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Ecological Risks of Heavy Metals Found in Soils at Informal E-Waste Processing Sites in Nigeria

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ABSTRACT

This study aimed to assess the levels of six heavy metals (Pb, Zn, Cu, Cr, Cd, Ni) in surface soils collected from five informal e-waste processing sites at Alaba International Market Lagos State. A total of 25 soil samples from distinct locations were analyzed for these metals following digestion through standard methods, subsequently estimating their ecological risks. Concentration ranges of heavy metals (mg/kg) in e-waste processing site soils were: Zn (148–12852) > Cu (24.1–23174) > Pb (18.5–8611) > Ni (12.0–158) > Cr (6.5–36.8) > Cd (0.5–37.1), distinct from reference soils' metal ranges: Ni (10.2–11.6), Zn (8.8–11.5), Pb (7.5–10.6), Cu (4.8–12.7), Cr (0.2–11.8), Cd (1.01–2.10). Heavy metal concentrations in e-waste site soils significantly exceeded control levels. Elevated concentrations, except for Cd in S3, were observed in S2, S3, and S5 compared to S1 and S4. Ecological risk index demonstrated higher risk in S3 than S2, and geo-accumulation index identified extreme pollution in S2, S3, and S4. The study also revealed strong positive linear relationships among specific heavy metals, implying potential co-exposure risks. This highlights the need for the comprehensive development of effective remediation strategies to mitigate the release of heavy metals from informal e-waste processing sites at the Alaba International Market to prevent them from risking Nigeria's environment.

Keywords: heavy metals, ecological risk assessment, e-waste, Alaba international Market, soil contamination
SDG Keywords: SDG 3- Good health and well-being, SDG 15- Life on Land

INTRODUCTION

Electronic waste (e-waste) has been defined as unwanted electrical and electronic equipment (EEE) or parts discarded with no intent of reuse [1]. E-waste is the fastest-growing solid waste in the waste stream [2], with about 50 million metric tons generated yearly worldwide [3-4]. This was attributed to an increased shipment of used electronic equipment or parts from a developed country to a developing country, resulting in an increased disposal of e-waste in developing countries. According to [5], this increased disposal of e-waste was

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attributed to an increased consumption of such equipment as mobile phones, refrigerators, and computers in the developing world to meet the demand for a better daily life. Moreover, an expansion of global trades enhanced transboundary movements of e-waste or used EEE with an endpoint destined for a developing country. This ultimately resulted in an increase in e-waste dumping in that country [3].

Since the advent of newer and more efficient technologies, the production of EEE has been enhanced significantly, making it more affordable and accessible to consumers. This resulted in a higher rate of turnover with a bigger volume of e-waste generated around the world [6]. Among the high volume of e-waste generated annually, most of the 57.4 million tons of e-waste generated were microwaves, toasters, video cameras, washing machines, cloth dryers, and electric stoves [7]. It was also reported that 33% of the total e-waste discarded worldwide was contributed by the USA and China [8]. EEE products have been shown by [9] to contain such hazardous elements as Pb, Cd, Ni, Cl, and Br, which pose threats to the environment and human health. Nigeria received a large volume of e-waste from developed countries for reuse or recycling, but most of them ended up in landfills after valuable materials were extracted [10].

Since 1979, the Alaba International Market has become a commercial hub for EEE serving not only Nigeria but also its neighbouring countries, including Ghana, Niger, Chad, Togo, and Benin Republic [11-12]. This market is located in Ojo, Igbede Lagos, Nigeria, where precious metals in e-waste were extracted by open burning or dismantled through informal processing. These activities were performed on bare soils with no personal protection. As a result, hazardous materials such as heavy metals were released, along with precious metals, into the environment, impacting not only on the environment but human health as well [13-17].

Several studies showed that traces of hazardous materials found in the e-waste processing areas at the Alaba International Market were higher than the minimum allowable level in soil and water [18-22]. Also, studies conducted in China and Vietnam showed that elevated amounts of heavy metals and toxic substances had been found in the blood of children and workers at informal e-waste processing sites [23-29], and in biological samples taken from breast milk, urine, hair, placenta, and other tissues from e-waste recyclers [30-35]. Concerns over the potential impacts on the public health and environment from heavy metals found in informal e-waste processing sites have prompted this study focusing on the following two objectives; 1) investigation of the levels of six heavy metals (Pb, Zn, Cu, Cr, Cd, and Ni) in surface soils collected from five different informal e-waste processing sites at Alaba International Market; and 2) assessment of the potential risks posed by these six heavy metals to the environment and health of residents living near the Market.

MATERIALS AND METHODS

Description of the Study Area

Since 2016, a study has been conducted to determine the potential risks of the informal e-waste processing activities carried out at Alaba International Market, Lagos State, Nigeria, to the environment and public health of the residents living near it. The geographic location of Alaba International Market and the relative distance of the five sampling sites in Ojo and one reference site in Lagos State Polytechnic (LASPOTECH) Ikorodu, Lagos state, Nigeria, selected for this study are presented in Figure 1 below.

