRISON A.O., IFY L.N., ANTHONET N.E. (2019) Probabilistic health risk assessment of heavy metals in honey, Manihot esculenta, and Vernonia amygdalina consumed in Enugu State, Nigeria. Environ Monit Assess, 191(7):424. https://doi.org/10.1007/s10661-019-7549-2

PALASH K.D. ARIFA N., MOSUMMATH H.A. (2020) Health risks assessment of heavy metal contamination in drinking water collected from different educational institutions of Khulna city corporation, Bangladesh. Advances in Environmental Technology, 4:235-250. https://doi.org/10.22104/AET.2021.4932.1331

POLLUTION CONTROL DEPARTMENT OF THAILAND (2011) National 3Rs Strategy. Pollution Control Department of Thailand, Bangkok, Thailand. (In Thai)

POLLUTION CONTROL DEPARTMENT OF THAILAND (2022) Report on the Situation of Municipal Solid Waste Disposal Sites in Thailand in 2022. Pollution Control Department of Thailand, Bangkok, Thailand. (In Thai)

PRABHAT K.R., SANG S.L., MING Z., YIU F.T., KI H.K. (2019) Heavy metals in food crops: Health risks, fate, mechanisms, and management. Environment International, 125:365-385. https://doi.org/10.1016/j.envint.2019.01.067

PRANAV P.D., DEBLINA D. (2024) Landfill leachate a potential challenge towards sustainable environmental management. The Science of The Total Environment, 926(18):171668. https://doi.org/10.1016/j.scitotenv.2024.171668

QING L., XIAOHUI L., LEI H. (2022) Health risk assessment of heavy metals in soils and food crops from a coexist area of heavily industrialized and intensively cropping in the Chengdu Plain, Sichuan, China. Frontiers in Chemistry, 10:988587. https://doi.org/10.3389/fchem.2022.988587

RAPISARDA V., MIOZZI E., LORETO C. (2018) Cadmium exposure and prostate cancer: insights, mechanisms and perspectives. Front Biosci, 23(9):1687–1700. https://doi.org/10.2741/4667

SEILKOP S.K., OLLER A.R. (2003) Respiratory cancer risks associated with low-level nickel exposure: an integrated assessment based on animal, epidemiological, and mechanistic data. Regulatory toxicology and pharmacology, 37(2):173–190. https://doi.org/10.1016/s0273-2300(02)00029-6

SEO C., LEE J.W., JEONG J.W., KIM T.S., LEE Y., GANG G., LEE S.G. (2023) Current technologies for heavy metal removal from food and environmental resources. Food science and biotechnology, 33(2):287–295. https://doi.org/10.1007/s10068-023-01431-w

SHETTY B.R., JAGADEESHA P.B., SALMATAJ S.A. (2025) Heavy metal contamination and its impact on the food chain: exposure, bioaccumulation, and risk assessment. CyTA - Journal of Food, 23(1):2438726. https://doi.org/10.1080/19476337.2024.2438726

SUMONA M., SOUMYADEEP M., MOHD A.H., BHASKAR S.G. (2015) Contemporary Environmental Issues of Landfill Leachate: Assessment and Remedies. Critical Reviews in Environmental Science and Technology, 45(5):472-590. https://doi.org/10.1080/10643389.2013.876524

SUSTAINABLE ENVIRONMENT RESEARCH INSTITUTE (2023) Study Project for Developing Public Policy on Waste Management System Reform and Promotion of Circular Economy (Phase 2). Chulalongkorn University, Bangkok, Thailand. (In Thai)

UGONNA C.N., PRECIOUS O.O., NNEKA I.O. (2020) A Review of the Health Implications of Heavy Metals in Food Chain in Nigeria. The Scientific World Journal, 2020:6594109. https://doi.org/10.1155/2020/6594109

UNEP (2024) Beyond an age of waste Turning rubbish into a resource, UNEP, Nairobi, Kenya.

USEPA (1989) Risk assessment guidance for superfund. Human health evaluation manual (Part A) (Vol. 1). Office of Emergency and Remedial Response, Washington, DC, USA.

USEPA (1996) Microwave Assisted Acid Digestion of Siliceous and Organically Based Matrices, Method 3052. USEPA, Washington, DC, USA.

USEPA (2002a) Guidance on Choosing a Sampling Design for Environmental Data Collection. EPA QA/G-5S, USEPA, Washington, DC, USA.

DOI: 10.6092/issn.2281-4485/21307

USEPA (2002b) Treatment Technologies for Mercury in Soil, Waste, and Water. Office of Solid Waste and Emergency Response, Washington, DC, USA.

USEPA (2005) Guidelines for Carcinogen Risk Assessment. EPA/630/P-03/001F, Washington, DC, USA.

USEPA (2011) Exposure factors handbook 2011 edition). https://cfpub.epa.gov/ncea/risk/recordisplay.cfm?deid=236252.

USEPA (2012) Regional Screening Levels (Formerly PRGs)—Summary Table. http://www.epa.gov/region9/superfund/prg.

USEPA (2013) Integrated risk information system (IRIS):Assessments. https://cfpub.epa.gov/ncea/risk/recordisplay.cfm?deid=2776.

USEPA (2018) Inductively Coupled Plasma-Optical Emission Spectrometry (ICP-OES), Method 6010D, USEPA, Washington, DC, USA.

WHO/FAO (2002) Joint FAO/WHO General Standard for Contaminants and Toxins in Food and Feed, Shedule 1 Maximum and Guideline Levels for Contaminants and Toxins in Food. Rotterdam, The Nertherlands.

WHO/FAO (2007) Joint FAO/WHO Food Standard Programme Codex Alimentarius Commission on Food, 13th session. Houston, USA.

WHO/FAO (2011) Joint FAO/WHO Food Standard Programme Codex Alimentarius Commission on Food, Fifth Session. The Hague, The Netherlands.

WORLD BANK (2012) What A Waste: A global review of solid waste management. Washington, DC, USA.

WORLD BANK (2018) What a Waste 2.0: A Global Snapshot of Solid Waste Management to 2050. World bank, Washington, DC, USA.

YAN B., WEI Q., LI X., SONG X., GAO Z., LIU J., ZHANG R. WANG M. (2023) Heavy Metal Content Characteristics and Pollution Source Analysis of Shallow Groundwater in Tengzhou Coal Mining Area. Water, 15:4091. https://doi.org/10.3390/w15234091

YONG M.L., CUI L.Q., BING Z., HUI J. (2023) Development and validation of single-step microwave-assisted digestion method for determining heavy metals in aquatic products: Health risk assessment. Food Chemistry, 402:134500. https://doi.org/10.1016/j.foodchem.2022.134500