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Chapter

Heavy Metal Pollution Resulting from Informal E-Waste Recycling in the Greater Accra Region of Ghana

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Abstract

This study investigated concentrations and spatial distributions of four heavy metals: Cadmium (Cd), Chromium (Cr), Copper (Cu), and Lead (Pb) in the soil and drainage systems resulting from informal e-waste recycling at Ashaiman, a town in the Greater Accra Region of Ghana. Twenty-four soil samples were randomly taken from two open burning sites, and three water samples from a drainage that flows through the scrapyards were digested using standard wet digestion methods. An atomic absorption spectrophotometer (AAS) was used to analyze three replicates per sampling location for the heavy metals. The results revealed that the soil and drainage samples were polluted, with the metallic levels exceeding the World Health Organization (WHO), the Food and Agricultural Organization (FAO) of the United Nations, and the Environmental Protection Agency (EPA) of Ghana limits. Geoaccumulation index (I_{geo}), pollution load index (PLI), and contamination factor (CF) further confirmed the contamination of the scrapyards by the heavy metals. Spatial distribution maps showed elevated levels of the heavy metals at portions designated for open burning and disposal of e-waste materials. The research corroborates studies on pollution of the environment by informal e-waste activities and underscores the urgent need for policy implementation and law enforcement to halt further pollution.

Keywords: e-waste recycling, heavy metals, pollution indices, spatial distribution, Ashaiman scrapyards-Ghana

1. Introduction

E-waste has other names, such as waste electrical and electronic equipment (WEEE) and e-scrap. There is no universally-agreed e-waste definition in both legislation and daily usage. This has generated countless definitions in e-waste regulations, policies, and guidelines. In this paper, we adopt the non-legal definition provided by Solving the E-Waste Problem (StEP) Initiative White Paper [1], which is as follows: “E-Waste is a term used to cover items of all types of electrical and electronic equipment (EEE) and its parts that the owner has discarded as waste without the intention

of re-use.” By this definition, selecting the Ashaiman scrapyards in the Greater Region of Ghana as the study area is seamlessly connected and justified. Due to their different lifespan profiles, different e-waste materials generate different volumes, potential environmental and health impacts, and economic values [2].

Owing to rapid changes in technological updates and upgrades of EEE, industrialization and modernization, an increase in disposable income, and the popularized increase in the use of EEE, there is an upsurge in the acquisition and utilization of electrical and electronic products. Consequently, e-waste generation has the world's largest and fastest growth rate. Asia contributed most to the generation of e-waste in 2019, generating close to 24.9 million Metric tons (Mt), followed by Europe (12.0 Mt), Americas (13.1 Mt), Africa (2.9 Mt), and Oceania (0.7 Mt) [2, 3].

As a result of free and illegal trading activities and the lack of implementation of environmental policies, Africa receives high quantities of potential e-waste materials from these continents. Liberia, Nigeria, Ghana, Benin, and Ivory Coast are major destinations for these “slightly used” materials [4]. Around 600,000 used EEE were imported into Nigeria in 2010. Also, close to 30% of second-hand imports into the country were considered non-functioning and thus regarded as e-waste. Ghana's e-waste quantities rose from 63,000 tons per year in 2003 to 169,000 tons per year in 2008, with a further increment to 215,000 tons in 2009. Only 30% of the total electrical appliances that arrived in Ghana in 2009 were determined to be new, with the rest regarded as used products, 15% of which were either faulty or out-moded and thus could not be sold, eventually ending up in the informal recycling sector [5].

However, e-waste materials in Ghana or Africa need to be better managed due to ignorance on the part of the public on the dangers of poor disposal systems, lack of safe systems of disposal, and absence of government policy and legislation or the enforcement of same. E-waste management in Ghana, just like in most African countries, is managed by the unhindered and poorly equipped informal sector [1]. Manual dismantling, acid leaching, open burning, and indiscriminate disposal of e-waste material are usually the methods of choice in the informal sector to recover valuable metals such as Cu, Au, and Ag that can be resold. These actions release toxic substances, including Polycyclic Aromatic Hydrocarbons, Organochlorine compounds, Phthalates, and heavy metals [2, 6]. The release of these compounds results in atmospheric pollution, and a reduction in the physicochemical characteristics of water quality, including pH, phosphate, oxygen, and chloride levels. Soil composition and viability to support plant life are compromised severely following e-waste contamination. [7–9]. Essentially, poor e-waste management has a negative outlook on the realization of the Sustainable Development Goals (SDGs), particularly Goals 3 (Good health and wellbeing), 6 (Clean water and sanitation), 8 (Decent work and economic growth), 11 (Sustainable cities and communities), 12 (Responsible consumption and production), and 14 (Life below water) [1].

Heavy metals are significant components of e-waste materials. The application of these metals in electrical gadgets is influenced by good electrical conductivity to minimize power losses, an inert environment in operations to ensure reliable functioning, and using metals compatible with manufacturing processes [10]. Heavy metals make up about 60.2% of significant constituents of e-waste, including elements such as Tin (Sn), Mercury (Hg), Antimony (Sb), and Arsenic (As) [11]. The parent circuit board of many electrical gadgets houses heavy metals like As, Cd, Pb, and Hg [2]. For example, Pb constitutes nearly 0.4–1.0 kg of the total mass of cathode ray tubes found in computer monitors and television sets, respectively. Also, personal

desktop computers (which weighed approximately 32 kg) contain Pb (6.3%), Cu (6.9%), Cobalt (Co) (0.02%), and Iron (Fe) (20.5%) [2, 11].

Heavy metals released during informal e-waste recycling are absorbed into living tissues, usually through inhaling toxic fumes and particulate matter and ingesting contaminated food and water [6]. Cadmium (Cd) is a known carcinogen of the lungs, kidneys, and prostate. Exposure to Cr causes cardiovascular diseases, hematological and neurological effects, and sometimes even death. Pollution resulting from Pb induces memory loss, dullness, anemia, convulsions, tremors, headache, and irritability, while respiratory irritation such as coughing and sneezing, gastrointestinal effects, including nausea, anorexia, diarrhea, and hematological effect result from exposure to Cu [12–15].

The informal sector dominates e-waste recycling activities in Ghana. This is mainly due to the need for more implementation of environmental-related laws and poverty. It is estimated that between 121,800 and 201,600 individuals are involved in the informal e-waste sector in Ghana. The formal recycling sector in Ghana receives only about 0.2% of e-waste for treatment [16]. Unsurprisingly, Ghana is noted for having one of the most significant e-waste recycling in Africa, at Agbogbloshie in Accra, Ghana.

This research assessed the pollution levels and spatial distributions of four heavy metals (Cd, Cr, Pb, and Cu) at two burning sites within the Ashaiman scrapyards in the Greater Accra Region of Ghana, where informal e-waste recycling occurs. Pollution levels of the heavy metals were investigated using selected pollution and contamination indices. The spatial distributions were also investigated using inverse distance weighted (IDW) method. The rest of the chapter is structured as follows: Section 2 describes Materials and Methods; Section 3 focuses on the Results. One of the key findings is that soil and drainage systems of the Ashaiman scrapyards were polluted with Cu, Pb, Cr, and Cd, mainly due to open burning and dumping of e-waste materials; Section 4 is devoted to Discussion; and Section 5 presents the Conclusions of the study.