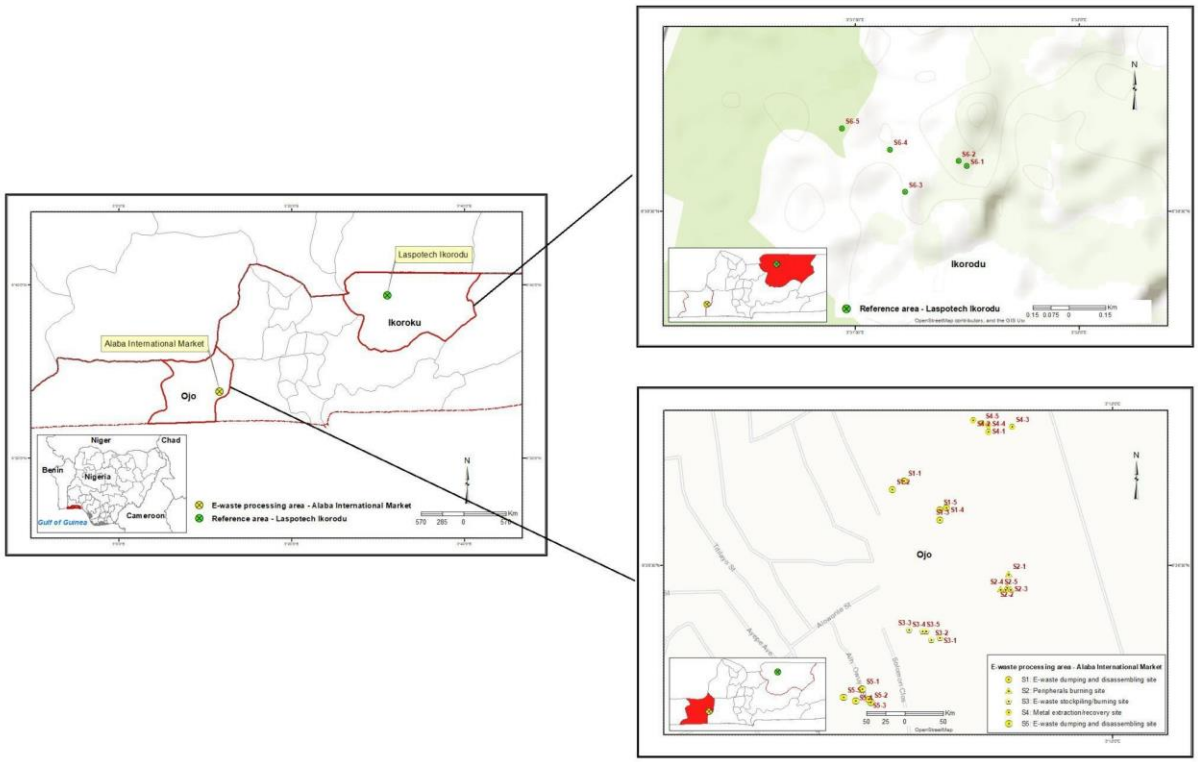

Figure 1. The geographic location of Alaba International Market and the relative distance of the five sampling sites in Ojo and one reference site in Ikorodu, Nigeria selected for this study

Field sampling

Surface soil samples were collected from five different e-waste processing sites, and one reference site at Alaba International Market. Samples collected were marked as: (i) e-waste dumping and disassembling site (S1), (ii) peripherals burning site (S2), (iii) e-waste stockpiling/burning site (S3), (iv) metal extraction/recovery site (S4), (v) e-waste dismantling site (S5), and (vi) reference site (S6). All the sampling sites were selected based on their distinctive representations of contaminated or uncontaminated soils. At each sampling site, five composite soil samples were randomly collected at a depth of 0–15 cm using a stainless-steel hand trowel and stored in sealed polyethylene bags. Each composite soil sample consisted of five sub-samples randomly collected from a sampling site with a total of 25 composite surface soil samples that were collected for analysis. Similarly, five composite samples were also taken from the reference site (S6) as a control.

Sample Preservation, Preparation and Analysis

In keeping with the procedures of quality assurance and quality control, soil samples were air-dried at room temperature without being exposed to direct sunlight for seven days. The soil samples were crushed by using an agate mortar and pestle and then sieved (< 2mm) to remove stones and foreign bodies to obtain true representative samples for further analysis [36]. Physical-chemical properties of surface soil (0–15 cm) are presented in Table S1. According to their texture, all the soil samples were sandy (>90% sand). The soil sample pH, measured by using a pre-calibrated JENWAY 3310 pH meter, was neutral to slightly alkaline at pH 7.55±0.48. Since the properties of soils from the same sampling site differed, the speciation of the heavy metals found in each soil sample might be different.

