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Evaluation of heavy metal contamination and health risk analysis in landfill and agricultural soils

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ABSTRACT

This study assesses heavy metal contamination levels and health risks for residents living near the Bang Ban landfill and surrounding agricultural areas. A microwave digestion extraction method, an analysis through inductively coupled plasma atomic emission spectroscopy, and health risk assessments for heavy metals, including cadmium, copper, manganese, nickel, lead, and zinc, were conducted in accordance with United States Environmental Protection Agency standards. Results indicated that cadmium levels in agricultural soil, as well as copper and nickel levels in landfill areas, exceeded the established standards. The sources of heavy metal contamination in the study area were primarily attributed to leachate from the landfill and application of chemicals in agricultural practices. While the health risks associated with heavy metal exposure leading to non-cancer-related diseases, as calculated through the Hazard Index, were within acceptable limits, the assessment of total carcinogenic risk indicated a potential risk.

Keywords: Landfill, heavy metals, health risk assessment, contaminated soil, leachate runoff

INTRODUCTION

The current advancement of industrialization and the increasing global population have led to a significant rise in waste generation [1], with humans producing approximately two billion tonnes of waste annually [2]. When compared to historical data, the rate of waste generation has more than doubled, particularly in Africa and South Asia [3]. In Thailand, a similar upward trend in waste generation has been observed, aligning with global patterns. For instance, waste generation in Thailand increased from 15.03 million tonnes in 2008 to 25.37 million tonnes in 2020 [4], then reached 26.95 million tonnes in 2023, which equates to an average waste generation rate of 1.12 kg per person per day. A comparison of waste volumes between 2022 and 2023 indicates a 5% increase [5]. The rise in waste generation in Thailand can be attributed to several factors, including economic development, industrialization, population growth, and changes in lifestyle [6].

Consequently, various waste management processes have been developed, such as incineration, landfilling, and composting, even though some countries have still encountered limitations in technology, budget constraints, and inadequate areas available for waste management. In Thailand, the predominant method employed for waste management is landfilling, including both sanitary landfilling and open dumping. This method is mainly applied due to its suitability for managing municipal waste in high volumes. Moreover, landfilling effectively eliminates large quantities of waste without requiring complex technology or significant maintenance costs. However, municipal waste in Thailand is often not properly sorted at the source and frequently contains hazardous waste, including batteries, pesticides, and fluorescent lamps [7]. Consequently, the decomposition of waste in landfills can generate leachate, leading to the release of pollutants into the environment.

Common contaminants found in leachate include organic and inorganic pollutants [8], with heavy metals posing significant risks to living organisms and the environment. To mitigate excessive pollutant leakage into the environment, effective leachate collection and treatment systems are essential. Nevertheless, despite implementing robust preventive measures, incidents of leachate leakage into the environment persist. These occurrences are often attributed to factors such as topography [9], climatic conditions [10], and unforeseen events, including leachate runoff during rainy seasons, landfill integrity failures, and natural and anthropogenic disasters (e.g., floods and fires). Therefore, it can be posited that leachate leakage from landfills may arise from two primary factors: 1) human activities; and 2) natural phenomena. Leachate leakage from landfill sites directly affects the environment, impacting surface water, groundwater, soil, and surrounding agricultural areas. The soil is particularly susceptible to the effects of leachate contamination, as it can readily absorb pollutants, especially heavy metals. The absorption of heavy metals by soil can lead to significant contamination issues, adversely impacting human health through pathways such as inhalation of contaminated soil and the transfer of heavy metals through the food chain from producers (plants) to consumers (humans).

To address these concerns, the U.S. Environmental Protection Agency (USEPA) [11] has developed methods for assessing health risks associated with direct exposure to heavy metals. This assessment includes: 1) evaluating exposure to heavy metals through inhalation, dermal contact, and incidental ingestion; 2) assessing non-cancer health impacts, which considers the individual metal components using hazard quotient calculations and multiple metal components through hazard index calculations; and 3) evaluating cancer-related health impacts by assessing the risks associated with individual metal components and multiple metal components via carcinogenic risk and total carcinogenic risk calculations.

The objectives of this research include investigating heavy metal contamination in soil and assessing the health impacts of heavy metal exposure. The study findings aim to provide valuable insights for improving landfill management practices in the future and contribute to the establishment of a database for studying heavy metal contamination in Thailand. This information may assist relevant national agencies in formulating regulations governing landfill operations and enforcing waste management laws.