2. Materials and methods

The Ashaiman scrapyards are located at the entry into the township from the Tema metropolis, about 0.12 km from the Accra-Tema Motorway. Covering a land size of about 0.07 km², it is located on latitude 5° 41'4.99" N and longitude 0° 01'37.28" W. The region is generally flat, with savannah grasses and shrubs being the dominant vegetation. The topsoil is primarily sandy clay, with the subsoil predominantly clay [17, 18].

The scrapyards house large metal containers, which store e-waste materials until they are ready to be worked on. Dismantling and sorting activities were performed in sheds and wooden structures at sections of the scrapyards. Burning of e-waste to isolate valuable metals was done on the open field, though few burning activities were observed at the dismantling and sorting areas. At the time of research, two main sites were identified where open burning occurred. E-waste materials in the scrapyards included refrigerators, television sets, computers, cables, radios, and incandescent light bulbs.

Located very close and separating the scrapyards from a dumpsite is a drain that flows from the northern end of the scrapyards and serves as irrigation for farming crops and drinking water for herds of cattle.

2.1 Sample collection

2.1.1 Soil samples

Two burning sites (F and H) were chosen for soil sampling. Site F is located at the central portion of the scrapyard. Major parts of this site were used for the open burning of e-waste, though a few sections served as dumping grounds for e-waste material after dismantling, sorting, and burning. Site H lay closer to the drain running through the scrapyard. This site was used both for open burning and dumping of e-waste materials. **Figure 1** shows a map of the scrapyard area.

Samples were taken in the early hours of 16 July 2019. At each burning site, five topsoil samples (marked 1A, 2A, 3A, 4A, and 5A) within a soil depth of 0–10 cm and five subsoil samples (marked as 1B, 2B, 3B, 4B, and 5B) within a depth profile of 10–20 cm, were randomly collected from different sections. Thus, 10 soil samples were taken from each burning site, and 20 samples were obtained from the two burning areas. Four other topsoil samples were taken at distances of 25 m, 50 m, 75 m, and 100 m from the scrapyard (marked as HV 20, HV 50, HV 75, and HV 100, respectively) to test the detection of heavy metals as one moved away from the scrapyard. Sampling was done with a newly purchased stainless-steel garden shovel and a standard measuring rule to determine the vertical depth of the soil profile. The coordinates at sampling points were recorded using GPS software. A map showing the sampling points of the soil samples is shown in **Figure 2**.

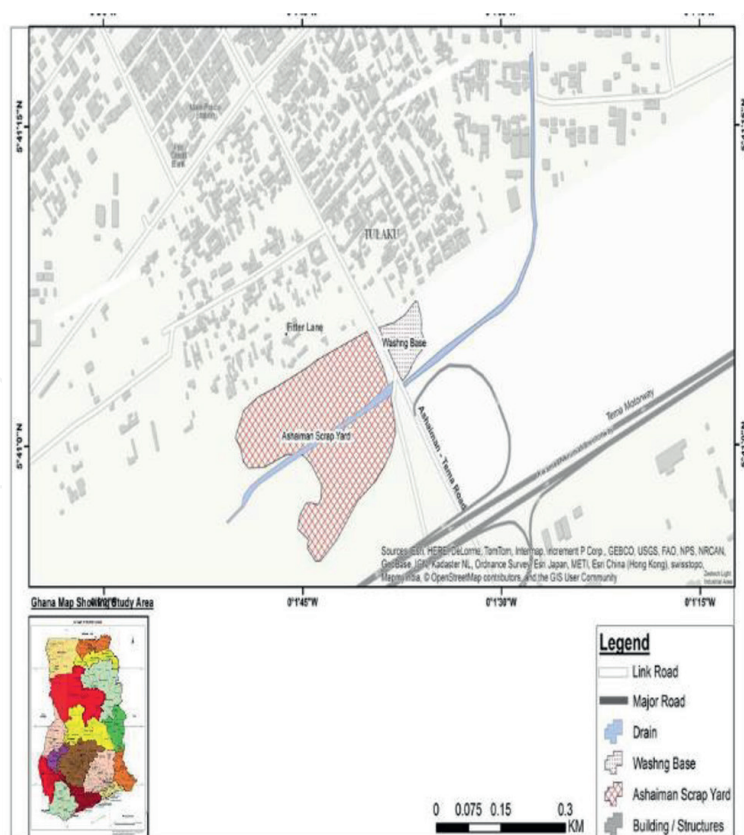


Figure 1.
Map showing scrapyard at Ashaiman.



Figure 2.
Aerial view of the sampling points at the scrapyard.

2.1.2 Water samples

Three water sediment samples were collected about 140 m north of the scrapyard and mixed to form the control sample (WS C). Within the scrapyard, a water sediment sample was collected (WS 1), about 370 m from the control sample. In contrast, a second sample (WS 2), purely water without sediment from the drain, was also obtained, about 30 m from the second water sediment sample. Coordinates were taken using GPS software. pH of these samples was taken on-site using a Hanna pH meter calibrated with buffer solutions of pH 4, 7, and 10.

Samples were collected into plastic bowls with tightly fitting lids pre-cleaned with nitric acid and sent to the Ghana Standards Authority for treatment and analysis.

2.2 Soil sample preparation and determination of pH

Soil samples were air dried at around 105°C to eliminate wetness and obtain only constant weights representing the soil. They were then passed through a 2 mm non-metallic mesh to separate and remove rocks exceeding 0.25 inches (6.35 mm). Manual milling with mortar and pestle thoroughly homogenized the soil particles passing the mesh. These preparations were necessary for good dissolution during chemical treatments

to increase the accuracy of the analysis [19]. To 3 g of each of the dried and sieved soil samples in a 25 ml beaker (which had been pre-cleaned and thoroughly washed with distilled water), 15 ml of aqua regia was added, and the resulting solution digested in a fume chamber for about 30 minutes to remove foreign materials that might interfere with the analytical test. Following cooling, distilled water was added to the digested sample and filtered into a 100 ml volumetric flask using the Johnson test paper filter paper with a diameter of 125 mm. Distilled water was added to the solution to the 100 ml mark.

Soil samples were prepared for pH analysis by dissolving 2 g of each sample in distilled water in a 1:1 ratio and stirring to a uniform suspended mixture using a clean glass rod. The samples were then allowed to settle for about 10 minutes. The samples were continually stirred for about 15 minutes using a magnetic stirrer on a magnetic sitter plate. The samples were allowed to settle, and their pH was determined by a handheld Hanna pH meter calibrated with pH buffer solutions 4, 7, and 10 [20, 21].

2.3 Water sample preparation

Water and sediment samples collected were filtered using the Johnson test paper filter paper with a diameter of 125 mm. In total, 10 ml of each filtrate was drawn into a 250 ml beaker, to which a 25 ml mixture was made up of 15 ml conc. HNO_3 and 10 ml conc. HCL was added and digested in a fume chamber for about 20 minutes. For efficient digestion of the water samples, an additional 10 ml of conc. HCL was added and heated in the fume chamber for about 15 minutes. Upon cooling, further filtration was carried out. Distilled water was added to the filtrate and made up to the 100 ml mark.

