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Environmental Evaluation of Heavy Metal Contamination at Landfill Sites within the Prestea Huni Valley Municipal Assembly

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Abstract

Landfill sites serve as the primary destination for municipal solid waste in most developing nations; however, the waste streams deposited there vary widely, from non-toxic to highly hazardous. When landfills are not engineered or properly managed, they become significant sources of environmental contamination through the leaching of heavy metals and the degradation of organic compounds. In the Prestea Huni Valley District Area (PHVDA), unengineered landfill sites pose a risk of severe pollution to adjacent soil systems. This study evaluated heavy metal contamination in nine soil samples collected from four municipal landfills located in Prestea, Aboso, Huni Valley, and Bogoso. Atomic Absorption Spectroscopy (AAS) was used to quantify soil heavy metal concentrations, while multivariate statistical analysis and standard pollution indices were employed to identify contaminant sources and assess environmental risks. The mean concentrations of heavy metals in the landfill soils decreased in the order of: Zn (1217.31 mg/kg) > Pb (534.63 mg/kg) > As (3.54 mg/kg) > Cd (0.83 mg/kg). According to hierarchical cluster analysis (HCA) and Pearson correlation coefficients, As and Cd are strongly correlated ($r = 0.68$) and share closely related geogenic and agricultural sources, whereas Pb and Zn are loaded independently, reflecting distinct anthropogenic pathways. The Potential Ecological Risk Index (PERI) and Nemerov Pollution Index (NPI) indicated that the Aboso landfill soil is the most heavily contaminated with heavy metals, followed by Prestea, Bogoso, and Huni Valley. The Aboso Landfill therefore exhibited the highest overall pollution level and ecological risk. It is highly recommended that unengineered landfill sites that have been in use for over a decade, such as Aboso and Prestea, be systematically decommissioned and remediated to safeguard human health and environmental integrity.

Keywords

Landfill Sites, Soil Contamination, Nemerov Pollution Index, Pollution Evaluation Models

1. Introduction

Soils are among the most diverse ecosystems, with around 25% of the world's species (Franzluebbers, 2002). Crucially, soil acts as a natural substrate where plants thrive, thereby providing the basis for both human and animal sustenance (Karlen et al., 2001; Lehmann et al., 2020). Detoxification and recycling of organic waste, as well as the recycling of several nutrients and gases from the environment, all occur in the soil (Wahsha et al., 2017). Therefore, healthy soil quality is important for plants, animals, and human health.

Human activities including intensifying agricultural land usage, soil sealing and biological invasions brought on by the introduction of non-native species have recently put soil quality at risk on a worldwide scale (Gbanie et al., 2013). In addition, it is the site for waste disposal, introducing contaminants into food, groundwater, surface water, and air. According to (Odukoya, 2015), soil pollution can affect the wholesomeness of food and drinking water.

Even though many countries have implemented measures to protect soil resources from pollution, soil quality continues to deteriorate at national and international levels (Kjeldsen et al., 2002). The pollution of soil resources has led to a decline in microbial activity (Pramila & Ramesh, 2011) and increase in toxic heavy metals and organic contaminants. Since 3000 BC, the bulk of the waste humans generate has been dispersed through the soil (Odom et al., 2021). As the world population has grown and the Industrial Revolution has occurred, waste, one of human society's inevitable byproducts, has multiplied (Gbanie et al., 2013). Most of this waste generated from domestic and industrial facilities ends up in landfill sites.

In many industrialised and developing nations, landfilling is the most popular method of waste management (Seshie et al., 2020). Landfills were formerly believed to be the best option for Municipal Solid Waste (MSW) disposal. However, this only applies to landfills that were appropriately constructed and engineered initially (Swati et al., 2017). A landfill site that is specially designed and built makes it possible for people to dispose of material waste in a way that is ecologically sound while minimising its impact (Swati et al., 2017), given that modern waste disposal facilities have been lined with multiple absorbent materials and layers of plastic sheets to prevent pollutants from seeping into the soil and groundwater structures (Adamcová et al., 2016). However, when solid waste is put in landfills without any preliminary treatment or protection of the soil, there is a danger of groundwater and topsoil contamination (Chaer et al., 2019), and such is the case in the Prestea Huni Valley Municipal Assembly (PHVMA).