EXPERIMENTAL

Study site and sample collection: The study site is located at the Bang Ban Landfill in Bang Ban District, Phra Nakhon Si Ayutthaya Province. This landfill manages the disposal of waste generated in the municipal area of Ayutthaya and handles hazardous waste for local government agencies within the province. The hazardous waste managed in the area includes batteries, fluorescent lamps, and hazardous waste generated within administrative facilities. Therefore, the research hypothesizes that heavy metal contamination in the soil of the landfill and surrounding agricultural areas originates from landfill operations and human activities in the area surrounding the landfill. Surface soil samples were collected from the surface layer at a depth of 0-15 cm. utilizing a soil sampling tool. The reason for collecting soil samples from the surface soil layer is that this layer is most likely to be directly exposed to the human body and pose potential health impacts. The sampling plan utilized simple random sampling techniques and composite sampling methods for soil collection [12] at each sampling point during the rainy season (May 2023). The soil in the landfill area was divided into two zones: 1) soil from within the landfill site; and 2) soil from selected agricultural areas adjacent to the landfill, which is commonly affected by leachate runoff during the rainy season. A total of 5 soil sampling points were established within the landfill area (sample ID L1-L5) and 7 points in the agricultural areas (sample ID A1-A7). The soil sampling in the landfill area was conducted following the soil sampling methodology outlined in the IAEA and Thailand guidelines [12, 13] to ensure comprehensive coverage of the entire landfill area in all directions. For agricultural areas, soil samples were collected from locations most affected by leachate runoff, and samples were randomly taken to cover the agricultural land in accordance with the soil sampling methodology for agricultural areas in Thailand [12]. The geographic coordinates of the sampling points and the sampling area layout are illustrated in Fig. 1. At each sampling point, approximately 1 kg. of soil was collected and stored in high-density polyethylene (HDPE) bags. To preserve sample integrity in the field, soil samples were kept in a cooler box at temperatures below 6 °C and protected from light during transportation to the laboratory [14]. When the soil samples arrived at the laboratory, they were air-dried for 48 hours or until the weight of the soil stabilized. Subsequently, the dried samples were sieved through a No. 10 mesh sieve [15], and the sieved soil samples were stored at 4 °C until further extraction and analysis of heavy metals were conducted [16].

Analytical process: The analysis of heavy metal contamination, including cadmium (Cd), copper (Cu), manganese (Mn), nickel (Ni), lead (Pb), and zinc (Zn) in the soil, was performed using microwave-assisted acid digestion followed by analysis through inductively coupled plasma atomic emission spectroscopy (ICP-AES).The microwave digestion was performed using a microwave digestion system (PerkinElmer Titan MPS series), and the heavy metals were analyzed with a ICP-AES (PerkinElmer 8300 series), adhering to the USEPA methods 3051A [17] and 6010D [18], respectively. The analytical procedure involved the following steps. First, a sieved soil sample weighing 0.5 g was placed into a digestion tube (microwave digestion vessel). Subsequently, 3 ml of concentrated

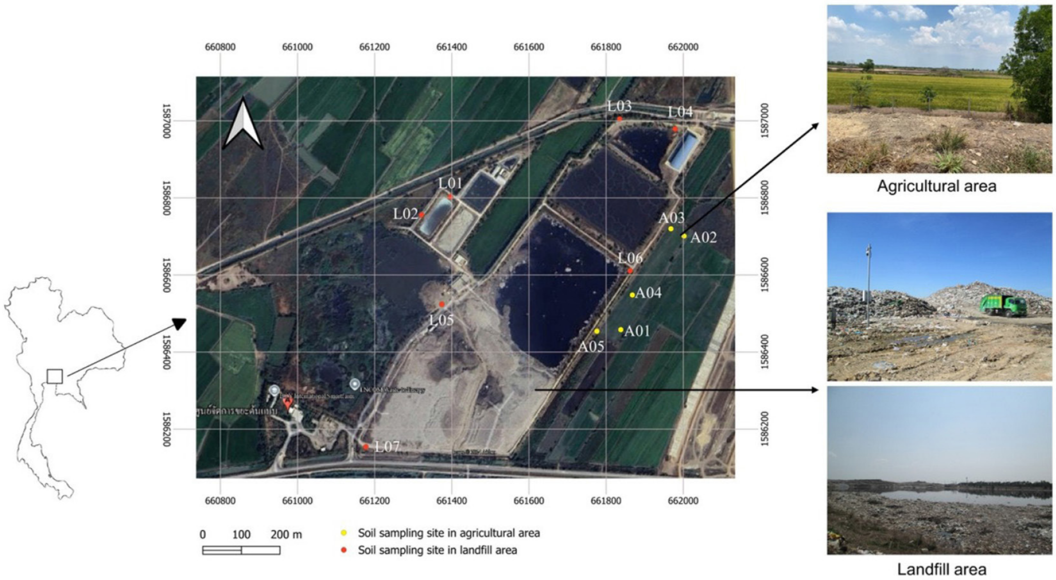

Fig. 1. Geographic coordinates of soil sampling points in study area, created using QGIS

hydrochloric acid (ThermoFisher, UK) and 9 ml of concentrated nitric acid (Kemaus, Australia) were added for overnight digestion without heating. After a night of pre-digestion, the digestion tube was closed and loaded into the microwave digestion system, with the temperature set at 175 °C for a duration of 10 minutes [19]. Upon completion of the digestion process, the samples were allowed to cool to room temperature before being filtered through Whatman filter paper No. 42, with a pore size of 2.5 µm. The filtrate was then adjusted to a final volume of 50 ml. The digested soil samples were analyzed for heavy metals using ICP-AES, with specific wavelengths selected for each element: Cd at 226.502 nm, Cu at 324.654 nm, Mn at 257.610 nm, Ni at 231.604 nm, Pb at 220.353 nm, and Zn at 213.856 nm.

Quality control and quality assurance: To ensure quality control during testing, all glassware and instruments involved in the digestion and analysis processes were immersed in a 10% nitric acid solution overnight and then thoroughly dried before use. The quantification of heavy metals involved the creation of a standard curve by diluting standard heavy metal solutions with Milli-Q water. The linearity of the standard curve was tested using the correlation coefficient (R^2). The precision and accuracy of heavy metal analysis using ICP-AES were set to have a relative standard deviation (RSD) of 5% based on triplicate determinations of concentration. The percent recovery for the analysis was compared with the average of a certified reference material (Sigma-Aldrich, Switzerland). The results indicated that R^2 from the standard curves for Cd, Cu, Mn, Ni, Pb, and Zn ranged from 0.99953 to 0.999987, which is within the acceptable range of $R^2 > 0.995$. Additionally, the percentage recovery ranged from 102% to 110%, falling within the acceptable range of 80–120% recovery. Thus, the values for R^2, % recovery, and RSD were within the standard quality control parameters for the analysis [20-22].