The concentrations of heavy metals were determined by the pseudo-total extractable fractions process for soil analysis using the modified USEPA method 3051 A [37]. All analyses

were performed in triplicates using high purity acids, and distilled water for dilution. Dried samples of 1± 0.1 g soil sample were added to a mixture of 12 mL of HNO_3 and HCl at a ratio of 3:1; which was then heated for 2 hours on the hot plate at 100^oC. The samples were intermittently opened at a 20-min interval to reduce the pressure build-up until all bubbling ceased. After cooling, the final solution was filtered through Whatman No. 42 filter-paper into a 50 mL standard volumetric flask and made up to50 mL with distilled water. The filtrate was poured into a50mL standard vial and stored at -4^oC until analysis. The blank solutions were prepared and treated in similar procedures. The concentrations of Pb, Cd, Cr, Zn, Cu, and Ni were measured using a Perkin Elmer 1100 atomic absorption spectrometer (AAS) in optimum conditions [39]. The final average metal concentrations were recorded in mg/kg.

Quality Control and Evaluation of Analytical Performance

The field blank and laboratory blank samples were prepared and analyzed throughout the study, along with the analysis of heavy metals in each soil sample to ensure the quality of the data. The linear correlation coefficient of the metal standard calibration curve was above 0.957. Analytical quality assurance was assessed using a recovery study, certified standard reference material obtained from the International Atomic Energy Agency (IAEA – 433, Marine Sediment), and NIST 2710 Montana soil for all the selected metals. The BCR 141r standard reference material, characterized for aqua regia-recoverable trace elements, was used. Replicate analyses were performed on spiked reference samples to yield a mean, which was used to determine the accuracy and standard deviation (SD) of the mean to measure analysis precision [39-40]. The samples and references were analyzed in triplicates. Procedural blanks were included with each batch of extraction to guarantee the accuracy and reproducibility of the results. All the chemical reagents used in this study were guaranteed reagents. The spike recoveries of the elements were Pb (95±3.0%), Cd (93±2.1%), Cr (97±1.6%), Cd (94±3.1%), Zn (90±2.2%), and Ni (98±1.8%). The quality assurance carried out with AAS ensured that procedural blank and reference materials were introduced, following the batch analysis of ten samples. The same procedure was performed for all the triplicate samples. All the soil samples were analyzed at the advanced research laboratory of the Department of Environmental Management and Toxicology, Federal University of Petroleum Resources, Delta State, Nigeria.

The Ecological Risk Assessment Model

The ecological risk assessment model was used to assess the potential ecological risk of heavy metals found in soil samples collected from e-waste processing sites. The parameters used in this study included contamination factor (CF), ecological risk (Er), and index of geo-accumulation (I_{geo}) [41]. The ecological risk assessment represents the sensitivity of the biological communities in the soil to the concentration of toxic metals and overall contamination of the soil or soil quality illustration.

Contamination factor (C_f)

$$C_f = \frac{C_s}{C_n} \qquad \text{Equation 1}$$

Where:
C_s: mean concentration of the metals
C_n: background concentration level

Based on the CF value, the levels of heavy metal pollution in the soil samples were categorized into five different scales; unpolluted (≤2), low polluted (2–4), moderately polluted (4–16), strongly polluted (16–32), and extremely polluted (>32) [42].

Ecological risk index (E_r)

The ecological risk index developed by [43] was used to assess the potential ecological risks posed by heavy metals. The strength of this index lies in the fact that it is summative and

can explain the underlying ecological risks associated with a contaminated site. The ecological risk index (E_r) for each heavy metal of interest is calculated using the following equation:

$$E_r = C_f \times Trf \quad \text{Equation 2}$$

Where:
C_f: contamination factor
Trf: toxic response factor

The toxic response factors for Zn, Cr, Cu, Pb, Cd, and Ni are given as 1, 2, 5, 5, 30, and 5, respectively [44-46].The E_r values can be interpreted as follows; low ecological risk (< 40), moderate risk ($40 \leq E_r < 80$),considerable risk ($80 \leq E_r < 160$), high risk ($160 \leq E_r < 320$), very high risk ($E_r \geq 320$). The E_r values of all metals (RI – Risk index) were a sum of each ecological risk index for individual heavy metal in this study [47].

Index of geo-accumulation (I_{geo})

$$I_{geo} = \log (C_n/1.5B_n) \quad \text{Equation 3}$$

Where:
C_n: concentration of heavy metal n from this study,
B_n: background concentration of heavy metal n [48]
1.5: a factor of possible lithological changes

The I_{geo} values can be interpreted as follows; unpolluted ($I_{geo} < 0$), low polluted to moderately polluted ($0 \leq I_{geo} < 2$), moderately polluted ($2 \leq I_{geo} < 3$, moderately to heavily polluted ($3 \leq I_{geo} < 4$), heavily polluted ($4 \leq I_{geo} < 5$), and extremely polluted ($I_{geo} \geq 5$).