2.4 Determination of heavy metal concentrations

For each soil/water sample, calibration curves were prepared using heavy metal standards: 0.50, 1.00, 2.00, and 4.00 mg L^{-1} standards were each prepared in the spectrophotometric quantification of Cr, Cu, and Pb while calibration curves of concentrations 0.10, 0.20, 0.40, and 0.80 mg L^{-1} were ready in the case of Cd. For each soil/water sample, duplicate analyses were performed using Perkin Elmer 400 atomic absorption spectrophotometer with air-acetylene gas serving as fuel for the flame. Serial dilutions were performed on the samples where concentrations were very high, and after that, their dilution factors were factored in determining their concentrations.

2.5 Permissible limits of heavy metals in soil and water

As a guide, levels of heavy metals from the study will be compared with local and international standards of specification of heavy metals in soil and water bodies, as depicted in **Table 1**. Ghana's EPA utilizes the standards Romania set for heavy metal levels in the soil. This and Ghana EPA permissible limits for heavy metals were used as national standards to compare the heavy metals investigated in the samples. The WHO/FAO standards, available at <https://www.researchgate.net/publication/345903051> and <http://www.fao.org/3/t0234e/T0234E06.htm#ch5.5>, were used as heavy metal limits in soil and water. These standards have also been used by other authors elsewhere.

2.6 Indices for determination of soil pollution

Three pollution indices were employed to evaluate how much the four heavy metals had polluted the scrapyards and its environment. The geoaccumulation index

Heavy metal	EPA Ghana limit in soil (ppm)	EPA Ghana limit in water (ppm)	WHO/FAO limit in soil (ppm)	WHO/FAO limit in water (ppm)
Cd	1	—	3	0.01
Cr	30	0.1	100	0.1
Cu	20	—	100	0.2
Pb	20	0.1	50	5

Table 1. Ghana EPA and WHO/FAO permissible levels of heavy metals in soil and water.

(I_{geo}) determines the contamination of heavy metals by assessing their concentrations in sampled soils relative to background concentrations during pre-industrial periods [22, 23]. I_{geo} is computed using the mathematical formula:

$$I_{geo} = \log_2 (C_n / 1.5B_n) \quad (1)$$

C_n measures the heavy metal levels in the sediment under investigation, while B_n represents the geochemical background level [24]. The constant of 1.5 is to lessen the possible variations in the background data. Based on the results obtained, soils can be categorized into seven quality grades of pollution, as follows: practically unpolluted, where $I_{geo} < 0$; unpolluted to moderately polluted, where $I_{geo} = 0-1$; moderately polluted, where $I_{geo} = 1-2$; moderately to strongly polluted, where $I_{geo} = 2-3$; strongly polluted, where $I_{geo} = 3-4$; strongly to extremely polluted, where $I_{geo} = 4-5$ and extremely polluted, where $I_{geo} > 5$ [25].

The contamination factor (CF) evaluates quantities of an element in a sample normalized over the pre-industrial baseline value of the component [26]. Mathematically, CF is expressed as

$$CF = C_e / C_i \quad (2)$$

Where C_e and C_i are, respectively, the heavy metal concentration levels in the sample of interest and the background value of the heavy metal of interest, based on values obtained, soil or sediments can be classified as no or low contamination, where $CF < 1$; moderate contamination, where $1 < CF < 3$; considerable contamination, where $3 < CF < 6$; very high contamination, where $CF > 6$ [27].

The pollution load index (PLI) [28] examines the mutual contribution of groups of metals to the pollution of a site. Mathematically,

$$PLI = (CF_1 \times CF_2 \times CF_3 \times CF_4 \times CF_5 \times \dots \times CF_n)^{1/n} \quad (3)$$

where CF represents the contamination factor of each heavy metal element in a sampled soil and n is the number of heavy metals under consideration. The PLI indicates whether the site under consideration is lightly polluted, where $PLI \leq 1$; moderately polluted; where $1 < PLI \leq 3$; highly polluted, where $PLI > 3$ [27, 28].

For instance, the metallic pollution levels in a study conducted by Fosu-Mensah et al. [28] were assessed using the WHO/FAO standards, whose links have been provided already.

2.7 Statistical and data analysis

Descriptive statistical variables, such as the mean, maximum, minimum, and standard deviation of heavy metal concentrations computed using Microsoft Excel software 2016 version. Pearson correlation, t-test, and coefficient of variation (CV) of the heavy metal concentrations were calculated by SPSS, version 21.0.

3. Results

3.1 Soil pH

Tables 2 and 3 show levels of heavy metals with their respective pH. pH values ranging from a mildly acidic pH of 5.88 to high alkaline pH of 8.03 was recorded for site F with an average of 7.13. At site H, samples had pH values between 6.07 and 7.78 and a mean of 6.94. pH values recorded were within the WHO benchmark of 6.5–8.5, except for three samples (5.88 at site F and 6.07, 6.38 at site H), which recorded pH values below the 6.5 minimum threshold.

Site /sample	Latitude	Longitude	Concentration of selected heavy metals (ppm)				pH
			Cd	Cr	Cu	Pb	
F							
1A	5.682713N	0.029065W	0.92	73.02	82.60	99.63	7.36
1B	5.682713N	0.029065W	n.d.	123.07	70.74	13.58	7.14
2A	5.682441N	0.029085W	0.05	49.08	129.37	276.78	6.86
2B	5.682441N	0.029085W	0.03	13.97	29.97	38.73	5.88
3A	5.682558N	0.028997W	0.17	162.50	122.30	83.48	6.80
3B	5.682558N	0.028997W	0.12	117.27	92.22	14.10	7.35
4A	5.682700N	0.028879W	0.11	60.81	219.82	32.97	7.38
4B	5.682700N	0.028879W	0.02	36.37	73.64	40.25	7.46
5A	5.682575N	0.029130W	0.52	67.49	74.42	38.75	7.04
5B	5.682575N	0.029130W	1.57	69.74	253.42	132.45	8.03
MEAN			0.39	77.33	114.85	77.07	7.13
MIN			0.02	13.97	29.97	13.58	5.88
MAX							
STDV			1.57	162.50	253.42	276.78	8.03
			0.53	44.57	70.34	80.10	0.56

n.d., not detected.

Table 2.
Concentration and pH of soil samples at site F.

Site /sample	Latitude	Longitude	Concentration of heavy metals (ppm)				pH
			Cd	Cr	Cu	Pb	
H							
1A	5.683217N	0.029051W	0.29	17.11	108.76	84.29	7.78
1B	5.683217N	0.029051W	0.34	15.40	7.07	59.43	6.58
2A	5.683190N	0.028980W	1.67	30.11	5.24	300.25	6.91
2B	5.683190N	0.028980W	1.05	15.95	10.76	514.80	7.09
3A	5.683153N	0.028938W	13.56	25.25	12.40	1781	7.38
3B	5.683153N	0.028938W	2.34	22.32	14.05	46.61	7.44
4A	5.683145N	0.029027W	6.87	21.11	48.00	572.79	6.50
4B	5.683145N	0.029027W	0.53	17.31	6.85	261.26	6.07
5A	5.683328N	0.028788W	7.96	23.10	185.77	1000.85	7.24
5B	5.683328N	0.028788W	6.79	22.32	84.76	556.20	6.38
MEAN			4.14	21.00	48.37	341.41	6.94
MIN			0.29	15.40	5.24	1781	6.07
MAX			13.56	30.11	185.77	1000.85	7.78
STDV			4.46	4.65	60.58	317.96	0.54

Table 3.
 Concentration and pH of soil samples at site H.

