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Environmental Pollution of Heavy Metals in a Vietnamese Informal E-waste Processing Village

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Abstract

Inappropriate handlings of informal e-waste processing have increasingly become a global environmental and public health issue of concern. This study was conducted to quantify the concentrations of five heavy metals found in the environmental media at an exposed village and a reference village in Northern Vietnam. The correlations between a pair of the heavy metals found in a medium, and between a pair of the environmental media was found. The results showed that drinking water was safe for heavy metal exposure in both studied villages. However, at the exposed village, the levels of the heavy metals found in indoor soil were, in descending order, Pb (678.42 ± 846.11 mg kg^{-1}) > Ni (148.77± 163.80 mg kg^{-1}) > Cr (61.99 ± 42.50 mg kg^{-1}) > As (7.62 ± 3.33 mg kg^{-1}) > Cd (6.34 ± 12.39 mg kg^{-1}). The levels of Pb, Cd, Cr, and Ni in indoor soil and surface dust in the exposed village were significantly higher than those in the reference village at p<0.001. The average concentrations of Pb, Cd, Cr, Ni and As in indoor soil were 3.57, 8.78, 1.90, 4.41, and 1.08 times, respectively, higher than those in outdoor soil at p<0.001. The levels of Pb and Cd found in indoor soil at the exposed village were 9.69 and 3.17 time, respectively, higher than the maximum allowable limits in Vietnam. Significant correlations between the pairs of the heavy metals in a medium and between the pair of the environmental media was found at the exposed village. This finding suggested that inappropriate activities conducted at an informal e-waste processing facility could be a major contributor to the heavy metal contaminations. This study highlighted the importance of release mitigation of a hazardous heavy metal from an informal e-waste processing facility to prevent its potential effects on human health.

Keywords: E-waste; Environmental pollution; Indoor soil; Outdoor soil; Heavy metals; Vietnamese village

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Introduction

Electronic waste, coined e-waste, has emerged globally as a fast-growing solid waste of significant environmental health concern [1-2]. E-waste was reported being informally processed for disposal or recycling in many countries, including China, Ghana, Nigeria, India, Thailand, the Philippines, and Vietnam [3]. Improper e-waste disposal or recycling has resulted in environmental contaminations negatively impacting on ecosystem and causing health risks from hazardous exposures [4-5]. In Vietnam, e-waste has become an issue of public health and environmental concerns due to the impact of its discarding and improper recycling. A large amount of e-waste was collected and treated by the informal private sector, using a simple, manual dismantling process to recover only a small portion of precious metals or plastics, and then dispose of or export its remaining parts [6-7]. The Vietnamese government has promulgated several legislations and governance frameworks on waste management, including Amendment Law on Environmental Protection (National Assembly, Vietnam, 2005, 2014), National Strategy for Integrated Solid Waste Management up to 2025, Vision Towards 2050 (The Prime Minister, Vietnam, 2009, 2018), Decree on Management of Waste and Discarded Materials (The Prime Minister, Vietnam, 2015), Decision on Prescribing Retrieval and Disposal of Discarded Products (The Prime Minister, Vietnam, 2013, 2015), and Circular on Recall and Treatment of Discarded Products (Ministry of Natural Resources and Environment, Vietnam, 2017). None of these, however, were relating to the regulation of informal e-waste processing in Vietnam [7-10].