The PHVMA, located in Ghana's Western Region and known for its extensive mining activities, has witnessed rapid urbanisation and industrialisation, leading to increased waste generation (Kwesi et al., 2018). To manage this waste, landfill sites have been established in designated areas, such as Aboso, Prestea, Bogoso, and Huni Valley. While these landfill sites are necessary for waste disposal, improper management could lead to soil contamination (Ismail et al., 2015), reduced agricultural productivity (Ali et al., 2014), and threaten groundwater quality in the area (Swati et al., 2017). Currently, in the PHVMA, the landfill sites at Bogoso, Huni Valley, Prestea, and Aboso are not engineered. This could lead to soil contamination (Mukhopadhyay et al., 2020). To ensure public and environmental health, the quality of heavy metals in waste soil and their possible ecological harm are evaluated in this study. It also determines the spatial distribution of heavy metals and their likely sources.

2. Materials, Methods Used

2.1. Description of Study Area

The Prestea-Huni Valley Municipality served as the study location and it is one of the 14 MMDAs in the Western Region of Ghana. The municipality shares a northern border with the Wassa Amenfi East and Amenfi Central Districts. To the west of PHVMA is the Amenfi West District. The Municipality of Tarkwa Nsuaem is located in the southwest. The municipality's administrative centre is in Bogoso. The PHVMA settlements included in this research were Bogoso, Prestea, Aboso, and Huni Valley. The map of the study area is shown by **Figure 1**. It is located within latitudes 5˚15'N - 5˚40'N and longitudes 1˚40'W - 2˚15'W. The municipality spans approximately 1200 km^2 (Kwesi et al., 2018). The area has a population of 229,301, of whom 117,744 are males and 111,557 are females (Anon, 2021).

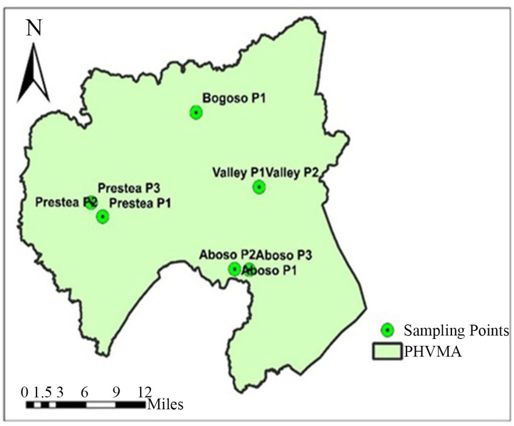

Figure 1. Map of study area with sampling locations.

2.2. Soil Sampling Techniques and Locations

A total of nine representative soil samples were collected from four Final Waste Disposal Sites (FWDS) to evaluate heavy metal concentrations. A systematic judgmental sampling design was employed to ensure adequate spatial coverage across varying waste-age profiles and topographic features. The nine samples were distributed as follows: 2 samples from the Hunu Valley site, 3 from the Abosso site, 3 from the Prestea site, and one sample from the Bogoso site. Sampling points were selected based on proximity to active tipping faces and zones of leachate accumulation to represent a "worst-case" contamination scenario.

Points were spaced approximately 100 meters apart to capture spatial heterogeneity within the landfill boundaries. Sampling was conducted during the period. At each location, soil cores were extracted from a depth of 0 - 20 cm using a stainless-steel hand auger, with precise coordinates recorded through handheld GPS. To ensure sample integrity, non-soil debris—including metals, plastics, glass, and stones—was manually removed in the field. Samples were then homogenised, sealed in airtight polyethylene bags, and transported to the Environmental Monitoring Laboratory at the University of Mines and Technology (UMaT) for heavy metal analysis.

2.3. Data Analysis

Descriptive statistics, including arithmetic means and standard deviations, were computed for each landfill site to characterise heavy metal distribution. For the Bogoso site, where the sample size ($n = 1$) precluded statistical dispersion analysis, reported values were treated as point-source concentrations. Given the high spatial proximity of sampling points, mean values were utilised for spatial distribution mapping. To assess the variability of heavy metal concentrations, the Coefficient of Variation (CV%) was calculated and categorised as moderate (CV ≤ 50%), high (50% < CV ≤ 100%), or extraordinarily intense (CV > 100%) according to (Nezhad et al., 2015).

Handling of Data below Detection Limits

To ensure statistical integrity for the calculation of means, CV%, and subsequent pollution indices, data points recorded below the method detection limit (LOD) were handled using the full detection limit (LOD), providing a conservative estimate of heavy metal loading.