3.2 Heavy metal concentrations at the burning sites of the scrapyards

The concentrations of the four heavy metals obtained are detailed in **Tables 2** and **3**. At site F, Cd ranged from a non-detection level to a maximum concentration of 1.57 ppm and an average of 0.48 ppm. Except for a subsoil sample with a concentration of 1.57 ppm, all Cd concentrations at site F were below the Ghana EPA permissible limit of 1.0 ppm and the WHO/FAO standard of 3 ppm. At site H, Cd concentrations were comparatively higher, with a minimum of 0.29 ppm, a maximum of 13.56 ppm, and an average concentration of 4.14 ppm, which exceeded Ghana EPA and the WHO/FAO standards.

A minimum concentration of 13.97 ppm and a maximum concentration of 162.50 ppm were recorded for Cr, with an average concentration of 77.33 ppm at site F. Most Cr concentrations exceeded the Ghana EPA threshold value of 30 ppm. Three samples also had Cr concentrations (123.07 ppm, 162.50 ppm, and 117.27 ppm) above the WHO/FAO standard of 100 ppm. However, Cr levels from site H were below the permissible limit of WHO/FAO and Ghana EPA with minimum and maximum concentrations of 15.95 ppm and 30.11 ppm, respectively, and an average of 21.00 ppm.

At site F, minimum and maximum concentrations of 29.97 and 253.42 ppm were recorded for Cu, with an average concentration of 114.85 ppm. They exceeded the permissible levels of Ghana EPA (20 ppm) and the WHO/FAO standards of 100 ppm. Also, at site H, Cu recorded minimum and maximum concentrations of 5.24 and 108.76 ppm, respectively, and an average concentration of 48.37 ppm, above the national and international standard limits.

At site F, a minimum concentration of 13.58 ppm and a maximum concentration of 276.78 ppm were recorded for Pb with an average concentration of 77.07 ppm, which

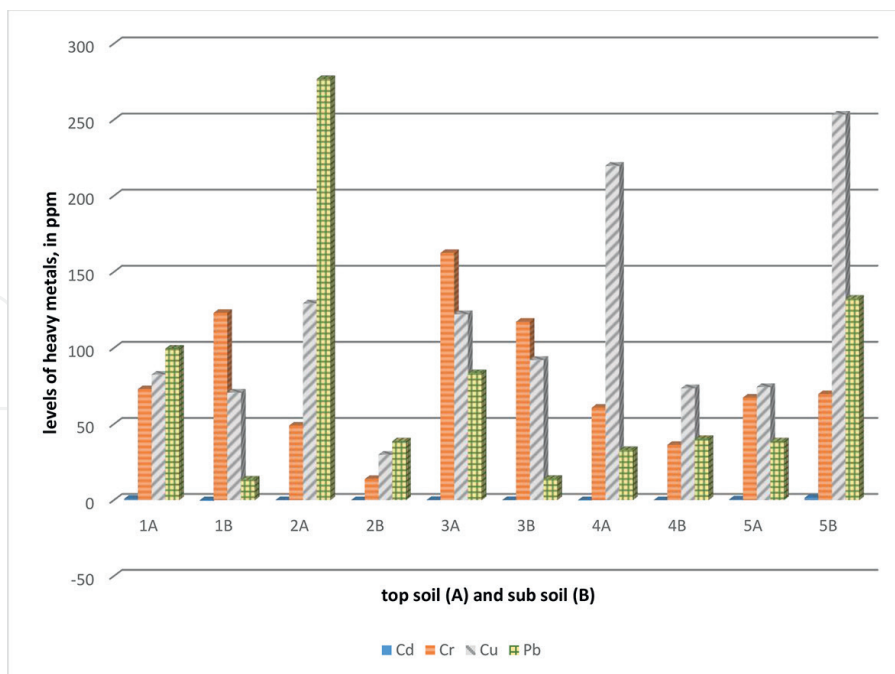


Figure 3.
Heavy metal levels in samples from site F.

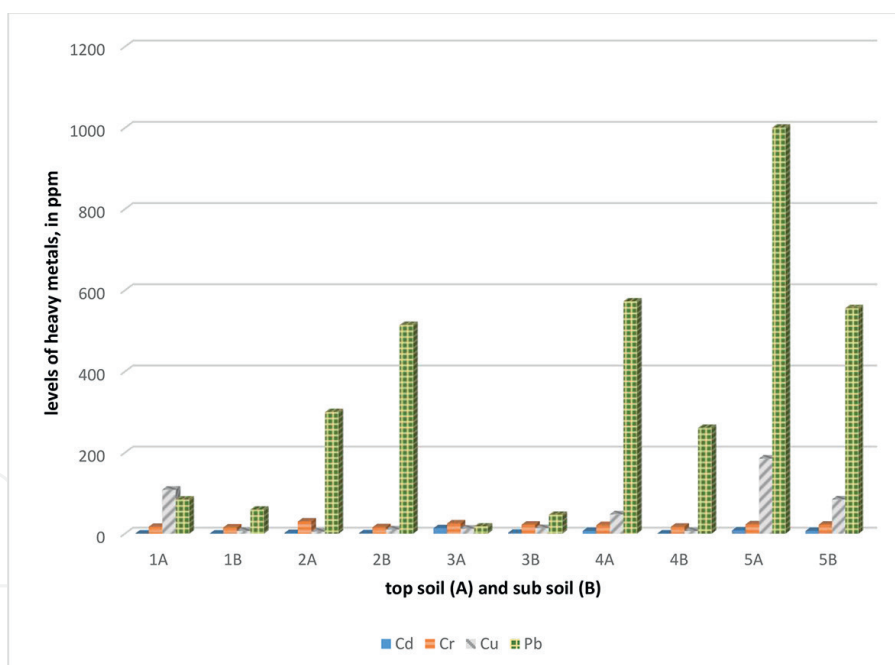


Figure 4.
Heavy metal levels in samples from site H.

was above the WHO/FAO and Ghana EPA standard of 50 ppm and 20 ppm, respectively. Pb in the sampled soil had a minimum concentration of 17.81 ppm, a maximum concentration of 1000.85 ppm, and an average concentration of 341.43 ppm at site H, exceeding the Ghana EPA and WHO/FAO standard limits.

The extent of pollution at sites F and H can be respectively expressed as $Cu > Cr > Pb > Cd$ and $Pb > Cu > Cr > Cd$. This is also illustrated graphically in **Figures 3 and 4**.

Cities	Cd	Cr	Cu	Pb	Reference
Koforidua, Ghana	3	47	14,300	3530	[6]
Ibadan, Nigeria	2.50 ± 0.08	42.4 ± 2.6	3483 ± 980	5650 ± 750	[29]
Bangalore, India	0.478	54	429	126	[30]
Wenling, China	3	101.29	180.66	18730	[31]
Ashaiman, Ghana	796	23.10	185.77	1000.85	Current research

Table 4.
 A review of research studies on heavy metals concentrations (ppm) in e-waste soil.