Statistical Analysis

The concentrations of each heavy metal were presented as mean ± SD. Descriptive statistical parameters were calculated using SPSS version 26.1. Correlation between heavy metals assessed was performed using Pearson's correlation coefficient. Another exploratory data analysis was performed with cluster and the principal component analysis (PCA). PCA is a standard multivariate statistical method to reduce the dimensions of a data set, which is typically used to identify the origin of a particular contaminant in environmental studies [49-52]. The analysis explains the relationship between variables via multivariate techniques used to analyze data tables and extract relevant information for later representation. PCA with an eigenvalue greater than one was extracted with loading rotated for the maximum variance. The statistical significance of differences and variance analysis ($p < 0.05$) was performed using a one-way analysis of variance (ANOVA) and least significant difference (LSD) test. Evaluation of the heavy metals in soils would reveal the magnitude of contamination and the potential risks associated with the presence of heavy metals in soils.

RESULTS

Heavy Metal Concentrations in Soils of Studied Areas

The descriptive statistics of heavy metal (Pb, Zn, Cu, Cr, Cd, Ni) concentrations in surface soil (0–15 cm) collected from the Alaba International Market in Lagos and control soil in S6 were presented in Table 1.

Table 1. Mean concentrations of the six heavy metals (Pb, Zn, Cu, Cr, Cd, and Ni) from five e-waste processing sites at the Alaba international Market, Lagos, and reference site at LASPOTECH, and permissible limits from WHO and DPR in Nigeria

Sampling site	Mean in mg/Kg					
	Pb	Cd	Cr	Zn	Cu	Ni
S1 (n = 5)	238±9.3	3.1±1.4	21.6±4.5	849±10.7	684±12.0	16.1±1.3
$t_{(stat)}$	2.68	2.56	3.67*	3.56*	2.41	1.56
S2 (n = 5)	984±10.6	11.5±3.1	28.8±4.2	3563±5.7	3127±16.3	113±1.6
$t_{(stat)}$	7.31*	9.22*	3.39*	5.68*	8.62*	4.98
S3 (n =5)	3423±13.3	17.7±1.7	20.3±3.1	4143±12.7	7567±12.0	68.4±3.7
$t_{(stat)}$	2.01	2.15	2.75	3.27*	1.87	2.48
S4 (n = 5)	2446±10.9	9.7±1.3	19.1±4.8	2385±6.5	446±6.6	19.8±9.5
$t_{(stat)}$	2.08	4.16*	1.60	3.48	1.76	1.44
S5 (n = 5)	487±7.8	5.7±0.7	23.5±3.1	6382±14.9	446±6.6	23.2±2.6
$t_{(stat)}$	2.92*	9.17*	5.92*	3.42*	3.33*	2.99*
Range (Study site)	238-3423	3.1-17.7	19.1-28.8	849-6382	446-7567	16.1-113
S6 (n=5)	8.8±5.5	1.4±0.7	8.0±1.3	10.2±3.4	10.8±3.8	11.0±2.3
Range (Control)	3.3-14.3	0.7-2.1	6.7-9.3	6.8-13.6	7.0-14.6	8.7-13.3
[53], Intervention value	530	12	360	720	190	210
[54], Target value	85	0.8	100	140	36	35

Note: T-test, $t_{critical}$ = 2.78, (d.f. = 4).

The statistical analysis conducted revealed significantly higher concentrations of heavy metals, except for chromium, at sites associated with e-waste processing (S2 and S5) when compared to those primarily involved in storage and physical separation (S1, S3, and S4).The concentrations of the heavy metals (mg/kg) in the range of 238–3423 for Pb, 849–6382 for Zn, 446–7567 for Cu, 19.1–28.8 for Cr, 3.1–17.7 for Cd, and 16.1–113 for Ni were found in the study sites at 0–15 cm depth. The concentrations of the heavy metals found in the control soil were: 3.3–14.3 for Pb, 6.8–13.6 for Zn, 7.0 -14.6 for Cu, 6.7–9.3 for Cr, 0.7–2.1 for Cd, and 8.7–13.3 for Ni. Among the six heavy metals tested, Cu, Zn, and Pb were found to be more abundant in the e-waste burning activity area. The mean values for Cu in sites S1, S2, S3, and S4 exceeded the WHO intervention value of 190 mg/kg. The Pb concentrations in S2, S3, and S4 were 28 to 40 times greater than the Nigerians DPR target value of 85 mg/kg. As shown in Table 1, statistically higher concentrations of all the heavy metals, except Cr in S3 (stockpiling/burning site), were found in S2 (peripheral burning site) and S5 (dismantling site) than in S1 (dumping/disassembly site), S3 (stockpiling/burning site), and S4 (metal extraction/recovery site). All the Zn concentrations in sites S2, S3, S4, and S5 exceeded the WHO intervention value of 60 mg/kg [55]. Cadmium was approximately 20 times higher than the WHO target value of 0.8 mg/kg. However, the concentrations of Cr were found to be below the target values in all five sampling sites.