Although many studies have investigated the environmental pollution and human health risks caused by heavy metals exposure, most of the investigations have targeted at contamination hotspots from intensive e-waste processing activities to retrieve metals by open burning, incineration, smelting, and acid leaching [11-18]. Incidences of heavy metal concentrations with As, Cd, Pb, Zn, and Se have been found in surface soils, plants, and ground water samples collected from Mandoli industrial area, one of the major informal e-waste recycling sites in India [16]. Also, high levels of various heavy metals were found in different environmental media associating with e-waste processing facilities in many countries in the world. For example, Cu, Pb, Zn, Sn, and Sb were found in Bangalore, India [17], Cu and Pb were found in the soil and plant samples in Nigeria and China [12], Cu, Pb, Zn, and Ni were found in soil samples in Sue Yai Utit, Thailand [18], and Cd, Cr, Cu, Pb, and Zn were found in Southern China [4]. A study conducted in Qingyuan, Guangdong, China, further suggested that the informal e-waste processing facilities employing methods such as acid leaching, dismaltling, burning and abandoned were allegedly responsible for Cd, Cu, Pb, and Sb contaminations in nearby soils [19]. To discern the relationship between the e-waste processing and the findings of heavy metals in different environmental media, this study was conducted to collect and analyze empirical data on five heavy metals found in environmental samples collected from two villages in Northern Vietnam; one with intensive e-waste processing activities (exposed village), and the other known to be lack of these intensive activities (reference village). The data collection was conducted in 2018 to quantify the concentrations of five heavy metals in environmental media, including drinking water, cooked rice, surface dust, and soils; and to elucidate the correlations among the five heavy metals found in different environmental media.

Materials and methods

1) Study area

This study was conducted at two villages in Northern Vietnam; one at Bui Village as the exposed village where villagers were known to be exposed to e-waste processing and the other at Nhuan Trach Village as the reference village where villagers were not known to be exposed to e-waste processing. These two villages were selected on the basis of their similarities in population, cultural background, and socioeconomic status. Both villages are located in Cam Xa Commune, My Hao District, Hung Yen Province, Northern Vietnam. Of the two villages selected, Bui Village has a nearly 15-year history of informal e-waste processing in an area of about 2 km^2 with the total population of 1430 people in 2018. In 2018, 40-50% of the residents in Bui Village were regularly involved in processing metals and plastics from e-waste. The main processes involved recovery of metals by manually dismantling, fractionation of metal and plastic, and sorting of electric parts as well as shredding plastic casings into chips for resale. The amount of the e-waste dismantled in each household of Bui Village fluctuated from 1 to 10 tons per month. The output capacity from dismantling and sorting of e-waste in the entire Bui Village averaged 40-50 tons per month. E-waste processing operations in Bui Village were family-based, taking place in the yards of houses in proximity of living quarters. Business owners often employed labors in their neighborhood to help with the processing work. Processing e-waste to extract valuable metals for sale or reuse was a dominant family business for residents in Bui Village, which could potentially cause serious heavy metal pollution there. As a reference village, Nhuan Trach Village was located in the upstream of a river running through both villages, about 5 km away from Bui Village, with an area of 1.85 km^2 and a population of 1,400 people in 2018. The residents of Nhuan Trach Village were mainly farmers and small business traders.

2) Field sampling

This study was approved by the Thammasat University Ethical Committee in Thailand, and supported by local authority and residents. A written informed consent was obtained from each participant prior to the study.

At Bui Village, a total of 43 households engaging in e-waste processing were recruited to participate in the environmental surveys in their houses. In each household, one sample each of drinking water (after treatment), cooked rice, and surface dust wipe as well as two composite samples of soils (indoor and outdoor) were collected for analysis. A composite sample of soils was an aggregate of 4 to 5 subsamples of indoor or outdoor soil randomly collected inside or outside of a household. At Nhuan Trach Village, a total of 37 households were selected for the surveys. Similar to Bui Village, one sample each of drinking water (after treatment), cooked rice, surface dust wipe and indoor soil were collected for analysis. Unlike Bui Village, however, no outdoor soil samples were taken at Nhuan Trach Village.

3) Sample preservation, preparation and analysis

In keeping with the procedures of quality assurance and quality control, drinking water samples were collected in acid-washed plastic bottles from each household and then delivered to the laboratory for analysis. Water samples were prepared following Method 200.8, Revision 5.4 [20]. Digestion of the non-filtered samples was done by following the method prescribed under EPA 3015A - microwave-assisted acid digestion of aqueous samples and extracts [21]. A water sample (20mL) was digested with 0.5 mL of 65% HNO_3 for 30 min until the solution became transparent. The solution was then filtered and maintained at a total of 25 mL with deionized-water.

Different environmental media were sampled by using different methods. For sampling indoor and outdoor soils, a 20 g sample of the upper layer of soil was collected from each household and placed in a labeled zip-lock bag. For sampling cooked rice, a 100 g sample from each household was collected, placed in a labeled zip-lock bag, and stored at 4-5°C until analysis. The collected soil and cooked rice samples were prepared following Method 200.8, Revision 5.4 [20].