Heavy metal concentrations in this study were similar to other research works in e-waste research, as shown in **Table 4**. Generally, Cu and Pb were in high concentrations in most of the research studies. Also, Cd concentrations are lower in most e-waste soils in other research works.

3.3 Statistical analysis

Pearson correlation revealed a positive relationship ($p < 0.05$ and $p < 0.01$) between Cd and Cu, Cd and Pb, and Cu and Pb in the subsoil at both investigated sites. These relationships are depicted in **Tables 5** and **6**.

Positive correlations were established between concentrations of heavy metals within the subsoil at both sites. This is shown in **Table 7**.

Coefficient of variation (CV) was computed for each heavy metal at both e-waste burning sites. Cr showed the least variation with CV values of 57.63% and 22.14%, respectively, at sites F and H. At sites F and H, CV values for Cd were high (136.77% and 107.76%, respectively), while Pb had CV values of 103.92% at site F and 93.13% at site H. A CV value of 61.24% was obtained for Cu at site F. Comparatively, a higher measurement of Cu was recorded at site H, with a CV value of 125.25%.

An independent t-test was conducted at $p < 0.05$ to determine the statistical significance of the mean concentration of the heavy metal. Results showed the following:

- i. A significant difference between Cd concentrations at site F (Mean (M) = 0.39, standard deviation (SD) = 0.53) and Cd concentrations at site H (M = 4.14, SD = 4.46), with a t-value of -2.50 and p-value = 0.02 (data are not normally distributed; skewed);
- ii. A significant difference between Cr concentrations at site F (M = 77.33, SD = 44.57) and Cr concentrations at site H (M = 21.00, SD = 4.65), with a t-value of -3.98 and p-value = 0.001 (data are normally distributed);
- iii. A significant difference between Cu concentrations at site F (M = 114.85, SD = 70.33) and Cu concentrations at site H (M = 48.37, SD = 6.58), with a t-value of 2.27 and p-value = 0.04 (data are normally distributed); and
- iv. A significant difference between Pb concentrations at site F (M = 77.07, SD = 80.10) and Pb concentrations at site H (M = 341.43, SD = 317.96), with a t-value of -2.55 and p-value = 0.02 (data are not normally distributed; skewed).

	[Cd]	[Cr]	[Cu]	[Pb]
[Cd]	1.00	-.02	.97b	.96a
[Cr]	-.02	1.00	.17	-.28
[Cu]	.97b	.17	1.00	.90a
[Pb]	.96a	.28	.90a	1.00

^asignificant correlation at the 0.05 level (2-tailed).

^bsignificant correlation at the 0.01 level (2-tailed).

Table 5.
Pearson correlation between heavy metal levels in the subsoil at site F.

	[Cd]	[Cr]	[Cu]	[Pb]
[Cd]	1	.79	.98b	.54
[Cr]	.79	1.00	.65	.08
[Cu]	.98b	.65	1.00	.61
[Pb]	.54	.08	.61	1.00

^bsignificant correlation at the 0.01 level (2-tailed).

Table 6.
Pearson correlation between heavy metal levels in the subsoil at site H.

	[Cd]	[Cr]	[Cu]	[Pb]	Site H
[Cd]	.97b	.65	.99b	.59	
[Cr]	.05	.30	-.01	-.76	
[Cu]	.95a	.72	.97b	.41	
[Pb]	.90a	.50	.95a	.76	
Site F					

^asignificant correlation at the 0.05 level (2-tailed).

^bsignificant correlation at the 0.01 level (2-tailed).

Table 7.
Pearson correlation between heavy metals in the subsoil at site F and site H.

3.4 Indices of pollution

3.4.1 Index of geoaccumulation

Table 8 shows the I_{geo} of sampled soil of the two sites. The I_{geo} showed site F was practically uncontaminated with Cd (average $I_{geo} = -1.58$) and Cr (average $I_{geo} = -1.07$) but moderately polluted with Cu (average $I_{geo} = 0.53$) and Pb (average $I_{geo} = 0.76$). At site H, I_{geo} showed moderate to strong pollution with Cd (average $I_{geo} = 2.16$) and Pb (average $I_{geo} = 2.64$), a practically unpolluted soil with Cr (average $I_{geo} = -2.72$), and Cu (average $I_{geo} = -1.63$). Site H appears more contaminated than site F, probably due to its use as a burning and dumping site for e-waste materials.

Soil sample	Igeo of heavy metals							
	Site F				Site H			
	Pb	Cu	Cr	Cd	Pb	Cd	Cu	Cr
1A	1.73	0.29	-0.89	1.03	1.49	-0.64	0.69	-2.98
1B	-1.14	0.07	-0.13	n.d.	0.99	-0.39	-3.26	-3.13
2A	3.21	0.94	-1.46	-3.24	3.32	1.89	-3.69	-2.17
2B	0.37	-1.17	-3.27	-3.99	4.10	1.22	-2.65	-3.08
3A	1.48	0.86	0.27	-1.39	-0.75	4.91	-2.45	-2.42
3B	-1.09	0.45	-0.20	-1.86	0.64	2.38	-2.26	-2.60
4A	0.14	1.70	-1.15	-2.01	4.26	3.93	-0.49	-2.68
4B	0.42	0.13	-1.89	-4.76	3.12	0.23	-3.30	-2.96
5A	0.37	0.14	-1.00	0.22	5.06	4.15	1.46	-2.55
5B	2.14	1.91	-0.95	1.81	4.21	3.92	-0.33	-2.60
MEAN	0.76	0.53	-1.07	-1.58	2.64	2.16	-1.63	-2.72

n.d., not detected.

Table 8.
Igeo of selected heavy metals at sampled sites F and H.

Soil sample	Site F					Site H				
	CF		PLI			CF		PLI		
	Pb	Cu	Cd	Cr		Pb	Cd	Cu	Cr	
1A	4.98	1.84	3.06	0.81	2.18	4.22	0.96	2.42	0.19	1.17
1B	0.68	1.57	-	1.37	1.36	2.97	1.14	0.16	0.17	0.55
2A	13.8	2.88	0.16	0.55	1.36	15.01	5.55	0.12	0.34	1.34
2B	1.94	0.67	0.09	0.16	0.37	25.74	3.50	0.24	0.18	1.40
3A	4.17	2.72	0.57	1.81	1.85	0.89	45.22	0.28	0.28	1.33
3B	0.71	2.05	0.42	1.30	0.94	2.33	7.80	0.31	0.25	1.09
4A	1.65	4.89	0.37	0.68	1.19	28.64	22.91	1.07	0.24	3.58
4B	2.01	1.64	0.06	0.40	0.52	13.06	1.75	0.15	0.19	0.91
5A	1.94	1.65	1.75	0.75	1.43	50.04	26.54	4.13	0.26	6.13
5B	6.62	5.63	5.25	0.78	3.51	27.81	22.64	1.88	0.25	4.14
MEAN	3.85	2.55	1.30	0.86	1.47	17.07	13.80	1.08	0.24	2.16

Table 9.
CF and PLI of selected heavy metals at sampled sites F and H.