2.4. Heavy Metal Analysis

Heavy metal concentrations in the soil samples were determined following standard acid digestion protocols. Dried and pulverised soil samples (1.0 g each) were subjected to aqua regia digestion using a 1:3 mixture of concentrated HNO_3 and HCl. The samples were digested at 105˚C in conical flasks until the volumes were reduced. After cooling to room temperature, the digests were quantitatively transferred to 100 mL volumetric flasks, diluted to the mark with deionised water, and filtered through Whatman No. 42 filter paper. The resulting filtrates were analysed for Arsenic (As), Zinc (Zn), Cadmium (Cd), and Lead (Pb) using an Atomic Absorption Spectrophotometer (AAS). The instrument was calibrated using analytical-grade multi-element standard solutions to establish linearity, with a method detection limit of 0.002 mg/kg.

Quality Assurance and Quality Control (QA/QC)

To ensure the accuracy and reproducibility of the analytical data, rigorous QA/QC protocols were implemented throughout the digestion and determination phases. Procedural blanks were prepared alongside the batch samples to monitor for reagent-grade contamination and potential carry-over effects during the analytical process. Precision was assessed through replicate analyses, with relative percent difference (RPD) values maintained below 5%. Analytical accuracy was verified using certified reference materials (CRMs) to determine the percentage recovery of each heavy metal; recovery rates were maintained within the acceptable range of 95% - 110%. Instrument stability was further verified by periodically re-analysing mid-range calibration standards every ten samples to check for potential baseline drift.

2.5. Spatial Analysis

Geostatistical methods were employed to visualise the spatial distribution of soil contamination (Dai et al., 2019). Specifically, Inverse Distance Weighting (IDW) within ArcGIS (version 10.3) was utilised to generate maps showing heavy metal concentrations at various sampling points across the study's towns. Additionally, IDW provided a visual representation of the Possible Ecological Risk Index (PERI) results, which clarified the distribution of heavy metals in all target locations and highlighted the potential ecological threats that the landfills posed to the surrounding communities. Also, the sources of soil pollution causing heavy metal contamination and the relative contributions of each source were revealed by geographical analysis (Fosu et al., 2023).

2.6. Heavy Metals Quality in Landfill Soil and Their Potential Ecological Risk Index

The Pollution Load Index (PLI) (Memoli et al., 2019), the Geoaccumulation Index (I_{geo}) (Xu et al., 2019), the Nemerow pollution index (NPI) (Martínez-Guijarro et al., 2019), and the Potential Ecological Risk Index (PERI) (Lin et al., 2021) were used to evaluate the heavy metal contamination in landfill soils at PHVDA. The I_{geo} is mainly used to evaluate contamination of certain heavy metals in relation to the concentration of the geochemical background, whereas PLI is used to determine the pollution level for all heavy metals. I_{geo} is mainly used to evaluate contamination of certain heavy metals in relation to the concentration of the geochemical background, whereas PLI is used to determine the pollution level for all heavy metals. The soil quality was thoroughly assessed using NPI. The environmental hazards posed by the heavy metals were assessed using the PERI. The following formulas were used to determine these indicators:

$$\mathrm{Pl}_i = \frac{C_x^i}{C_b^i} \tag{1}$$

$$I_{geo} = \log_2 \frac{Pli}{1.5} \quad (2)$$

$$PLI = (Pl_1 \times Pl_2 \times Pl_3 \times Pl_4 \times \ldots \times Pl_n)^{1/n} \quad (3)$$

$$NPI = \left(\sqrt{\frac{(Pli)^2_{max} + (Pli)^2 average}{2}} \right) \quad (4)$$

$$PERI = \sum_{i=1}^{n} T_x^i \times Pli \quad (5)$$

The pollution index (PI) for heavy metals was calculated by comparing the concentration of each heavy metal in the soil (mg/kg) with its corresponding background value (also mg/kg). These background values for soil were obtained from the Canadian Soil Quality Guidelines for the Protection of Environment and Human Health (2001); *n* represents the number of heavy metals, and b represents the biological toxicity factor for each heavy metal (Hakanson, 1980). The Canadian Soil Quality Guidelines were utilised due to the absence of specific, comprehensive national soil quality standards for heavy metals in Ghana, thereby providing a robust and internationally recognised benchmark for environmental risk assessment in this study. The specific background values used for each heavy metal were: Arsenic (As): 12.0 mg/kg; Zinc (Zn): 200.0 mg/kg; Cadmium (Cd): 1.4 mg/kg; and Lead (Pb): 70.0 mg/kg. The biological toxicity factors (T_r) used specifically for the Potential Ecological Risk Index (PERI) were adapted as follows: Arsenic (As): 1; Zinc (Zn): 1; Cadmium (Cd): 30 and Lead (Pb): 5 (Hakanson, 1980). The assessment methods used are shown in **Table 1**.