Dried samples of 0.5±0.001 g cooked rice and 0.25 ± 0.001 g soil were pre-digested with 5 mL of 65% HNO_3, 2mL of 30% H_2O_2 for rice and 9 mL of 65% HNO_3 and 2 mL of 30% H_2O_2 for soil in a digestion vessel and then digested in a microwave digestion (Start D Microwave Digestion System, Milestone, USA) to obtain complete sample dissolution. The digestion program for rice/soil was the following: ramp to 180°C in approximately 20 min and remain at 180°C for 20 min (power: 1200W, pressure: 45 bar) [22]. Wipe samples from the surface of a furniture in a household were collected, following the standard procedure of NIOSH Manual of Analytical Methods (NMAM) 9102 [23]. The wipe samples collected were stored in the cool condition of 4-5°C until treatment or analysis. Procedures for the preparation and digestion of the collected wipe sample followed that prescribed under Method 3052 - Microwave-assisted acid digestion of siliceous and organically based matrices [22]. Wipe samples were pre-digested with 9 mL of 65% HNO_3 and 2 mL of 30% H_2O_2 for 30 min in a digestion vessel and then digested in microwave digestion to obtain complete sample dissolution [22]. The digestion program for wipe samples was the following: ramp to 180°C in approximately 20 min and remain at 180°C for 20 min (power: 1200W; pressure: 45 bar). After the solution had cooled to room temperature, the digest solution was filtered and diluted to 50 mL with deionized water.

All digested solutions were filtered and diluted to appropriate concentrations before analysis. The concentrations of Pb, Cd, Cr, As, and Ni were measured using ICP-MS Perkin Elmer NexION 350X in optimum conditions.

4) Quality control

To ensure the quality of the data, field blank and laboratory blank samples were prepared and analyzed throughout the study along with analysis of heavy metals in each of the environmental media sampled. The standard calibration curve was plotted by the six working standard solutions at a concentration of 0.1, 0.5, 1, 5, 10, and 20 µg L^{-1}, respectively, prepared from a stock solution for each of the five heavy metals and diluted by deionized water. The linear correlation coefficient of the metal standard calibration curve was above 0.999. Analytical quality assurance was assessed using certified reference materials obtained from the National Institute of Standard and Technology for all the target metals. Reagent blanks, analytical duplicates, and a matrix sample spiked with standards for each set of twenty samples were also used to test the analysis accuracy and precision. All of the chemical reagents used in this study were guaranteed reagents. The spike recoveries of the elements were between 80% and 115%. All samples were analyzed at the laboratory of the Department of Medical Testing and Environmental Analysis, The National Institute of Occupational and Environmental Health, Hanoi, Vietnam.

5) Statistical analysis

The concentrations of each heavy metal were presented as mean ± SD and median (min-max). For each heavy metal, the concentration below the limit of detection (LOD) for that metal was assigned a value of one half the LOD for further calculation. The Two-Related Samples test was utilized to compare two sets of observations within a group. The Mann-Whitney U test was used for comparison between two groups of non-normally distributed data. Spearman's Rho correlation analysis (r_s) was conducted to determine the relationships among the concentration of heavy metals found in environmental media in this study. All of the statistical analyses were performed using SPSS version 20.0.

Results and discussion

1) Concentrations of heavy metals in the environment

The concentrations of the five heavy metals found in the environmental media from Bui Village and Nhuan Trach Village are presented in Table 1.