Statistical analysis: The data are presented as mean ± standard deviation (SD) from triplicate analyses. Pearson's correlation analysis and Principal Component Analysis (PCA) with varimax rotation and Kaiser normalization were employed to identify potential sources of heavy metal contamination in soil. The Pearson correlation coefficient was used to determine relationships between each pair of heavy metals [23], while PCA was used to identify hypothetical sources of contamination [24]. All statistical analyses were conducted using the SPSS software.

Health risk assessment: The health risk assessment framework developed by the USEPA [11] was used in this research to evaluate potential health risks associated with exposure to heavy metals in contaminated soil. This assessment considers risks related to inhalation, dermal contact, and incidental ingestion of soil contaminants. The health risk assessment is divided into three components: exposure assessment, non-carcinogenic health risk assessment, and carcinogenic health risk assessment [25, 26].

Exposure assessment: This step identifies the pathways through which toxic substances enter the body and quantifies the intake via inhalation, dermal contact, and ingestion, as shown in Equations (1-3).

$$CDIing = \frac{Cs \times IngR \times EF \times ED \times CF}{BW \times AT} \quad (1)$$

$$CDIder = \frac{Cs \times SA \times AF \times EF \times ABS \times ED \times CF}{BW \times AT} \quad (2)$$

$$CDIinh = \frac{Cs \times InhR \times EF \times ET \times ED}{BW \times AT \times PEF} \quad (3)$$

Where, CDI represents the average daily intake of heavy metals through ingestion (CDIing), dermal contact (CDIder), and inhalation (CDIinh) in units of mg/kg/day; C is the concentration of heavy metals in soil (mg/kg dry weight); IngR is the soil ingestion rate (200 mg/day for children, 100 mg/day for adults) [27]; EF is the exposure frequency (350 days/year for both children and adults) [27]; ED is the exposure duration (6 years for children, 30 years for adults) [28]; BW is body weight (15 kg for children, 70 kg for adults) [19]; AT is the average time (ED x 365 days) [29]; SA represents the exposed skin surface area (4350 cm^2 for adults, 1600 cm^2 for children) [28]; AF is the skin adherence factor (0.2 mg/cm^2 for children, 0.07 mg/cm^2 for adults) [29]; ABS is the dermal absorption factor (0.001 for Cd, Cu, Mn, Ni, Pb, and Zn) [29]; InhR is the inhalation rate of soil (7.6 m^3/day for children, 20 m^3/day for adults) [11,30]; and PEF is the particle emission factor (1.36×10^{-9} m^3/kg for both children and adults) [29]; CF is conversion factor (10^{-3} kg/mg for both children and adults) [11].

Non-carcinogenic health risk assessment: This assessment evaluates the health risks associated with exposure to individual heavy metals present in contaminated soil through each exposure pathway. The risk is quantified by calculating the Hazard Quotient (HQ) as shown in equations (4-6), determined by the ratio of the chronic daily intake (CDI) to the reference dose (RfD) [11]. Cumulative health risks from exposure to multiple heavy metals across all exposure pathways are assessed by calculating the hazard index (HI), as shown in equation (7) [11].

$$HQing = \frac{CDIing}{RfDing} \quad \textbf{(4)}$$

$$HQder = \frac{CDIder}{RfDder} \quad \textbf{(5)}$$

$$HQinh = \frac{CDIinh}{RfDinh} \quad \textbf{(6)}$$

$$HI = \sum_{i=1}^{n} HQi \quad \textbf{(7)}$$

Where, HQing represents the ingestion hazard quotient; HQder denotes the dermal absorption hazard quotient; HQinh indicates the inhalation hazard quotient; RfDing is the ingestion reference dose (mg/kg day); RfDder is the dermal absorption reference dose (mg/kg day); RfDinh is the inhalation reference dose (mg/kg day); and HI represents the hazard index

Carcinogenic health risk assessment: The carcinogenic health risk assessment evaluates the risk associated with exposure to heavy metals known to potentially cause cancer through ingestion, dermal contact, and inhalation. The health risk from exposure to individual heavy metals is quantified using the carcinogenic risk (CR), which is calculated according to Equations (8-10) [25]. Furthermore, the cumulative health risk from multiple heavy metals is assessed by calculating the total carcinogenic risk (TCR) using equation (11).

$$CRing = CDIing \times SFing \quad \textbf{(8)}$$

$$CRder = CDIder \times SFder \quad \textbf{(9)}$$

$$CRinh = CDIinh \times SFinh \quad \textbf{(10)}$$

$$TCR = \sum_{i=1}^{n} CRi \quad \textbf{(11)}$$

Where CR represents the carcinogenic risk of individual carcinogenic metals through ingestion (CRing), dermal absorption (CRder), and inhalation (CRinh); SF is the slope factor for each individual metal through ingestion (SFing), dermal absorption (SFder), and inhalation (SFinh) measured in units of mg/kg/day; and TCR denotes the total carcinogenic risk.

The reference dose and slope factor values are presented in Table 1. The interpretation and results of the non-carcinogenic health risk assessment, based on the calculated HQ and HI values, and the carcinogenic health risk assessment, based on the calculated CR and TCR values, are summarized in Table 2.