Table 1. Assessment methods of PLI, I_{geo}, PERI and NPI.

PLI	NPI	I_{geo}	PERI
0 - 1; low level	<0.7; safety	<0; unpolluted	<150; low risk
1 - 2; moderate	0.7 - 1; precaution	1 - 2; moderately polluted	150 - 300; moderate risk
2 - 5; high level	1 - 3; moderate	2 - 4; highly polluted	300 - 600; considerable risk
>5; very high	>3; severe	>4; extremely polluted	>600; high risk

2.7. Source Apportionment

The degree of association between heavy metals was evaluated using the Pearson correlation coefficient (PCC) (Huang et al., 2018). There may be a significant correlation between heavy metals with $P < 0.05$ (two-tailed). The interrelationships among heavy metals suggest they come from comparable geographic regions or share similar geochemical features (Zhang et al., 2018). Additionally, Hierarchical Cluster Analysis (HCA) was carried out utilising the standardised data, using Z-scores and Ward's method with squared Euclidean distances. HCA and PCC analyses were performed in OriginPro 2023 to identify likely sources of soil metals in the landfill soil.

3. Results and Discussion

3.1. Landfill Soil Heavy Metals Concentration

As shown in Table 2, the mean concentrations of Zn at both the Aboso (2236.51 mg/kg) and Prestea (1192.04 mg/kg) landfills exceeded the Canadian Soil Quality Guidelines' permissible agricultural/residential limit of 200 mg/kg (and the commercial/industrial threshold of 360 mg/kg). Similarly, the mean Pb concentration at the Aboso landfill (1548.73 mg/kg) significantly exceeded the permissible environmental limit of 140 mg/kg (CCME, 2001). Conversely, the mean concentrations of As and Cd remained below their respective environmental limits across all sites, though localised hotspots still present potential exposure risks (Chaer et al., 2019). Lead is among the least mobile metallic elements in soil, making its accumulation highly persistent and hazardous (Chaer et al., 2019). Its elevated concentration is often associated with the disposal of household dry-cell batteries and electronic waste in municipal waste streams (Fosu et al., 2023). The high concentrations of Zn and Pb in the Aboso and Prestea soils are likely driven by localised small-scale mining discharges, discarded galvanised building materials, and the indiscriminate disposal of consumer electronics, batteries, and lead-based paints/coatings (Chaer et al., 2019; Fosu et al., 2023).

Table 2. Heavy metal concentrations in Landfill Soil (mg/kg).

Sample ID	As (mg/kg)	Zn (mg/kg)	Cd (mg/kg)	Pb (mg/kg)
Aboso P1	1.364	145.314	0.368	8.709
Aboso P2	5.786	150.49	0.082	4354.447
Aboso P3	1.798	6413.727	0.571	283.044
Mean	2.986 ± 2.430	2236.510 ± 3617.577	0.340 ± 0.246	1548.733 ± 243.688
Huni Valley P1	1.128	24.184	<0.002	<0.005
Huni Valley P2	0.612	28.665	<0.002	<0.005
Mean	0.58 ± 0.565	26.425 ± 3.164	<0.002	<0.005
Bogoso P1	5.051 ± 0.581	617.286 ± 0.852	2.120 ± 0.978	67.493 ± 3.584
Prestea P1	3.512	236.683	0.613	19.596
Prestea P2	5.697	1595.868	1.469	30.48
Prestea P3	6.947	1743.57	2.283	47.898
Mean	5.385 ± 1.739	1192.04 ± 830.654	1.455 ± 0.835	32.658 ± 14.276
CV (%)	59.521	140.395	95.046	210.755

Concentrations of Zn in soil samples at Aboso (2236.510 ± 3617.577 mg/kg) and Prestea (1192.04 ± 830.654 mg/kg) were higher than the permissible limit (1000 mg/kg) of the Canadian Soil Quality Guidelines for the Protection of Environment and Human Health. Thus, the high Zn concentration in the Aboso and Prestea soil samples may be attributed to mining activities and household waste (zinc-containing products such as cosmetics, coatings, and paints) (Wuana &