Table 1 shows that the mean concentrations of Pb and Cr in drinking water at Bui Village were 1.30 ($p<0.05$) and 1.04 ($p>0.05$) times, respectively, higher than those at Nhuan Trach Village. Otherwise, Ni and As concentrations in drinking water at Bui Village were significantly lower than those at Nhuan Trach Village. There may be attributable to the releases not only from natural source, but also from anthropogenic sources such as fertilizer, pesticide use, smelting operations, industrial activities and disposal of household in other areas [24-27]. On an average, the concentrations of all of the five heavy metals were relatively low, less than the reference values of 0.01 mg L^{-1} for Pb and 0.05 mg L^{-1} for Cr as listed in the Vietnamese technical regulation on drinking water quality (QCVN 01: 2009/ BYT) [28]. The quality of drinking water in the study area was, therefore, considered safe for heavy metal exposure for local people that use it for drinking and cooking based on the results of some previous studies [29-31]. Also, results of the study conducted in 2012 to 2014 showed that the concentration levels of heavy metals in water collected from a river that runs through Bui Village where e-waste was processed were not high, showing the levels of As (3.60-5.10 μg L^{-1}), Cd (<0.50 μg L^{-1}), Pb (2.40-8.70 μg L^{-1}), Cu (3.60-190 μg L^{-1}), Ni (5.70-15.00 μg L^{-1}), Zn (15.00-45.00 μg L^{-1}), and Fe (3.40-4.10 μg L^{-1}). Except for Cu, the values for the remaining heavy metals mentioned above were lower than their respective reference values listed under the technical regulation on surface water quality in Vietnam (QCVN08:2008/BTNMT) [32].

Rice is the major crop grown in the study area; therefore, it is critical to consumer's health to ensure that it is safe for consumption. The mean number of Ni found in cooked rice at Bui Village reached 4.94 times higher than that found in Nhuan Trach Village ($p<0.001$). However, the levels of Pb and Cr found in Bui Village were 1.4 and 1.1 times, respectively, lower than those found in Nhuan Trach Village. Cd and As in rice samples were all under the maximum allowable limits prescribed under CODEX STAN 193-1995 General Standard For Contaminants and Toxins in Food and Feed (WHO/FAO, 2017) and the national technical regulation on the limits of heavy metals contamination in food (QCVN 8-2:2011/BYT, Vietnam, 2011). There are no standards for Pb, Ni, and Cr established in Vietnam; therefore, these levels of contaminations in rice found in this study could be used as enforcement references for the sake of health protection. The reason for this suggestion is that food ingestion has been proven as an important pathway for heavy metal residues to gain entry into human bodies [29, 31, 33-34].

Table 1 also showed that the median concentrations of Pb and Cd detected in cooked rice were 0.37 and 0.07 mg kg^{-1}, respectively, which were much higher than the levels of 0.02 and <0.01 mg kg^{-1}, respectively, found in duplicate food in a study conducted at the same Bui Village in 2014 [35]. Other studies also reported various concentrations of Pb found in rice, including a lower concentration of Pb found in rice grains from an e-waste dismantling area in Taizhou, China [29, 36], and a higher concentration of Pb and Cd found in rice in other areas in China [4, 31]. However, the levels of Cr, Ni, and As found in cooked rice in this study were higher than those reported in many of the previous studies conducted in e-waste processing areas in China, [34]. The high level of Ni contamination in cooked rice found in Bui Village may be attributable to a long-term accumulation of Ni from open burning of e-waste in rice fields after harvest, which was a common practice observed in that village [32].

Table 1 Concentrations of the five heavy metals found in the environmental media from Bui Village (exposed village) and Nhuan Trach Village (reference village) in Northern Vietnam