Pearson Correlation Analysis

In this study, the correlations between different heavy metals (Pb, Cd, Cr, Zn, Cu, and Ni) were analyzed to understand the ecological risks posed by these contaminants. Pearson's

correlation coefficient (r) was used to quantify the strength and direction of the linear relationships between the variables. Table 2 shows a significant positive correlation between Pb and Cu (r = 0.986, p<0.05), between Cd and Cu (r = 0.928, p<0.05), and between Pb and Cd (r = 0.898, p<0.05).

Table 2. Correlation analysis between different heavy metals collected from e-waste processing sites at the Alaba International Market, Lagos

	Pb	**Cd**	**Cr**	**Zn**	**Cu**	**Ni**
Pb	1.000					
Cd	**0.898**	1.000				
Cr	0.172	0.464	1.000			
Zn	0.308	0.495	0.631	1.000		
Cu	**0.986**	**0.928**	0.231	0.254	1.000	
Ni	0.327	0.687	0.662	0.358	0.448	1.000
Note: In the Pearson correlation coefficient test, values in bold are significant at $p < 0.05$						

The results showed that a high concentration of lead (Pb) was correlated with a high concentration of copper (Cu) in the same sampling site. Likewise, this positive relationship could also be found between Cd and Cu, and between Pb and Cd. The correlation coefficients between various sites engaged in different e-waste processing activities are presented in Table 3.

Table 3. Correlations between e-waste processing sampling sites at Alaba international Market

	S1(Dumping and Disassembling)	**S2 (Peripheral burning)**	**S3 (Stockpiling and burning)**	**S4 (Metal extraction/recovery)**	**S5 (Dismantling)**
S1(Dumping and Disassembling)	1.000				
S2 (Peripheral burning)	**0.998**	1.000			
S3 (Stockpiling and burning)	**0.852**	**0.874**	1.000		
S4 (Metal extraction/recovery)	0.584	0.551	0.440	1.000	
S5 (Dismantling)	**0.763**	**0.728**	0.327	**0.665**	1.000

Note: In the Pearson correlation coefficient test, values in bold are significant at $p < 0.05$; strong correlation ($\pm 0.60 \leq r \leq \pm 1.00$); moderate correlation ($\pm 0.40 \leq r \leq \pm 0.50$); weak correlation ($r < \pm 0.40$)

These coefficients reveal significant positive correlations that ranged from strong associations, such as between S1 and S2, S1 and S3, and S2 and S3, to comparatively weaker correlations like those observed between S1 and S5, S2 and S5, and S4 and S5. These positive correlations suggested that a high level of heavy metal was found in one processing activity site (e.g., S1), and a similar level of the same heavy metal could be found in another processing activity site (e.g., S2). Likewise, the same was also true to S1 and S3, S2 and S3, S1 and S5, S2 and S5, and S4 and S5.

Principal Component Analysis and its Impact on Heavy Metal Concentrations

The data matrix of the five e-waste processing sites and six heavy metals was used for PCA analysis to understand the relationship between the sampling sites and the heavy metal concentrations. Results of the PCA analysis are presented in Figure 2 and Figure 3 below.

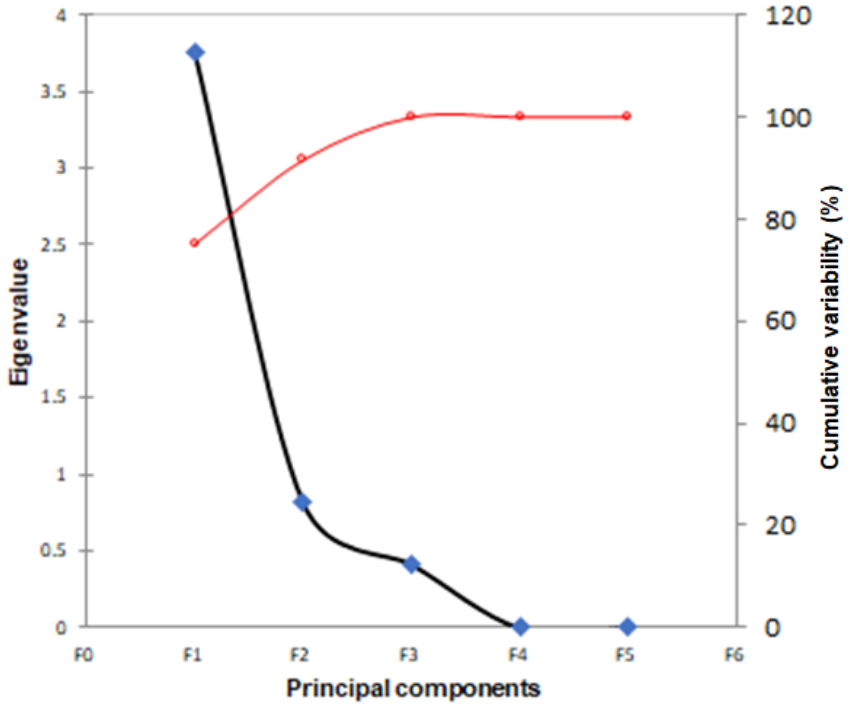

Figure 2. Scree plot for the heavy metals in the soil samples from the e-waste processing sites at Alaba International Market