RESULTS AND DISCUSSION

Evaluation of heavy metals in soil: The analysis results for Cd, Cu, Mn, Ni, Pb, and Zn contamination in the study area, along with soil heavy metal standard values and contamination data from other landfills reviewed in the literature, are presented in Table 3. The findings revealed that in agricultural soils near the landfill, Mn had the highest concentration, followed by Zn, Ni, Cu, Pb, and Cd. In contrast, landfill soils exhibited the highest levels of Cu, followed by Ni, Mn, Zn, Pb, and Cd. The ability of the soil in the study area to effectively adsorb heavy metals is largely attributed to its distinctive properties. Intorpetch [32] identified a high clay mineral content in the soil through sampling and analysis. Additionally, Pakvilai [33] utilized geophysical surveying methods, specifically resistivity testing, to examine the soil types and characteristics within the landfill and adjacent agricultural areas. The study revealed that soil layers at depths of 0–10 meters consist of clay, clayey silt, silty sand, and sand, respectively. These findings underscore the prevalence of clay minerals in the upper soil layers, which play a critical role in enhancing the soil's capacity to adsorb heavy metals. When comparing the average heavy metal contamination with international standards set by the CCME, Finnish government, and WHO/FAO, Cd in agricultural soils exceeded permissible limits established by the CCME for agricultural soils and the Finnish government. In landfill soils, Cu and Ni

Table 1. Reference doses and cancer slope factors for heavy metals [11, 31]

Index	Cadmium	Copper	Manganese	Nickel	Lead	Zinc
Refing	1.00×10^{-3}	4×10^{-2}	4.70×10^{-2}	2.00×10^{-2}	1.4×10^{-3}	0.3
Refder	2.5×10^{-5}	1.2×10^{-2}	1.84×10^{-3}	5.40×10^{-3}	5.24×10^{-4}	6×10^{-2}
Refinh	1.00×10^{-3}	4×10^{-2}	1.43×10^{-5}	2.06×10^{-2}	3.52×10^{-3}	0.3
CFing	0.0038			1.7	0.0085	
CFder				42.5		
CFinh	6.3				0.042	

Table 2. Interpretation of non-carcinogenic health risk assessment using HI and HQ and carcinogenic health risk assessment using CR and TCR [11]

Health risk assessment index	Value range	Classification
Hazard quotient (HQ) and Hazard index (HI)	HQ, HI < 1	No human health risk of non-carcinogenic health effects
	HQ, HI > 1	No obvious human health risk of carcinogenic health effects
Carcinogenic risk (CR) and Total carcinogenic risk (TCR)	CR, TCR $<10^{-6}$	No obvious human health risk of carcinogenic health effects
	10^{-6} < CR, TCR < 10^{-4}	Adverse carcinogenic health effects on human health, but within acceptable limits
	CR, TCR > 10^{-4}	Adverse carcinogenic health effects on human health and unacceptable

Table 3. Comparison of heavy metal concentrations (mg/kg dry weight) in soil samples from Bang Ban landfill (N=36) with international standards and similar studies from other landfill areas reported in the literature.

Present study								
Area	Sample ID		Concentration of heavy metals in soil (mg/kg dry weight)					
			Cd	Cu	Mn	Ni	Pb	Zn
Agricultural area	A01	mean	1.60	29.90	99.85	17.90	6.10	62.45
		SD	0.072	0.226	1.760	0.292	0.720	0.250
	A02	mean	1.80	28.8	90.45	18.45	6.95	63.05
		SD	0.100	0.212	1.003	0.200	0.931	0.103
	A03	mean	1.25	31.10	133.10	21	3.80	54.40
		SD	0.112	0.363	10.830	0.343	0.665	0.222
	A04	mean	1.50	32.15	83.20	20.75	2.20	51.15
		SD	0.010	0.450	0.083	0.150	0.065	0.073
	A05	mean	3.35	15.40	631	69.25	7.90	103.90
		SD	0.220	0.080	0.358	0.380	0.437	0.380
	Average concentration in agricultural area		1.9	27.48	207.52	29.47	5.39	66.99
Landfill area	L01	mean	0.05	17.85	248.2	9.35	4.2	37.2
		SD	0.052	0.370	0.630	0.205	0.212	0.20
	L02	mean	1.65	23.25	279	12.4	3.05	44.7
		SD	0.171	0.243	1.63	3.115	0.492	0.403
	L03	mean	1.5	39.65	221.7	21.15	6.55	70.05
		SD	0.115	0.345	2.002	0.146	0.934	0.632
	L04	mean	1.2	21.3	57.25	17.95	3.1	41.25
		SD	0.113	0.113	0.240	0.223	0.28	0.150
	L05	mean	1.35	23.75	189.65	13.9	7.55	61.45
		SD	0.066	0.210	0.380	0.173	0.613	0.103
	L06	mean	1.05	54.2	139.1	16.3	2.9	44.4
		SD	0.131	0.225	0.720	0.060	0.229	0.060
	L07	mean	-	6005	100.55	1228	15.35	111.4
		SD	Not detected	86.400	1.103	11.250	0.328	0.513
	Average concentration in landfill area		0.971	883.57	182.46	188.44	6.10	70.11
Average concentration in Bang Ban landfill			1.36	526.86	189.42	122.20	5.80	62.12