Elements	Bui Village (Exposed village)		Nhuan Trach Village (Reference village)		p^*
	Mean ±SD	Median (min-max)	Mean ±SD	Median (min-max)	
Drinking water (µg L^{-1})					
Pb	1.90 ± 1.90	1.31 (0.30 - 9.02)	1.46 ± 2.24	0.35 (0.35 - 10.77)	0.018
Cd	<LOD (0.20)		<LOD (0.20)		
Cr	0.88 ± 0.54	0.66 (0.19 - 2.10)	0.85 ± 0.60	0.65 (0.10 - 2.19)	0.643
Ni	4.05 ± 6.45	1.60 (0.15 - 29.13)	4.14 ± 2.94	3.40 (0.40 - 13.38)	0.022
As	0.18 ± 0.12	0.15 (0.15 - 0.81)	0.38 ± 0.36	0.15 (0.15 - 1.61)	<0.001
Cooked rice (mg kg^{-1})					
Pb	0.43 ± 0.30	0.37 (0.18 - 1.75)	0.60 ± 1.02	0.30 (0.13 - 6.32)	0.981
Cd	0.19 ± 0.27	0.07 (0.02 - 1.09)	0.08 ± 0.06	0.06 (0.02 - 0.22)	0.471
Cr	0.61 ± 0.15	0.56 (0.46 - 1.17)	0.68 ± 0.21	0.62 (0.41 - 1.29)	0.042
Ni	9.58 ± 9.98	6.89 (0.36 - 42.17)	1.94 ± 3.22	1.13 (0.46 - 15.21)	<0.001
As	0.15 ± 0.02	0.15 (0.06 - 0.19)	0.15 ± 0.04	0.15 (0.03 - 0.21)	0.957
Surface dust (µg 100 cm^{-2})					
Pb	7.04 ± 8.35	4.83 (0.47 - 47.84)	2.31 ± 1.53	1.83 (0.54 - 6.92)	<0.001
Cd	0.08 ± 0.06	0.07 (0.001 - 0.29)	1.00 ± 1.44	0.13 (0.04 - 5.95)	<0.001
Cr	1.11 ± 0.92	0.88 (0.03 - 4.50)	0.90 ± 0.90	0.60 (0.24 - 4.61)	0.073
Ni	11.98 ± 11.25	9.24 (0.14 - 65.56)	2.74 ± 5.67	1.20 (0.33 - 32.96)	<0.001
As	0.14 ± 0.14	0.08 (0.01 - 0.76)	0.07 ± 0.10	0.04 (0.005 - 0.60)	<0.001
Indoor soil (mg kg^{-1})					
Pb	678.42 ± 846.11	309.82 (21.32 – 3,317.89)	33.94 ± 9.39	31.10 (20.22 - 75.25)	<0.001
Cd	6.34 ± 12.39	1.79 (0.15 - 70.81)	0.37 ± 0.34	0.28 (0.11 - 2.16)	<0.001
Cr	61.99 ± 42.50	52.35 (23.59 - 273.45)	36.51 ± 11.42	32.84 (19.6 - 73.65)	<0.001
Ni	148.77 ± 163.80	67.33 (17.19 - 620.93)	31.54 ± 11.68	27.29 (15.38 - 58.76)	<0.001
As	7.62 ± 3.33	6.80 (2.37 - 23.77)	7.97 ± 2.04	7.60 (5.19 - 14.48)	0.145

Remark: *In the Mann-Whitney U test, mean numbers were statistically significant (two-sided) at $p<0.05$; LOD: limit of detection.

Dust is a significant environmental medium that can provide information on the level, distribution, and ultimate destination of contaminants present in the surface environment [37]. Results of this study showed that the mean concentrations of the five heavy metals in surface dust were, in descending order, Ni> Pb> Cr> As> Cd. The dust concentrations of Ni, Pb, and As at Bui Village were 4.37, 3.04, and 2.05-fold, respectively, higher than those at Nhuan Trach Village at $p<0.001$. This indicated a close connection between the e-waste processing activities and the elevated levels of Pb, Ni, and As in surface dust. This also indicated the presence of heavy metal particles in the dust, though at relatively low concentrations, posing a health threat to local people, especially young children through a direct or indirect ingestion of contaminated dust.

Although little work has been documented on the use of wipe sampling technique to collect indoor surface dust, high concentrations of heavy metals have been reported in dust resulting from e-waste processing in China [37-40], Thailand [18], India [16, 41], Philippines [42], and Vietnam [32, 35]. In this study, a high concentration of Pb found in the indoor surface dust samples at the family-run e-waste dismantling facilities at Bui Village was attributable to the quick release of Pb into ambient air as compared to Cr, Cd, Ni, Cu, and As. A study conducted in South China revealed that Cd, Cr, Cu, and Pb concentrations in indoor surface dust from an e-waste processing site were 3-15 times higher than the corresponding values in the reference village, indicating that heavy metals existed in indoor surface dust at the exposed area could potentially pose serious risks to human and environmental health [43].