3.4.2 Contamination factor and pollution load index

Table 9 provides information on the two sites' CFs and PLIs. The CF values showed site F was moderately contaminated with Cd (average CF = 1.30) and Cu (average CF = 2.55), less contaminated with Cr (average CF = 0.86), and considerably contaminated by Pb (average CF = 3.85). At site H, CF showed very high

contamination of the soil with Cd (average CF = 13.80) and Pb (average CF = 17.07), no or low contamination of the soil with Cr (average CF = 0.24), moderately contaminated soil with Cu (average CF = 1.08). Again, results show more contamination at site H than at site F, possibly because of the dumping activities and the open burning.

The PLIs of both sites were found to be moderately polluted, with respective average values of 1.47 and 2.16 at sites F and H.

3.5 Spatial distributions of the heavy metals

Figures 5–8 show spatial distribution patterns of the heavy metals at the two sites, which were analyzed using the inverse distance weighted (IDW) interpolation method. The analysis revealed elevated levels of heavy metals in subsoil (Cd, Pb at site H and Cr, Cu at site F). Spatial maps also showed that site H was more polluted with Pb and Cd, while site F was mainly Cr and Cu.

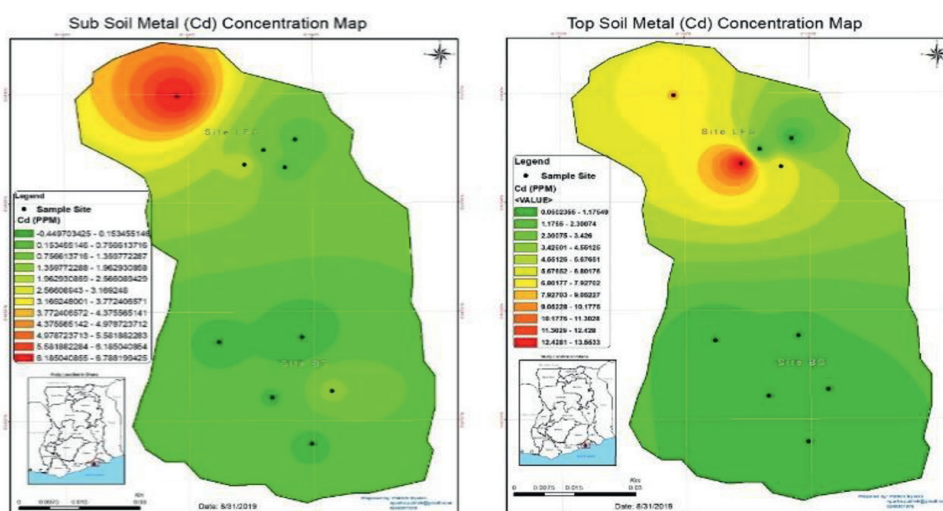


Figure 5. Spatial distributions of Cd in subsoil (L) and topsoil (R) of sites F and H.

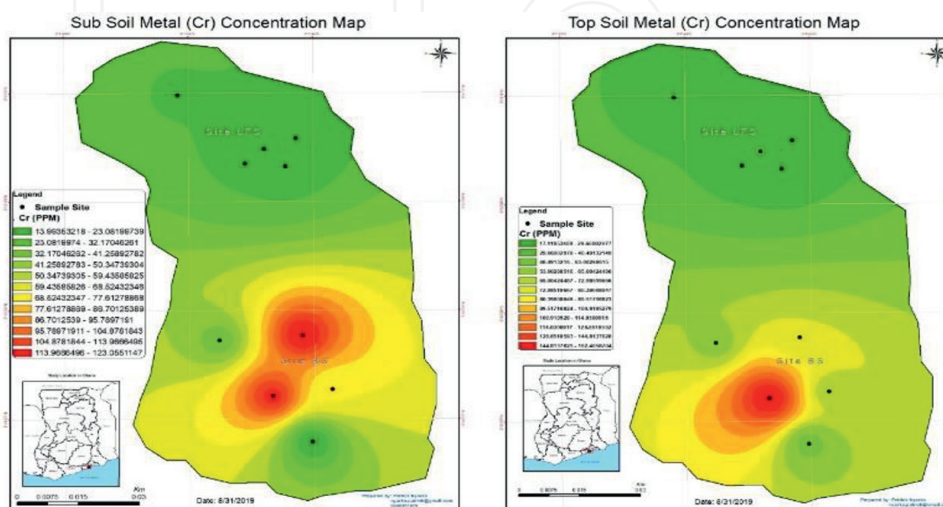


Figure 6. Spatial distributions of Cr in sites F and H's subsoil (L) and topsoil (R).

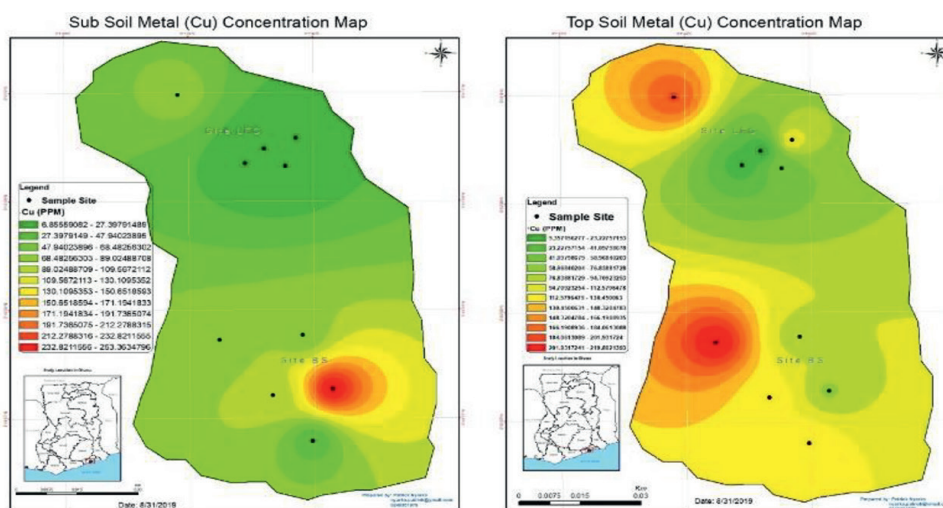


Figure 7.
 Spatial distributions of Cu in subsoil (L) and topsoil (R) of sites F and H.