Literature review of heavy metals concentration in soil sample from dumping site in other study							
Locations		Cd	Cu	Mn	Ni	Pb	Zn
Ngaliema Mimosa landfill, Congo [34]		7.20	677.54	-	-	452.68	600.39
Khulna landfill, Bangladesh [35]		0.80	-	661.63	-	188.67	-
Amakom Dumpsite, Ghana [36]		5.9	347	-	34	309	-
Iwofe Landfill, Nigeria [37]		2.4	26.2	349	23.4	27.9	131
Tehran landfill, Iran [38]		0.42	61.6	1150.5	24.5	32.3	109
Kaifeng land-fill, China [39]	Farmland soil	1.27	52.30	-	200.41	33.72	258.07
	Landfill soil	1.82	128.58	-	252.31	80.57	486.57
Standard of heavy metals concentration in soil, ppm							
Standard		Cd	Cu	Mn	Ni	Pb	Zn
Maximum permissible limit for agricultural soil established by Canadian Council of Ministers of the Environment (CCME) [40]		1.4	63	-	45	70	250
Maximum permissible of industrial soil established by Canadian Council of Ministers of the Environment (CCME) [40]		22	91	-	89	600	410
Threshold limit value established by government of Finland [41]		1	100	-	50	60	200
Maximum permissible levels established by WHO/FOA [42, 43]		3	100	2000	50	100	300

concentrations surpassed the limits for all standards. A comparison of average heavy metal concentrations in the study area with other landfill sites worldwide indicated that Mn, Pb, and Zn contamination levels at Bang Ban were lower. However, Cd, Cu, and Ni levels were higher than in other contaminated areas. Specifically, (1) Cd levels exceeded those in soils at Khulna, Tehran, and agricultural soils near Kaifeng dumping sites; (2) Cu levels were higher than in all locations except Ngaliema Mimosa landfill; and (3) Ni levels were greater than those in soils at Amakom, Tehran, and Iwofe dumping sites.

Heavy metals source analysis: The inter-relationships between pairs of heavy metals were analyzed using Pearson correlation coefficients, as presented in Table 4. Additionally, PCA was employed to further investigate contamination sources, with results shown in Table 5 and Fig. 2. Positive correlations, such as those between Cu-Ni, Cu-Pb, Ni-Pb, Pb-Zn, Cd-Mn, Cu-Zn, Ni-Zn, and Mn-Zn, suggest a common source for these metals, while negative correlations, including Cd-Cu and Cd-Ni, indicate distinct origins [58-60]. The results of the PCA of heavy metal contamination in soil are presented in Table 5 and Fig. 2. The data used for the PCA was deemed appropriate for statistical analysis, as indicated by a Kaiser-Meyer-Olkin (KMO) value greater than 0.5 (KMO = 0.572) and a Bartlett's Test P-value of less than 0.001 (p-value = 0.0000) [44]. The PCA results identified two components that accounted for 91.227% of the total variance. The first component (PC1) exhibited a strong correlation with Cu, Ni, Pb, and Zn, while the second component (PC2) showed a strong correlation with Cd and Mn. The rotated component matrix utilizing varimax with Kaiser normalization demonstrated that the total variance of PC1 and PC2 was 58.197% (eigenvalue = 3.492) and 33.029% (eigenvalue = 1.982), respectively.

Table 4. Correlation coefficient of heavy metals in soil using Pearson's correlation

	Cd	Cu	Mn	Ni	Pb	Zn
Cd	1	-0.498**	0.621**	-0.464**	-0.156	0.241
Cu		1	-0.182	0.999**	0.825**	0.658**
Mn			1	-0.144	0.100	0.407*
Ni				1	0.836**	0.688**
Pb					1	0.865**
Zn						1

* p-value < 0.05; ** p-value < 0.01

Table 5. Rotation component matrix of heavy metals in the study area

Element	PC1	PC2
Cd	-0.228	0.901
Cu	0.932	-0.323
Mn	0.088	0.885
Ni	0.944	-0.282
Pb	0.953	0.065
Zn	0.874	0.447
Ergen value	3.492	1.982
% of variance	58.197	33.029
Cumulative % variance	58.197	91.227

Comparative studies of heavy metal contamination in areas of Ayutthaya without pollution sources indicated that the contamination levels of heavy metals in the Bang Ban landfill exceeded those in other areas of Ayutthaya Province, such as Uthai District, particularly for Cd, Cu, and Zn. This suggests that the contamination in the Bang Ban landfill and the surrounding agricultural areas results from anthropogenic activities in the study area. PC1, which includes Cu, Ni, Pb, and Zn, is attributed to leachate runoff during the rainy season from the landfill.