Okieimen, 2011). Also, when improperly disposed of, building materials, such as galvanised metal with a zinc coating to prevent corrosion, can transfer Zn into the landfill's soil (Odukoya, 2015). According to (Mohiuddin et al., 2011), Zn pollution could also be attributed to the indiscriminate disposal of pesticides and fertilisers. In this study, Aboso P2 recorded the highest Pb concentration (4354.447 mg/kg), followed by Aboso P1 (283.044 mg/kg). Pb concentration at Aboso P1 was 8.709 mg/kg. The average lead concentration in Aboso's soil samples was 1548.733 ±243.688 mg/kg, was well above the 200 mg/kg guideline established by the Canadian Soil Quality Guidelines for the Protection of Environment and Human Health (2001). This was lower than the mean Pb concentration (4400 mg/kg) recorded at a landfill site in Tangier (Morocco) in a study by (Chaer et al., 2019).

3.2. Spatial Distribution

Figure 2 illustrates the spatial distribution of the four target heavy metals (As, Zn, Cd, and Pb) across the sampling locations, utilising an Inverse Distance Weighting (IDW) interpolation method where a colour gradient from red to blue signifies high to low concentration zones, respectively. Despite the presence of visible localised hotspots, statistical analysis reveals no significant differences ($p > 0.05$) in overall metal distribution between the sites.

The mean concentrations of As decreased in the order of Prestea (5.39 mg/kg) > Bogoso (5.05 mg/kg) > Aboso (2.99 mg/kg) > Huni Valley (0.87 mg/kg). Elevated As levels at Prestea and Bogoso are primarily attributed to the local geology, characterised by auriferous and manganese-rich formations of the Birimian Supergroup that naturally release arsenic during weathering (Wuana & Okieimen, 2011). This geogenic baseline is further augmented by anthropogenic inputs from industrial, household, and agricultural waste, specifically arsenic-based pesticides.

For Zn, the mean concentrations followed the decreasing order of Aboso (2236.51 mg/kg) > Prestea (1192.04 mg/kg) > Bogoso (617.29 mg/kg) > Huni Valley (26.43 mg/kg). The elevated Zn levels at Aboso and Prestea reflect active mining operations and associated mechanical waste; furthermore, the regional lithology is known to possess naturally high zinc concentrations (Kwesi et al., 2021).

The mean concentrations of Cd decreased in the order of Bogoso (2.12 mg/kg) > Prestea (1.46 mg/kg) > Aboso (0.34 mg/kg) > Huni Valley (<0.002 mg/kg). These elevated levels at Bogoso and Prestea are strongly linked to the improper disposal of Ni-Cd batteries, plastics, and glass (Chaer et al., 2019).

Finally, the mean Pb concentrations decreased in the order of Aboso (1548.73 mg/kg) > Bogoso (67.49 mg/kg) > Prestea (32.66 mg/kg) > Huni Valley (<0.005 mg/kg). The exceptionally high Pb concentrations at Aboso are largely driven by the high density of local auto-mechanic and vulcanising workshops that utilise and subsequently dispose of lead-acid car batteries at the landfill site (Fosu et al., 2023). **Figure 2** is the Maps showing the spatial distribution.