The mean values of the heavy metal concentrations in indoor soil in Bui Village were high in a sequence of Pb > Ni > Cr > As > Cd. These concentrations of heavy metals were substantially higher than those found at Nhuan Trach Village. Results of the study also revealed that, except for As, the elevated concentrations of Pb, Cd, Ni, and Cr found in the indoor soil samples in all of the informal e-waste processing facilities at Bui Village were 19.99, 17.12, 4.72, and 1.70 times, respectively, higher than those from Nhuan Trach Village, which were significant at $p<0.001$. However, the As concentration in the indoor soil samples at Nhuan Trach Village was slightly higher than that at Bui Village ($p<0.05$), which may be attributable to the releases not only from natural source, but also from other sources such as pesticide use and smelting operations in other areas [44-46].

The mean concentrations of Pb (678.42 ± 846.11 mg kg^{-1}) and Cd (6.34 ± 12.39 mg kg^{-1}) in indoor soil at Bui Village were 9.69 and 3.17 times, respectively, higher than the standard values set for Pb (70.00 mg kg^{-1}) and Cd (2.00 mg kg^{-1}) under the Vietnamese technical regulation [27]. The concentrations of Pb and Cd found in 76.74% and 48.84%, respectively of the indoor soil samples from Bui Village were higher than those standard values set under the same regulation above. Despite that the average concentrations of Cr and As found in this study were below the respective standard values set under the Vietnamese technical regulation, the concentration of As was much higher than its reference value of 0.68 mg kg^{-1} established by USEPA 2018 - Regional Screening Levels [47]. There is currently no quality standard set for Ni in soils in Vietnam, but more attention should be paid to this heavy metal due to its important human and environmental health implications.

2) Distributions of the heavy metals in indoor and outdoor soil in Bui Village

The distributions of the heavy metals in indoor and outdoor soil samples collected from family-run e-waste processing facilities at Bui Village were examined and the results are presented in Table 2.

The concentrations of Pb, Cd, Cr, Ni, and As found in the indoor soil samples were 3.57, 8.78, 1.90, 4.41, and 1.08 times, respectively, higher than those in the outdoor soil samples as shown in the average indoor- to outdoor-soil ratios in Table 2. There were highly significant differences in the heavy metal concentrations found between the indoor and outdoor soil samples ($p<0.001$), except for As ($p>0.05$). Apparently, the spatial distribution of heavy metal concentrations was highly distance-associated, decreasing the concentration with the increase of distance from the source of e-waste processing. This spatial distribution pattern indicates that heavy metal concentrations may linger near the pollution source, instead of diffusing to the surrounding areas through ambient air, which likely occurred under a low vapor pressure [48].

The data on the heavy metal concentrations found in soil samples were comparable to those reported earlier from the same e-waste processing area in Vietnam and from other areas in China, Thailand, and India. Lead (Pb) was reported as the most abundant element derived from the e-waste processing area. The mean heavy metal concentrations in the soil samples in this study were considerably higher than the corresponding values obtained from other e-waste processing areas in China [12, 19, 48-50], India [16-17] and Vietnam [32], but much lower than those reported from several intensive e-waste processing sites in China [4, 51], Vietnam [35], Thailand [18], and India [16]; where open burning of circuit boards and other metal chips, smelting, and acid digestion that could release a significant amount of toxic pollutants into the surrounding environment; were known to occur.

Obviously, the concentrations of heavy metals found in soils varied widely among studies. The differences could result from 1) the different types of e-waste processed; e.g., cathode-ray tube (CRT) displays, electronic circuit, printed circuit boards containing metal parts, and plastic; and 2) the different characteristics of e-waste processing activities in a facility; e.g., sorting of e-waste, roasting, manually dismantling, shredding of plastic parts, fractional recovery of valuable metal parts, and acid bathing to recover precious metals. Additionally, previous studies showed that some heavy metals contained in e-waste could easily be released to the soil during the process of acid-leaching and smelting, resulting in high hazardous metal emissions reported in these areas [16, 19]. However, these processing activities were not observed in Bui Village.

3) Correlations among heavy metals in different environmental media

The closely related environmental media were grouped into two pairs; 1) indoor soil and outdoor soil, and 2) indoor soil and surface dust. A correlation coefficient for each of the five heavy metals found in each pair of the environmental media at Bui Village was calculated and the results are presented in Table 3.