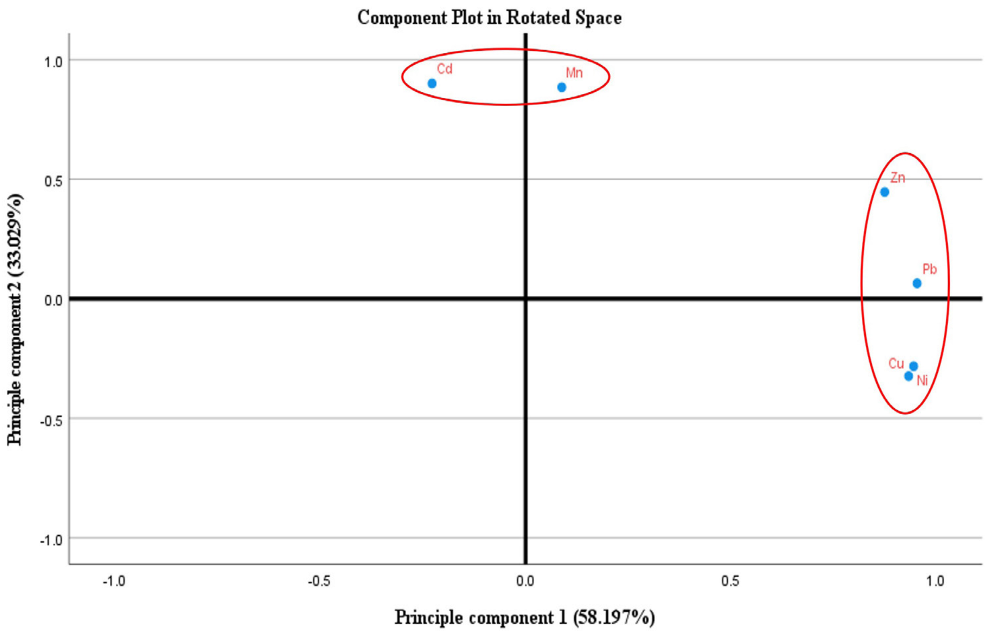

Fig. 2. Loading plot of PCA analysis of heavy metals concentration in soil

The leachate is caused by the decomposition of hazardous waste within the landfill. For example, Ni is linked to the degradation of battery and plating waste, while Cu and Zn derive from the breakdown of electronic and plastic waste. Pb contamination results from the decomposition of electronic waste, batteries, glass, and paint. In contrast, PC2, which includes Mn and Cd, is associated with the leaching of contaminated leachate into the soil, combined with agricultural sources due to the use of heavy metal-contaminated chemicals. For instance, Cd originates from the decomposition of glass and battery waste, plastic, and the application of fertilizers, whereas Mn is linked to alloy metals, cosmetic waste, fertilizers, and pesticides. These findings provide insight into the sources of heavy metal contamination in the soil and are consistent with the research hypothesis.

Exposure assessment: The assessment of exposure to heavy metals was quantified through the Chronic Daily Intake, including CDIing, CDIder, and CDIinh, from contaminated soil in the landfill and agricultural areas, as presented in Table 7. The study identified ingestion as the primary route of heavy metal exposure in both agricultural and landfill areas, followed by dermal contact and inhalation. Children are more vulnerable than adults, with higher contaminant intake. In agricultural areas, Mn posed the highest exposure risk for children and adults via ingestion, while Cd had the lowest risk through inhalation. In landfill areas, Cu was the highest risk for children and adults through ingestion, with Cd again being the lowest through inhalation.

Non carcinogenic health risk assessment: Non-carcinogenic health risks associated with heavy metal exposure in agricultural and landfill areas were assessed by calculating the HQ and HI, as summarized in Table 7. The evaluation revealed that Mn exhibited the highest HQ values for both children and adults through ingestion in agricultural areas. Similarly, Cu had the highest HQ values for children and adults through ingestion in landfill areas. In contrast, Zn showed the lowest HQ values for both children and adults via inhalation in both areas. The predominant pathway of exposure to heavy metals in both agricultural and landfill areas was ingestion, followed by dermal contact and inhalation, respectively. However, for Mn, the pathway associated with the highest risk was ingestion, followed by inhalation and dermal exposure. The elevated health risk associated with Mn inhalation, compared to dermal exposure, can be attributed to its neurotoxic effects, which may occur even at low exposure levels. Inhalation serves as a critical route for Mn entry into the body, thus directly impacting the nervous system. This mechanism elucidates why Mn poses a greater health risk through inhalation than through dermal contact.

The HQ calculations indicated that the values for Cd, Cu, Mn, Ni, Pb, and Zn, across ingestion, dermal contact, and inhalation, were consistently less than 1 in both agricultural and landfill areas. This finding suggests that exposure to these metals does not result in substantial health impacts or risks associated with non-carcinogenic diseases. Moreover, the assessment of non-carcinogenic health risks from multiple metal exposures, evaluated through HI calculations, indicated that heavy metal exposure does not pose considerable health risks in either agricultural or landfill areas, as all HI values were below 1.

Notably, the risk associated with metal exposure in landfill areas was higher than in agricultural areas, with children exhibiting greater vulnerability than adults (HI for children > HI for adults).

Table 6. Assessment of heavy metal exposure based on CDI value from agricultural and landfill soil through ingestion, dermal contact, and inhalation pathways

Area	Element	Chronic daily intake of heavy metals (mg/kg/day)					
		Children			Adult		
		CDIingC	CDIderC	CDIinhC	CDIingA	CDIderA	CDIinhA
Agricultural area	Cd	2.43×10^{-5}	3.89×10^{-8}	6.79×10^{-10}	2.60×10^{-6}	7.93×10^{-9}	3.83×10^{-10}
	Cu	3.51×10^{-4}	5.62×10^{-7}	9.82×10^{-9}	3.76×10^{-5}	1.15×10^{-7}	5.54×10^{-9}
	Mn	2.65×10^{-3}	4.25×10^{-6}	7.41×10^{-8}	2.84×10^{-4}	8.66×10^{-7}	4.18×10^{-8}
	Ni	3.77×10^{-4}	6.03×10^{-7}	1.05×10^{-8}	4.04×10^{-5}	1.23×10^{-7}	5.94×10^{-9}
	Pb	6.89×10^{-5}	1.10×10^{-7}	1.93×10^{-9}	7.38×10^{-6}	2.25×10^{-8}	1.09×10^{-9}
	Zn	8.57×10^{-4}	1.37×10^{-6}	2.39×10^{-8}	9.18×10^{-5}	2.79×10^{-7}	1.35×10^{-8}