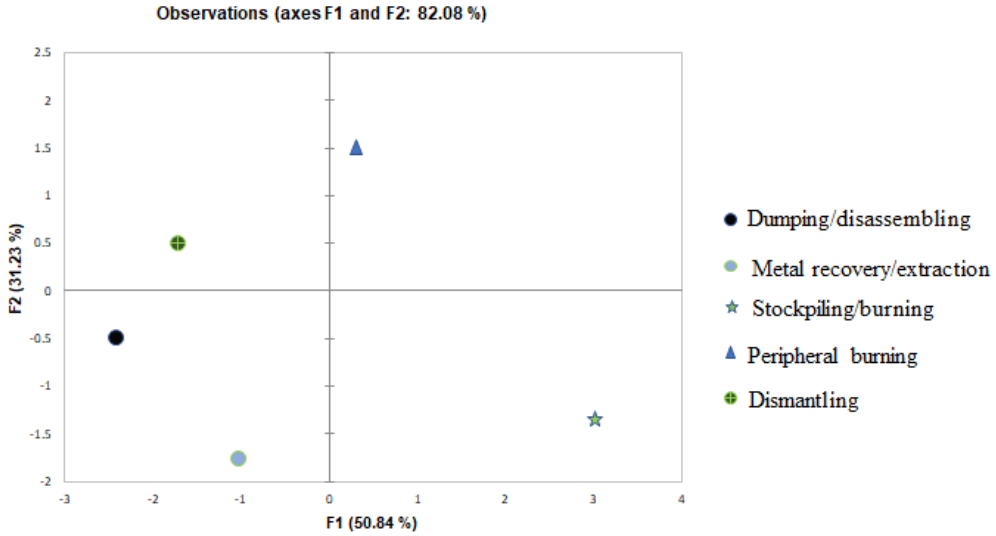

Figure 3. The plots of the principal component analysis for activity sites from Alaba International Market e-waste processing sites

As shown in Figure 2, the principal components (F1–F5) exert influence over the dispersion of heavy metals and their interrelationships within the study sites. The use of (PCA) reveals linear connections among the concentrations of heavy metals in the soil samples

collected from each e-waste processing site. Moreover, it aids in the interpretation of correlations among the six heavy metals present in these exposed sites. Notably, metals exhibiting strong correlations are grouped within specific principal components or factors. This multitude of principal components collectively dictates how these elements are distributed across the sites within the Alaba International Market. The plot in Figure 3 displays the distribution of the site activities under investigation. The analysis reveals that different principal components have an impact on the exposed sites. The F1 component has a strong impact on S2, S3, and S4, while F2 affects S1 and S5 more. The analysis also determines those principal components (PCs) with a strong anthropogenic influence of e-waste activities as well as those factors caused by a mixture of other anthropogenic or natural processes influences. The major two PCs (F1 and F2) that explained the influence of e-waste activities accounted for 82.1% of all the data variation based on their cumulative variability. Figure 3 shows that F1was equivalent to 50.8 % of the total variance with high positive loading on Pb, Cd and Cu. However, F2 amounted to 31.2 % of the total variance with high positive loading on Ni and Cr. The Zn concentrations were partially influenced by e-waste activities, but majorly from other activities and natural sources.

Pollution Indices for Risk Assessment

The contamination factor, index of geo-accumulation, and ecological risk index were used to assess the risks posed by heavy metals in soil samples collected from both informal e-waste processing sites and a reference site. The results of these calculations are shown in Table 4. Table 4 provides information about the contamination factor of the five different heavy metals in soil samples taken from different sites in the e-waste processing sitesand the reference site.

Table 4. Contamination factor (C_f) and index of geo-accumulation (I_{geo}) of the heavy metals found in the soil samples collected from five informal e-waste processing sites and one reference site

Sampling site	Parameter	Pb	Cd	Cr	Zn	Cu	Ni
S1	Cf	54.3	8.9	2.0	60.1	194	3.3
	I_{geo}	5.2	2.6	0.4	5.3	7.0	1.1
S2	Cf	208	32.9	2.7	252	888	22.9
	I_{geo}	7.1	4.5	0.9	7.4	9.2	3.9
S3	Cf	722	50.9	1.9	293	2150	13.9
	I_{geo}	8.9	5.1	0.4	7.6	10.5	3.2
S4	Cf	516	27.8	1.8	169	127	4.0
	I_{geo}	8.4	4.2	0.3	6.8	6.4	1.4
S5	Cf	103	16.4	2.2	452	127	4.7
	I_{geo}	6.1	3.5	0.6	8.2	6.4	1.7
S6	Cf	0.8	0.1	0.7	0.9	1.1	3.6
	I_{geo}	0.1	0.1	0.1	0.1	0.1	3.7

The results show that the contamination factor (C_f) and the geo-accumulation index (I_{geo}) of the six heavy metals at the reference site (S6) were generally lower than that of the exposed sites, except Ni, which was higher than the value at S1. Based on Table 4, a comparison of C_f and I_{geo} of all of the heavy metals showed the sequences, in descending order, was Cu > Zn > Pb > Cd > Ni > Cr.