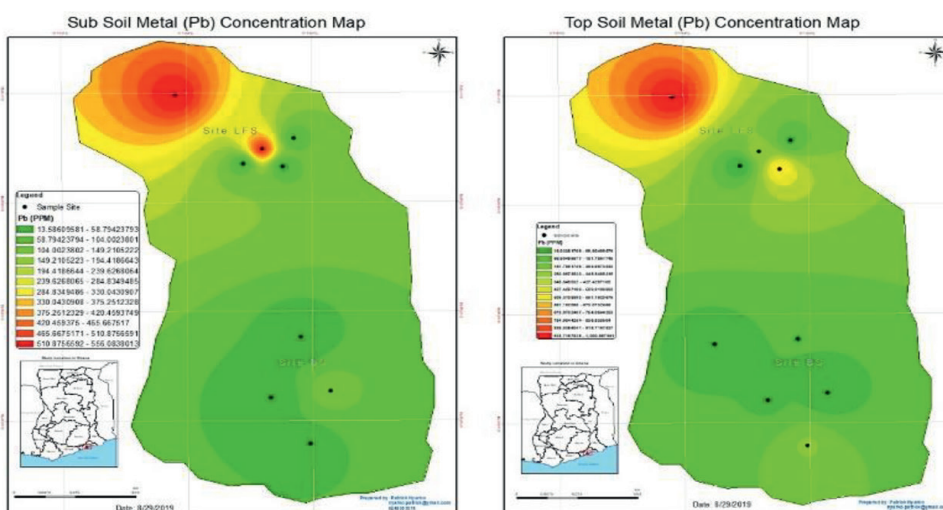


Figure 8.
 Spatial distributions of Pb in subsoil (L) and topsoil (R) of sites F and H.

3.6 Concentration differences at increasing distance from the scrapyards

The study also sought to determine levels of heavy metals in the soil components at different distances from the scrapyards. This was important to evaluate the extent to which informal e-waste activities affected nearby communities. The result is provided in **Table 10**. Soil samples taken 25, 50, 75, and 100 m from the scrapyards were mainly sandy. pH values were mildly acidic and were within the 6.5–8.5 WHO thresholds. This indicates a decreasing pH as one moves away from the scrapyards.

Results revealed no level of Cd in these soil samples. Samples within the 25 m distance recorded respective concentrations of 20.73 and 24.94 ppm for Cr and Cu and were within safe levels set by WHO/FAO but slightly above permissible levels of Ghana EPA concerning Cu. However, Pb recorded concentrations of 155.17 ppm, which exceed the safe levels of Pb as determined by both WHO/FAO and Ghana EPA. The pH of the soil sample at 25 m was almost neutral at 6.97.

Sample	Latitude	Longitude	Concentration of selected heavy metals (ppm)				pH
			Cd	Cr	Cu	Pb	
HV 25	5.682392N	0.027973W	n.d	20.73	24.94	155.17	6.97
HV 50	5.682438N	0.027473W	n.d	25.18	96.73	74.72	6.58
HV 75	5.682677N	0.026773W	n.d	4.12	4.60	5.97	6.71
HV 100	5.6826190N	0.026582W	n.d	n.d	1.26	8.97	6.72
MEAN				16.68	31.88	61.21	6.75
MIN				4.12	1.26	5.97	6.58
MAX				25.18	96.73	155.17	6.97
STDV				11.10	44.48	70.22	0.16

n.d., not detected.

Table 10.
Heavy metal levels at distances from the scrapyard.

Levels of Cr and Cu in samples within the 50 m boundary were within the safe limits set by WHO/FAO, but above permissible levels of Ghana EPA, with respective concentrations of 25.18 and 96.73 ppm. Pb quantified in these samples shows levels were above the 50-ppm threshold of WHO/FAO and the 20-ppm threshold of Ghana EPA, reaching levels of 74.72 ppm. The pH of the soil sample at 50 m was mildly acidic (6.58). Samples taken 75 m from the scrapyard had concentrations of 4.122 ppm (Cr), 4.600 ppm (Cu), and 5.965 ppm (Pb), while at a 100 m distance variation samples analyzed revealed no levels of Cr, 1.260 ppm of Cu, and 8.970 ppm of Pb.

3.7 Heavy metal concentration in water and water sediment

Table 11 compares levels of heavy metals at different sections and depths of a drain near the scrapyard. Water sediments outside the scrapyard showed lower concentrations of heavy metals than those obtained within the scrapyard. In contrast, none of the four heavy metals was detected in the water samples. Water sediment outside the scrapyard contained levels of Cd at 0.03 ppm, Cr at 11.95 ppm, and Cu and Pb concentrations, respectively, at 5.84 and 5.89 ppm. Water sediment within the scrapyard contained 0.49 ppm Cd and a concentration of 217.98 ppm for Cu. Cr had a concentration of 12.28 ppm, while Pb had a concentration of 44.77 ppm.

4. Discussion

Uncontrolled levels and spatial variabilities of e-waste have serious environmental repercussions. E-waste-laden environments have significant amounts of heavy metals. Such metals interfere with ecosystem integrity and health. Bioaccumulation and biomagnification of the metals remain persistent in the food webs. They pose severe hazards and risks to the biota. More significantly to humans, chronic exposure to these metals in uncontrolled scrap settings and using substandard resource recovery methods put them at high risk of several health damages, which include carcinogenicity, teratogenicity, mutagenicity, genotoxicity, immunosuppression, and physiological

Sample	Latitude	Longitude	Heavy metal concentration (ppm)				pH
			Cd	Cr	Cu	Pb	
WS C	5.684598N	0.026144W	0.03	11.95	5.84	5.89	7.55
WS 1	5.683145N	0.029027W	0.49	12.28	21798	44.77	7.49
WS 2	5.683328N	0.028788W	n.d	n.d	n. d	n. d	7.61
MEAN			0.26	12.12	111.91	25.33	7.55
MIN			0.03	11.95	5.84	5.89	7.49
MAX			0.49	12.28	21798	44.77	7.61
STD.V			0.33	0.23	150.00	27.49	0.06

n.d., not detected.

Table 11.
 Heavy metals concentrations in the water sample.

and biochemical disorders [32–34]. While the toxicological analysis of the above effects on scrap workers was beyond the scope of the study, the environmental profile analysis has discovered some heavy metals in the study area, which hitherto was unknown. This sets a baseline upon which future research dimensions can evolve.

The concentrations and spatial variations (using IDW) of the heavy metals and the pollution levels using Igeo, CF, and PLI have been quantified and presented in the previous section, together with pH variations at the two e-waste burning sites. Generally, the study revealed that topsoil concentrations of heavy metals were higher than those of the subsoil, with few exceptions. This general trend could be due to the strong affinity of the heavy metals, mostly Pb and Cu, with the abundance of organic matter and minerals found in the topsoil, preventing the percolation of the heavy metals into the subsoil [35–37]. Additionally, it can be inferred from the results that anthropogenic pollution of heavy metals has more effect on the topsoil than subsoil. However, heavy metals found in the subsoil are particularly worrying, as the absorption of nutrients and water by plants takes place through the root system in the subsoil. The subsoil is also home to diverse microorganisms, and toxic metals can destabilize their niche. The high concentrations of heavy metals in some subsoils than in topsoil can be attributed to the leaching capability of the topsoil. Due to the high porosity of the top, sandy soil, heavy metals such as Cd and Cr are retained less in the topsoil and are percolated towards the subsoil [38]. Furthermore, Cd and Cr are less bonded to organic matter and minerals in the soil [38–39]. The above trends are comparable to other studies [39–43]. Pb and Cu were the heavy metals with the highest concentration, possibly because they find more applications in EEE, such as printed circuit boards, cathode ray tubes, bare/insulated wires, refrigeration units, fluorescent bulbs, batteries, and fuses. Furthermore, since Pb is not biodegradable, concentrations of Pb could build up for all the operational years of the scrapyard, resulting in the high concentrations measured. Sources of chromium in the scrapyard include steel alloy, and colored plastics, which are used as combustible materials for the burning of e-waste materials. Comparatively, Cr concentrations at site F were higher than at site H, possibly because the metal containers housing e-waste materials were closer to site F. These are typically composed of steel and chromium, so any wear and tear on the metal add Cr concentration to the soil. Cd was the heavy metal with the least concentration. In addition to the leaching and percolation effect of the soil structure,