Table 2 The concentrations of the five heavy metals in outdoor soil samples and their average indoor-to outdoor-soil ratios from informal e-waste processing facilities at Bui Village, Northern Vietnam

Elements ($mg\ kg^{-1}$)	Outdoor soil		Average indoor to outdoor soil ratios	p^*
	Mean ±SD	Median (min-max)		
Pb	189.90 ± 239.07	76.94 (12.34 - 1102.79)	3.57	<0.001
Cd	0.72 ± 1.70	0.35 (0.10 - 11.32)	8.78	<0.001
Cr	32.66 ± 30.14	25.80 (7.11 - 203.36)	1.90	<0.001
Ni	33.77 ± 25.37	24.48 (12.75 - 121.78)	4.41	<0.001
As	7.07 ± 3.13	6.11 (3.53 - 19.92)	1.08	0.067

Remark: *Two-Related Samples test, mean values were considered statistically significant at $p<0.05$ (two-sided).

Table 3 Correlation coefficients for the five heavy metals found in each of the two pairs of the environmental media at Bui Village

Heavy metals	Correlation coefficient	
	Indoor soil vs Outdoor soil	Indoor soil vs Surface dust
Pb	$r_s = 0.463^{**}$	$r_s = 0.525^{**}$
Cd	$r_s = 0.405^{**}$	$r_s = 0.315^{**}$
Cr	$r_s = 0.440^{**}$	$r_s = 0.058$
Ni	$r_s = 0.341^{*}$	$r_s = 0.378^{**}$
As	$r_s = 0.381^{*}$	$r_s = -0.067$

Remark: * Significant at $p<0.05$ (2-tailed); ** Significant at $p<0.01$ (2-tailed)

Results of the study showed that the amounts of Pb, Cd, Cr, Ni, and As found in indoor soil at Bui Village were significantly correlated with those found in outdoor soil. The results indicated that all of the five heavy metals may be originated from the same pollution source. Also suggested is that a heavy metal found in indoor soil could contribute to that same metal found in outdoor soil in an e-waste processing facility at Bui Village.

Similarly, Pb, Cd and Ni found in indoor soil were positively correlated with those found in the surface dust. This indicated that the pollutants, Pb, Cd, and Ni, found in indoor soil may be attributed to those found in surface dust of a facility at Bui Village. This was in the agreement with the results of the previous researches [30-31]. Strong correlations were observed for the concentrations of Pb, Cd, Ni, and Zn found in soil and those in house dust conducted in an e-waste recycling area in South China [29]. Also, informal e-waste processing facilities could be contributor to heavy metal accumulations in indoor soil, outdoor soil, and surface dust. This, however, appears to be in contradiction with the results of a previous study conducted in the same area in that the concentrations of Pb, Cd, Mn, and Zn found in soil were not correlated with those found in dust [35]. A study conducted in a typical urban environment in China indicated that there was no significant correlation in the concentrations of Pb, Cr, Ni, Cd, Mn, Co, Cu, Zn, As, V, Se, and Sb between indoor dust and soil, implying that outside soil might be not the main pollution source for heavy metals in indoor dust [52].

Additionally, this study also determined the correlations between each pair of the five heavy metals found in indoor soil or outdoor soil, and the results are illustrated in Table 4.

The results showed that in indoor soil samples, the correlations between the concentrations of Cd and Pb, Cr and Pb, Cr and Ni, and Ni and Pb were all significant. In outdoor soil samples, the correlations between the concentrations of Pb and Cd, Ni and Pb, Ni and Cd, and Ni and Cr were highly significant. Also, the amount of Pb found in indoor soil was positively correlated with that of Cd and Ni found in outdoor soil. Likewise, the amount of Cd found in indoor soil was positively correlated with that of Pb and Ni found in outdoor soil.