Ecological risk index (Er) and potential ecological risk index (RI)

The ecological risk index (Er) and potential ecological risk index (RI) of the six heavy

metals found in the soil samples collected from the informal e-waste processing sites and the reference site were presented in Table 5.

Table 5. Ecological risk index and potential ecological risk index of heavy metals found in the soil samples collected from the informal e-waste processing sites and the reference site

Sampling site	Pb	Cd	Cr	Zn	Cu	Ni	RI = ∑Er
S1	181	178	2.7	40.1	648	10.9	1060
S2	692	659	3.6	168	2961	76.5	4560
S3	2407	1017	2.6	196	7166	46.3	10835
S4	1720	557	2.4	113	422	13.4	2828
S5	343	327	3.0	301	422	15.7	1412
S6	0.8	0.7	3.6	4.6	2.1	108	120

It shows that, except for the indices for Cr and Ni, the rest of the Er indices for the remaining four heavy metals (Pb, Cd, Zn, and Cu) found in S1 through S5 were consistently higher than that of the control (S6). This indicated that the findings of Pb, Cd, Zn, and Cu found in S1 through S5 were closely related to the activities of e-waste dismantling and burning conducted at the processing sites as their Er were greater than the background Er found in the control (S6). The Er of Cr and Ni, however, were below their respective background numbers shown in the control (S6).

DISCUSSION

This study unveiled a global issue – elevated concentrations of heavy metals, including lead (Pb), zinc (Zn), copper (Cu), cadmium (Cd), and nickel (Ni), within the soils of these informal e-waste processing sites. This discovery shows the extent of soil contamination, which carries substantial environmental implications. The repercussions extend to potential soil degradation, posing risks of soil pollution. Furthermore, the incineration of e-waste at select sites intensifies these concerns, exacerbating soil-related challenges. Results from this study on the heavy metal concentrations in topsoils (0–15 cm) of the study sites within the Alaba International Market were found to be comparable to the values reported from other areas in China [56-62], Thailand [63], India [64], a major city with high informal e-waste processing in West Africa [21], and Vietnam [28][65-66]. The increased heavy metal concentrations found in this study were likely due to anthropogenic activities at the e-waste processing sites at the Alaba International Market, affirming the findings of previous research. These alarming findings underscore the urgency of implementing immediate environmental management and remediation efforts, alongside the enforcement of stricter regulations. These measures are essential to protect both the environment and public health from the detrimental effects of informal e-waste processing activities.

The results of this study supported the existence of positive correlations between certain heavy metals. This positive linear relationship suggests that the presence of one contaminant may elevate the risk of exposure to others. Therefore, it emphasizes the necessity for a holistic approach to managing contaminants released from informal e-waste processing sites. As such, further research is needed to understand the interactions between different heavy metals and between different heavy metals and their effects on ecological systems. The results of this study may be useful for the development of effective remediation strategies to mitigate the ecological risks posed by heavy metals released from an informal e-waste processing site. The positive correlations found in this study are consistent with some previous findings reported. For example, [18] found high levels of Pb and Cu in soil samples collected from an e-waste contaminated site. Similarly, [61] also found a high positive correlation between Pb and Cd in

soil samples. The findings reported by [51] [62] [67-72] further lent support to a similar positive correlation observed between heavy metals found in contaminated soils samples.

The principal component analysis (PCA) played a pivotal role in revealing the influence of e-waste activities on heavy metal concentrations within the soil. This analysis unveiled two primary principal components, designated as F1 and F2, which collectively accounted for a significant portion of the data variation. F1, the first principal component, demonstrated a strong connection with specific heavy metals, including lead (Pb), cadmium (Cd), and copper (Cu). This finding underscores the interplay between these metals and e-waste processing activities. On the other hand, F2, the second principal component, exhibited a notable correlation with nickel (Ni) and chromium (Cr). These metals, too, are influenced by the e-waste processing operations under scrutiny. Crucially, the PCA effectively categorized the various exposed sites based on their heavy metal profiles. This categorization highlighted the substantial impact of e-waste activities on heavy metal release, distinguishing these sites from those influenced primarily by natural sources or other anthropogenic activities. Within this categorization, it became evident that sites directly involved in the processing of e-waste (S2, S3, and S4) were responsible for the highest levels of heavy metal release. Conversely, sites primarily engaged in storage and simple physical separation (S1 and S5) were more influenced by natural sources or other non-e-waste-related anthropogenic activities. Furthermore, the analysis reinforced the conclusion that a complex and significant positive correlation exists between e-waste processing activities and heavy metal concentrations at the exposed sites. This finding aligns with prior research, such as the study conducted by [57], which suggested that both heavy metal sources and various human activities collectively contribute to the mean concentration of heavy metals at e-waste processing sites.