Table 7. Non-carcinogenic health risk assessment of heavy metals in agricultural and landfill soil through ingestion, dermal contact, and inhalation pathways

Area	Group	Element	Noncarcinogenic health risk assessment			
			HQing	HQder	HQinh	HI
Agricultural area	Children	Cd	2.43×10^{-2}	1.55×10^{-3}	6.79×10^{-7}	1.699×10^{-1}
		Cu	8.78×10^{-3}	4.68×10^{-4}	2.45×10^{-7}	
		Mn	5.65×10^{-2}	2.31×10^{-3}	5.18×10^{-3}	
		Ni	1.88×10^{-2}	1.12×10^{-4}	5.11×10^{-7}	
		Pb	4.92×10^{-2}	2.10×10^{-4}	5.47×10^{-7}	
		Zn	2.86×10^{-3}	2.28×10^{-5}	7.98×10^{-8}	
	Adult	Cd	2.60×10^{-3}	3.17×10^{-4}	3.83×10^{-7}	2.098×10^{-2}
		Cu	9.41×10^{-4}	9.55×10^{-6}	1.38×10^{-7}	
		Mn	6.05×10^{-3}	4.70×10^{-4}	2.92×10^{-3}	
		Ni	2.02×10^{-3}	2.28×10^{-5}	2.88×10^{-7}	
		Pb	5.27×10^{-3}	4.29×10^{-5}	3.08×10^{-7}	
		Zn	3.06×10^{-4}	4.66×10^{-6}	4.50×10^{-8}	
Landfill area	Children	Cd	1.24×10^{-2}	7.95×10^{-4}	3.47×10^{-7}	5.335×10^{-1}
		Cu	0.282	1.51×10^{-3}	7.89×10^{-6}	
		Mn	4.96×10^{-2}	2.03×10^{-3}	4.56×10^{-3}	
		Ni	0.12	7.14×10^{-4}	3.27×10^{-6}	
		Pb	5.57×10^{-2}	2.38×10^{-4}	6.19×10^{-7}	
		Zn	2.99×10^{-3}	2.39×10^{-5}	8.35×10^{-8}	
	Adult	Cd	1.33×10^{-3}	1.62×10^{-4}	1.96×10^{-7}	5.976×10^{-2}
		Cu	3.03×10^{-2}	3.07×10^{-4}	4.45×10^{-6}	
		Mn	5.32×10^{-3}	4.14×10^{-4}	2.57×10^{-3}	
		Ni	1.29×10^{-2}	1.46×10^{-4}	1.84×10^{-6}	
		Pb	5.97×10^{-3}	4.86×10^{-5}	3.49×10^{-7}	
		Zn	3.20×10^{-4}	4.87×10^{-6}	4.71×10^{-8}	

Carcinogenic health risk assessment: The results of the calculations for CR and TCR for agricultural areas and landfill sites are presented in Table 8. The results of the CR calculations for individual heavy metals revealed that Ni had the highest CR values among children from accidental ingestion in both the landfill and agricultural areas. Conversely, Pb exhibited the lowest CR in adult and children through inhalation in both the landfill and agricultural areas.

The assessment of cancer risk from individual metals indicated that exposure to Ni through ingestion posed a cancer risk in children, with CR values of

6.41 x 10^{-4} in agricultural areas and 4.10 x 10^{-3} through ingestion and 1.64 x 10^{-4} through dermal contact in landfill areas. Additionally, adults exhibited a CR of 4.39 x 10^{-4} through ingestion in landfill areas. These values fall within the unacceptable risk threshold (CR > 10^{-4}). In contrast, exposure to Ni through dermal contact in children (2.56 x 10^{-5}) and ingestion in adults (6.86 x 10^{-5}), along with dermal exposure in adults (3.34 x 10^{-5}) in agricultural areas, presented an acceptable risk level (10^{-6} < CR < 10^{-4}). Therefore, prolonged exposure to Ni in soil can result in the development of cancers, specifically lung cancer and nasal cancer.

The TCR calculations based on multiple elements revealed that the TCR values for children (4.26 x 10^{-3}) and adults (4.723 x 10^{-4}) in landfill areas were higher than those in agricultural areas, where the TCR for children was 6.668 x 10^{-3} and for adults was 7.393 x 10^{-5}. The assessment indicates that cancer risk levels are concerning, particularly in landfill areas, where children and adults face unacceptable risks (4.260 x 10^{-3} and 4.723 x 10^{-4}, respectively).

In agricultural areas, children also show a notable risk (6.668 x 10^{-4}), while adults have a lower risk (7.393 x 10^{-5}), which falls within acceptable limits (10^{-6} < TCR < 10^{-4}).

This suggests that while there is a measurable risk for adults in agricultural settings, it is not considered critical.

Table 8. Carcinogenic health risk assessment of heavy metals in agricultural and landfill soil through ingestion, dermal contact, and inhalation pathways

Area	Group	Element	Carcinogenic health risk assessment			
			CRing	CRder	CRinh	TCR
Agricultural area	Children	Cd	9.23 x 10^{-8}	NC	4.28 x 10^{-9}	6.668 x 10^{-4}
		Ni	6.41 x 10^{-4}	2.56 x 10^{-5}	NC	
		Pb	5.86 x 10^{-7}	NC	8.09 x 10^{-11}	
	Adult	Cd	9.89 x 10^{-9}	NC	2.41 x 10^{-9}	7.393 x 10^{-5}
		Ni	6.86 x 10^{-5}	5.22 x 10^{-6}	NC	
		Pb	6.28 x 10^{-8}	NC	4.56 x 10^{-11}	
Landfill area	Children	Cd	4.72 x 10^{-8}	NC	2.19 x 10^{-9}	4.260 x 10^{-3}
		Ni	4.10 x 10^{-3}	1.64 x 10^{-4}	NC	
		Pb	6.63 x 10^{-7}	NC	9.15 x 10^{-11}	
	Adult	Cd	5.06 x 10^{-9}	NC	1.23 x 10^{-9}	4.723 x 10^{-4}
		Ni	4.39 x 10^{-4}	3.34 x 10^{-5}	NC	
		Pb	7.10 x 10^{-8}	NC	5.16 x 10^{-11}	