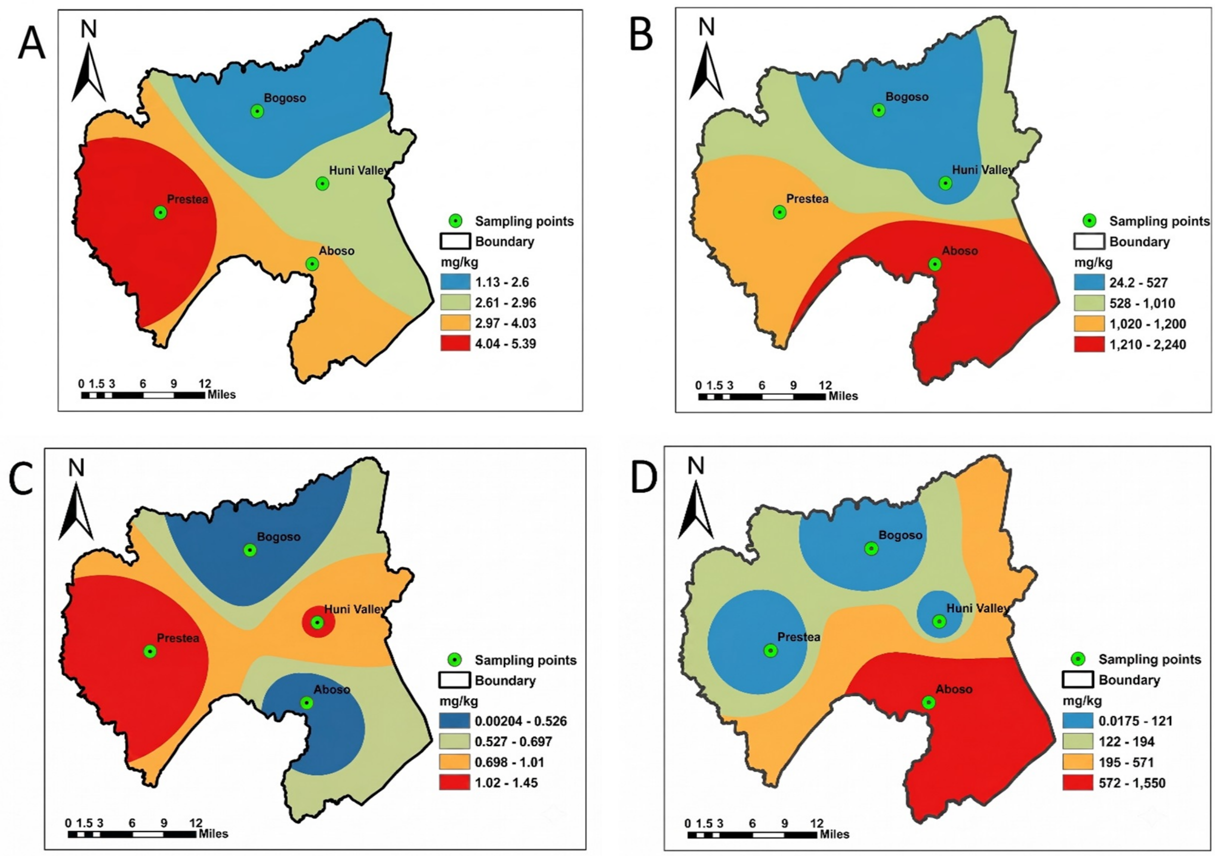

Figure 2. Maps showing the spatial distribution of: (A) Zn, (B) As, (C) Cd, (D) Pb.

Soil Contamination Risk

Soil pollution indices, including the Geo-accumulation Index (I_{geo}), Pollution Load Index (PLI), and Nemerow Pollution Index (NPI), were evaluated to quantify overall contamination levels (**Figure 3**). I_{geo} values showed no significant variation ($p > 0.05$) in heavy metal contamination across the four landfills. For As, Cd, and Zn, I_{geo} values fell into the "unpolluted" class across all sites. However, Pb displayed an I_{geo} value of 2.37 at the Aboso site, indicating moderately to strongly polluted conditions, while remaining in the unpolluted class at Prestea (-3.19), Huni Valley (−15.87), and Bogoso (−2.15). This localised lead pollution is directly tied to the improper disposal of lead-acid batteries from local mechanical and vulcanising workshops (Fosu et al., 2023).

This spatial variation is supported by the PLI results, which exceeded the critical pollution threshold of 1.0 only at the Aboso landfill (PLI = 2.54), indicating a highly polluted state. In contrast, the other three landfills fell well below the threshold, indicating low pollution loading: Prestea (0.53), Bogoso (0.51), and Huni Valley (0.01). The exceptionally low PLI at Huni Valley is attributed to the relatively young age of that specific landfill facility (Adamcová et al., 2017).

The Nemerow Pollution Index (NPI) confirmed these findings. Based on the assessment criteria, Aboso (2.4) and Prestea (2.2) were classified as moderately to heavily polluted. Under the NPI classification, Bogoso (1.3) was categorised as slightly polluted, while Huni Valley (1.0) reached the precautionary warning limit, indicating the need for immediate management interventions to prevent further degradation. The high pollution status at Aboso and Prestea is likely linked to human activities and the fact that these landfill sites have been operational for over two decades (Adamcová et al., 2017). At Aboso, Pb (1548.73 ±243.688 mg/kg) and Zn (2236.15 ±3617.577 mg/kg) were the primary contributors to the pollution status due to their high concentrations. In contrast, in Prestea, Zn (1192.04 ±830.654 mg/kg) was the principal pollutant.