Table 4 Correlation coefficients between each pair of the five heavy metals found in indoor soil or outdoor soil at Bui Village

Environmental media	Pair of heavy metals	Correlation coefficient
Indoor soil	Cd vs Pb	$r_s = 0.353^{*}$
	Cr vs Pb	$r_s = 0.425^{**}$
	Cr vs Ni	$r_s = 0.411^{**}$
	Ni vs Pb	$r_s = 0.911^{**}$
Outdoor soil	Pb vs Cd	$r_s = 0.801^{**}$
	Pb vs Ni	$r_s = 0.801^{**}$
	Cd vs Ni	$r_s = 0.763^{**}$
	Cr vs Ni	$r_s = 0.521^{**}$
Indoor soil vs Outdoor soil	Pb vs Cd	$r_s = 0.412^{**}$
	Pb vs Ni	$r_s = 0.377^{*}$
	Cd vs Pb	$r_s = 0.546^{**}$
	Cd vs Ni	$r_s = 0.466^{**}$

Remark: * Significant at $p<0.05$ (2-tailed); ** Significant at $p<0.01$ (2-tailed)

It has been documented that even a simple method to extract precious metals from e-waste could result in emissions of heavy metals into the environment; e.g., Pb and Cd in circuit boards, CRTs; Ni and Cd in rechargeable Ni-Cd batteries, CRTs and remnants of these valuable metals lingered in the environment after the disposal of e-waste [11, 18, 32, 41, 53-54]. In Bui Village, the major elements of the e-waste processed were CRT displays, personal computers, video cassette recorders, small domestic appliances, printed circuit boards, and plastic housings. Batteries did not appear to be processed in this study area. Therefore, the concentrations of Pb, Cd, and Ni were most highly correlated with each other, which was mainly attributed to the manual dismantling of CRT displays in Bui Village. Dismantling and sorting of e-waste were done in the e-waste processing workshops of Bui Village with unsafe recycling practices likely generated dust and fine particulates, that was one possible pathway of hazardous metal contamination in soil nearby emission sources [55].

There were, however, no significant correlations between the heavy metals found in soil or dust and those found in cooked rice. This, however, was in agreement with the result of an earlier study [30], but not with the other study, in which As, Pb, Cr, Cu contents in food were shown to be significantly correlated with those in soil. This indicates that soil could be an important contributor to food pollution of heavy metals [31].

Overall, the mean concentrations of the heavy metals found in soil samples at Bui Village were greatly higher than those found in drinking water, cooked rice, and surface dust. This may be attributable to a long-term processing of e-waste in this area, resulting in accumulation of heavy metals in soil. Moreover, the distribution of the heavy metals in each environmental medium revealed a large variation among different sampling points, implying that the environmental pollution levels of heavy metals varied with the different e-waste processing activities, type of e-waste processed, and scale/amount/duration of e-waste processed in each facility.

There might be a close relationship between the characteristics of e-waste processing work and the deposition of heavy metal substances. Particularly, results of this study showed that there may be a correlation between the concentration of Pb in indoor soil and surface dust and the average amount of e-waste processed per month at Bui Village at $r_s = 0.335$, $p<0.05$, and $r_s = 0.395$, $p<0.05$, respectively. Based on the spatial distribution patterns of the heavy metals discussed above, some appropriate safety methods could be instituted to reduce the emissions of heavy metals by such actions as covering up the processing facilities, and properly storing e-waste components inside the facilities.

Conclusions

Samples of the cooked rice, surface dust, and soil at the exposed village in this study were found to be contaminated with heavy metals. The significant correlations detected in the pairs of the five heavy metals and in the pairs of the environmental media in which each of the heavy metal found suggested that inappropriate e-waste processing activities could be responsible for heavy metal contaminations in vicinity areas. The concentrations of the heavy metal found in surface dust and indoor soil at the exposed village was significantly higher than those found at the reference village, implying that heavy metals emitted from an e-waste processing facility could result in a greater exposure to heavy metals; thus, posing higher risks to people living nearby. At the exposed village, the heavy metal concentrations appeared to decrease drastically from indoor soil to outdoor soil, indicating that an appropriate intervention is needed to regulate the establishment and operation of informal e-waste processing facilities. This study accentuated the importance of a followed-up investigation by using other methods, such as radioactive tracer, to better illustrate a profile of the heavy metals present in the environment and their potential risks to human health.

Declaration of interest statement

The authors declare that there is no conflict of interest.

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