the mild to acidic pH of soils has also been shown to be a factor in the high mobility of Cd, resulting in its lower concentrations in the soil component [29]. Site H had higher concentrations of Cd than site F because Cd-containing e-waste materials, including printed circuit boards, batteries, accumulators, cathode ray tubes, and ultraviolet lights, were located more at the former site than the latter. However, the low concentrations of Cd should not be underestimated, as Cd is one of the most toxic heavy metals, especially to aquatic organisms. Cd pollution is related to an increased mortality rate from obstructive lung disease. Cadmium absorption also causes shortness of breath and emphysema. All heavy metals under consideration exceeded national and international standards, suggesting that the open burning of e-waste materials to extract valuable metals leads to excessive pollution of the environment. Indeed, other studies and research reach similar conclusions, and in some cases, other pollutants, such as Poly Aromatic Hydrocarbons (PAHs), are further identified. Igeo, CF, and PLI metrics have substantiated the current study's heavy metal pollution variations.

Heavy metal adsorption and retention by soil increases generally within a pH range of 4–7 [38, 44], and therefore the pH ranges from the study could account for the elevated levels of heavy metals found in the samples. According to a study by [30], dumpsite samples could retain heavy metals within a pH range of 2–8. The high pH value recorded in sample 5B (8.03) could be due to alkaline batteries, steel mills, and ashes from the incineration processes at the e-waste site. The range of pH values for this study is comparable to other e-waste research [9, 28].

The general decline of pH at increasing distance from the scrapyards was expected as increasing distance from the scrapyards meant decreasing heavy metal concentrations, most alkaline. This result is comparable to a study by Tang et al. [45], where the pH at a dumpsite decreased from 5.9 to 4.7 at 18 m from the dump site. The current research indicates that activities at the scrapyards had an effect 25–50 m away from it. However, since soil samples taken at 25 and 50 m were close to the Accra-Tema motorway, contamination from road dust is still possible since heavy metals are found in tires and brake abrasion, combustion exhaust, and pavement wear [46]. Further research will be needed to evaluate this assertion. With a general decline in the concentrations of heavy metals from the 75 and 100 m distance, the high levels of heavy metals within the scrapyards can be attributed mainly to the e-waste activities. Comparably, Cr, Cu, and Pb concentrations were several times higher within the scrapyards than outside. This decreasing concentration of heavy metals with increasing distances from the scrapyards agrees with other studies, which explored the effect of increasing distance from the source on concentration levels of heavy metals [47–49].

Analysis of water sediments showed that levels of the toxic metals in the water sediments increased significantly within the scrapyards compared to the control sample, which was taken outside the scrapyards area. With the drainage lying at a lower plain to the two burning sites, and with the movement of air current across the drainage from the two burning sites, it can be fairly postulated that the e-waste activities are a possible source of heavy metals in the water-sediment, through the actions of wind drift, wet and dry depositions. Another possibility is the presence of e-waste materials near or inside the drainage, causing heavy metals to leach into it [50]. Compared to no detection levels within the water itself, the relatively concentrated amounts of heavy metals in sediments affirm studies associating the high affinity of heavy metals with the suspended matter in water environments [51–52]. Heavy metals in the wastewater were above the standard permissible levels of Ghana EPA and WHO/FAO. This is of major concern as it serves as an irrigation source for farming crops and as drinking water for herds of cattle near the scrapyards. Studies conducted

on vegetation and animals near the e-waste scrapyards revealed high levels of toxic metals in plants' root, stem, and leaves [53].

Sediment and water from the drain generally had neutral pH for both control samples and those taken within the scrapyards area. This observation differs from other studies [54–56] where the pH of water samples was in the acidic range (3.78–6.53). At lower pH, metals tend to have higher solubilities, leading to higher metal levels. This could be one of the primary reasons for detecting higher heavy metal concentrations in the water samples reported in the other studies [54–56] than in the current research. The highly positive correlation coefficients observed between pairs of heavy metals (0.90, 0.96, 0.97 in **Table 5** and 0.98 in **Table 6**) may be due to their dual complementary usage in certain EEE products. For instance, Cd and Pb find close applications in cathode ray tubes where Cd is used as the fluorescent powder coatings to produce color, while Pb is employed to absorb the UV lights and X-rays built. Cd-Cu alloy wires are more resistant to softening at higher temperatures, hence their co-occurrence in the waste. Pb alloyed to Cu acts as a lubricant and assists in chip breakup, increasing the machinability of the Cu metal. Since site H is a burning site and dumping grounds for e-waste materials, heavy metals can be carried from site F to site H. This could explain the high positive correlation (0.90, 0.95, 0.97, and 0.99) between heavy metals at different sites in **Table 7**. The weak correlations between heavy metals at the two sites could also indicate different and unrelated sources of contamination of the heavy metals.

Coefficient of variation (CV) results suggest that most heavy metals are widely dispersed rather than contained at locations. Wind effects, dry and wet deposition, and migration through water and soil are the primary sources of heavy metal dispersion or transport. High levels due to transport are a worry as it indicates e-waste recycling pollution is not limited to its immediate surroundings but can extend to other parts of the environment. Additionally, CV values provide insight into the sources of contamination. According to a study by [57], a CV of less than 20% indicates natural sources, while values greater than 50% imply anthropogenic sources. By inference, the heavy metal pollution was primarily due to anthropogenic sources, specifically e-waste activities, amplified by environmental factors.

5. Conclusions

The research showed that the heavy metal levels exceeded the permissible limits of the WHO/FAO and Ghana EPA standards. Pollution indices suggest the e-waste scrapyards were polluted with the four heavy metals investigated in varying degree. The CV results indicate that metal pollution is primarily anthropogenic-given and widely dispersed. Spatial distribution maps suggest contamination of the scrapyards, especially at the western north of site H and the central portion of site F. Consequently, environmental laws and regulations on the management and recycling of e-waste should be enforced by local authorities to prevent further pollution of the scrapyards and its environment. Public awareness and education on the adverse effect of informal recycling practices should be intensified. The study has further shown that Cd and Pb levels in the scrapyards suggest skewed distributions relative to Cr and Cu, which are normally distributed. This outcome provides insight into modeling the behavior of these metals in the future. Finally, future studies can also focus on investigating heavy metal contamination in workers at the scrapyards and herds of cattle around the environment.

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Competing interests

The authors declare there is no conflicting interest regarding this study.

Availability of data and material

All data generated or analyzed during this study are included in this published article.

Authors' contributions


The second and corresponding author supervised the entire research—conceptualization, synthesis of ideas, scope, experimental design, analysis framework, data interpretation, review, and manuscript editing. The first author performed the field and lab work. He also contributed to data analysis, manuscript writing, and editing.

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