3.3. Soil Ecological Risk

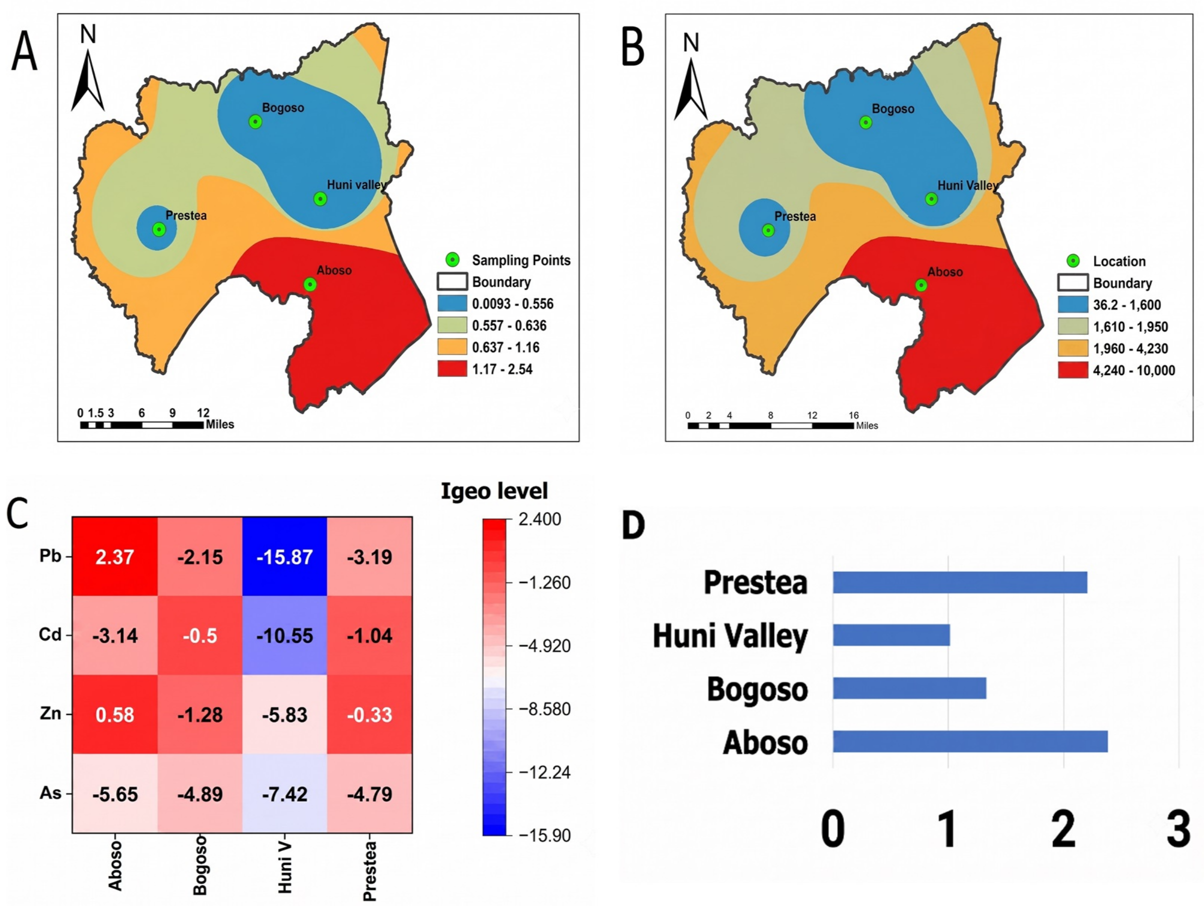

Figure 3. (A) PLI of heavy metals, (B) PERI of heavy metals, (C) Heat map of I_{geo} levels, and (D) NPI of heavy metals across the various locations.

The Potential Ecological Risk Index (PERI) was calculated to synthesise the toxicity of individual heavy metals into a comprehensive risk profile, as illustrated in Figure 3. At the site level, the total PERI values decreased in the following order: Aboso (10020.21, representing an extremely high ecological risk) > Prestea (1452.83, indicating high risk) > Bogoso (1068.86, indicating high risk) > Huni Valley (35.21, indicating low risk).