Detection of the high values of C_f and I_{geo} on Cu, Zn, and Pb indicated that these three heavy metals were commonly present in EEE, which were subject to processing before being released into the environment. These heavy metals were of the highest risks to the environment compared to Cd, Ni, and Cr. Similarly, a comparison of C_f and I_{geo} among the six sampling sites showed that the heavy metals found in S2, S3, and S4 were mostly higher than those in S1 and S5, suggesting that those found in S2, S3, and S4 were closely associated with the anthropogenic activities in e-waste burning, stockpiling, extracting, and recovery. Furthermore, high I_{geo} values on Cu, Zn, and Pb found in S2, S3, and S4 indicated a continued accumulation in the soil of these heavy metals due to e-waste processing activities. Although considered pollutants of public health and environmental concerns when present, Cr and Ni were not the subjects of the Er study as their presence did not appear to be closely associated with any of the e-waste processing activities in S1 through S5.

As mentioned above, assessments of the ecological risks (Er) of the six heavy metals were grouped into five categories from low ecological risk ($Er < 40$) to very high ecological risk ($Er > 320$) [73]. Chromium in soil samples from five exposed sites indicated a low ecological risk. The values of Cr in the soil were found below 40, indicating that the presence of Cr in these sites did not pose a significant ecological risk, which was consistent with the findings of previous studies [74]. The ecological risk posed by Ni was low to moderate at the burning sites and low at the metal extraction and dismantling sites. On the other hand, Cd, Pb, and Cu posed a very high ecological risk, with maximum values exceeding the threshold of 320. The order of heavy metal toxicity, based on their contribution to environmental risk, was Cu > Pb > Cd > Zn > Ni > Cr. [75] explained that the ecological risk index also reflected the sensitivity of biological communities to hazardous substances. The potential ecological risk (RI) values for all informal e-waste activity sites were very high. The RI index for these sites wase-waste stockpiling/burning site >peripheral burning site > metal extraction/recovery site > e-waste dismantling site > waste dumping and disassembling. In terms of ecological risk, burning presented a more significant risk compared to dismantling, ranging from considerable

at S1 to very high at S2 to S4.

The results indicated that Cu, Pb, Zn, and Cd posed a severe ecological risk to the soil's biological community, which was consistent with the findings of [76]. The site with the highest ecological risk was S3, where Cu had the highest concentration, followed by Pb and Cd. [77] emphasized the importance of considering metal toxicity and its impact on the environment when conducting an ecological risk assessment. Hence, it could be inferred that Cu posed the greatest concern in the soil, followed by Pb, which was reported to impact the neurological system of children [78]. The alarming concentrations of heavy metals in soil samples from the Alaba international market as revealed in this study underscore the urgency of implementing immediate environmental management and remediation efforts, alongside the enforcement of stricter regulations. These measures are essential to protect both the environment and public health from the detrimental effects of informal e-waste processing activities.

CONCLUSION

Results of this study on heavy metal contaminations in the soil samples collected from Alaba International Market showed that the soil was contaminated with heavy metals such as Cu, Zn, Pb, Ni, Cr, and Cd, with Cu being the most prevalent. The levels of heavy metals in the soil exceeded the maximum allowable limit as recommended by the Nigerian DPR (2002). The distribution of heavy metals varied across the exposed sites, and there was no significant correlation among them. The open burning sites posed the highest ecological risk among all the five sampling sites, followed by the dismantling sites. This study ranked the ecological risks of the selected heavy metals in the following order: Cu>Pb>Cd>Zn>Ni>Cr, with Cu, Cd, and Pb presenting the most severe ecological risks. Given these findings, it is imperative to implement proper e-waste management practices and undertake remediation efforts in the Alaba International Market sites to minimize the environmental pollution of heavy metals and their potential ecological risks to human health.

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AUTHORS CONTRIBUTIONS

Adedoyin Bankole: Concept, Sample collection, Field and laboratory analysis Manuscript writing, Data generation; Akinyemi Ogunkeyede: Original draft manuscript writing, data analysis; Hien Ngo: Content review, Language editing; Li Liang: Content review, Language editing; Harrison Agboro: Field analysis; Khadijah Isimekhai: Laboratory analysis and results interpretation; Ekaette Fadairo: Field and Data analysis; Gospel Isangadighi: Language editing; Efe Isukuru: Manuscript editing, Result interpretation; Charles Ogbodhu: Field analysis.

DECLARATION OF INTEREST STATEMENT

The authors declare no conflict of interest.

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