Comparison of health risks with other landfill sites: The HI and TCR values of various landfill sites, derived from the literature review, are presented in Table 9. The soil at the Bang Ban landfill poses greater non-carcinogenic health risks compared to the Gombe dumping site, Oum Azza landfill, and Can Tho landfill for both children and adults. However, in the agricultural areas surrounding the Bang Ban landfill, non-carcinogenic risks are higher only in comparison to the Gombe site.

In terms of carcinogenic risks, exposure to multiple heavy metals in the landfill exceeds levels reported at the Chiang Rak Noi, Lanzhou City, Oum Azza, and Bellville landfills. Similarly, the agricultural areas near the Bang Ban landfill exhibit higher carcinogenic risks compared to those reported at the Chiang Rak Noi, Lanzhou City, and Bellville landfills.These elevated risks are primarily due to higher levels of heavy metal contamination in the Bang Ban landfill and surrounding areas.

Table 9. Literature review of health risk assessment of heavy metal in landfill area

Study site	Health risk assessment			
	HI value of non carcinogenic health risk assessment		TCR value of carcinogenic health risk assessment	
	Children	Adult	Children	Adult
Chiang Rak Noi municipal landfill, Thailand [45]	1.7325	1.2068	2.60 x 10^{-5}	1.60 x 10^{-5}
Contaminated area in Lanzhou City, China [46]	6.18 x 10^{-1}	1.14 x 10^{-1}	1.80 x 10^{-5}	8.33 x 10^{-6}
Gombe dumping site, Nigeria [47]	7.41 x 10^{-2}	9.84 x 10^{-3}	-	-
Oum Azza landfill, Morocco [48]	4.25 x 10^{-1}	4.31 x 10^{-2}	7.60 x 10^{-4}	8.32 x 10^{-5}
Can Tho landfill, Vietnam [49]	1.93 x 10^{-1}	4.46 x 10^{-2}	-	-
Bellville landfill, South Africa [50]	0.279	0.120	6.00 x 10^{-5}	3.00 x 10^{-5}

The contamination is attributed to leachate runoff and migration, particularly during the rainy season. Internal landfill activities, such as the use of firefighting water during fires, further exacerbate leachate leakage. Other contributing factors include the landfill's proximity to sensitive areas, its topography, the nature of waste being dumped, scavenging activities, and specific soil properties. To mitigate health risks associated with heavy metal exposure from contaminated soil, it is crucial to reduce soil pollution from various sources. This can be achieved by minimizing the use of agricultural chemicals that contribute to soil contamination and by enhancing systems to prevent leachate migration from the landfill into the soil and the environment. Specifically, improving the leachate collection systems at the Bang Ban landfill is essential. Government agencies responsible for waste management regulations in Thailand should also enact legislation aimed at reducing landfill disposal practices and promote adoption of cleaner waste management technologies to decrease heavy metal contamination in the environment caused by landfilling.

CONCLUSIONS

The results of the soil contamination analysis indicate that the average concentrations of Cu and Ni in the soil at the Bang Ban landfill exceed the maximum permissible limits for agricultural and industrial areas according to the CCME, the maximum permissible limits of WHO/FAO, and the threshold limit value set by the Finnish Government. Additionally, Cd also exceeds the standards. The average concentration of Cd in agricultural areas exceeds the maximum permissible limits for agricultural soils, as specified by CCME, and the threshold limit value set by the Finnish Government, while the average concentration of Cd from the landfill area exceeds the threshold limit value set by the Finnish Government.

Source analysis of heavy metal contamination in soil, using Principal Component Analysis, revealed that Cu, Ni, Pb, and Zn are primarily associated with leachate runoff, while Cd and Mn are influenced by both leachate runoff and agricultural activities. Health risk assessment results indicate that the primary route of heavy metal exposure was ingestion, with Cu being most prevalent in the landfill area and Mn being most abundant in agricultural areas. Children had higher exposure levels than adults. Non-carcinogenic health risk assessments from soil exposure in both the landfill and agricultural areas indicated no cancer risk from either individual or multiple metals. Carcinogenic risk assessments for individual metals revealed unacceptable risk levels for Ni in children, particularly through ingestion in agricultural areas and both ingestion and dermal exposure in the landfill. When assessing risks from multiple metals, the exposure risk was found to be unacceptably high for children in both areas. For adults, health risks from multiple metal exposure were deemed unacceptable in the landfill but acceptable in the agricultural area.

AUTHOR CONTRIBUTIONS

Somkid Tangkan designed the research; Sirapassorn Phanthasa, Orawan Chamnanphudsa and Yawanart Ngamnon performed the experiments and collected samples; Somkid Tangkan and Wiriyabhorn Klomsungcharoen analyzed the data; Somkid Tangkan and Cherlyn Sirisetpop wrote the manuscript draft; Somkid Tangkan author revised the manuscript. All authors approved the final version of the manuscript.

CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest related to this publication.

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