Detailed risk indices for individual heavy metals are also shown in Figure 3, with the highest contributions observed as: Pb (7743.67) > Zn (2236.51) > As (29.83) > Cd (10.21) at Aboso; Zn (617.29) > Pb (337.46) > Cd (63.60) > As (50.51) at Bogoso; Zn (26.42) > As (8.70) > Cd (0.06) > Pb (0.025) at Huni Valley; and Zn (1192.04) > Pb (163.29) > As (53.85) > Cd (43.65) at Prestea.

These findings confirm that the Aboso landfill presents the most severe ecological threat to surrounding soils, vegetation, and groundwater, primarily driven by its exceptionally high Pb ($T_r = 5$) and Zn loading. This elevated risk correlates strongly with the landfill's older operational age and the high volume of municipal and industrial waste it receives. The comparative spatial indices for PLI, PERI, and NPI are graphically presented in **Figure 3**.

3.4. Source Apportionment

The resulting correlation matrix (**Figure 4**) indicated a strong positive correlation between Arsenic (As) and Cadmium (Cd) ($r = 0.68$). This suggests that As and Cd likely share homologous characteristics and may originate from the same anthropogenic source. The HCA results further confirmed this. The dendrogram delineated two distinct clusters that exhibited dissimilar geochemical associations, as depicted in **Figure 4**. This suggests that heavy metals from comparable input sources belong to the same cluster (Fosu et al., 2023). The squared Euclidean distance was used as the similarity measure; accordingly, heavy metals that appear close together in the resulting dendrogram are considered to share closely associated input sources.

In contrast, long-distance depicts dissimilarities (Akoto et al., 2016). **Figure 4** suggests that the toxic metals Arsenic (As) and Cadmium (Cd) grouped in cluster 1, likely represent a primary source of contamination. The findings reveal that improper waste disposal, including fertilisers and pesticides, could enrich the soil with As and Cd (Fosu et al., 2023). Zn and Pb were loaded in cluster 2, with a long squared Euclidean distance, as shown in **Figure 4**, indicating dissimilar sources (Akoto et al., 2016). **Figure 4** shows the results of two different statistical analyses. The Pearson Correlation Coefficient is a measure of the correlation between two variables. The hierarchical cluster analysis is a method for grouping similar variables. Multivariate Statistical Analysis of Heavy Metals in Landfill Soil is shown in **Figure 4**.

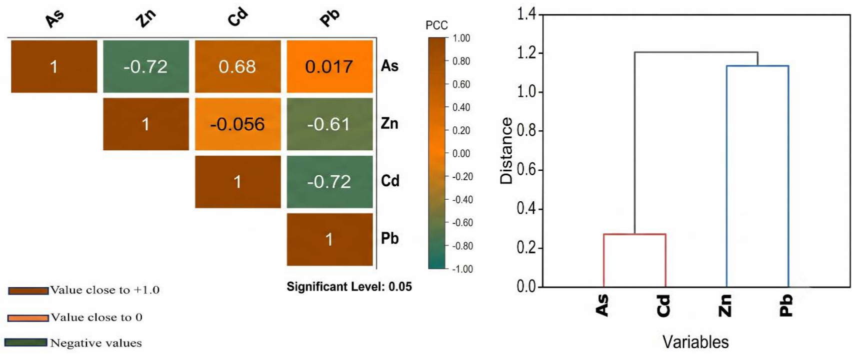

Figure 4. Multivariate statistical analysis of heavy metals in landfill soil: Pearson correlation matrix and hierarchical cluster analysis (HCA) dendrogram.

4. Conclusions

This study evaluated heavy metal (As, Zn, Cd, Pb) concentrations, spatial distributions, and associated ecological risks in landfill soils across the Prestea Huni Valley Disposal Area (PHVDA). The principal findings of this research are summarised as follows:

1) The mean concentrations of heavy metals in the landfill soils followed the decreasing order of: Zn (1217.31 mg/kg) > Pb (534.63 mg/kg) > As (3.54 mg/kg) > Cd (0.83 mg/kg).

2) The spatial distribution of heavy metals showed no statistically significant variation ($p > 0.05$) between sites, though localised hotspots were identified. Prestea recorded the highest average As concentration (5.39 mg/kg), Bogoso recorded the highest Cd concentration (2.12 mg/kg), while Aboso recorded the highest concentrations for both Zn (2236.51 mg/kg) and Pb (1548.73 mg/kg).

3) The Nemerow Pollution Index (NPI) indicated that the Aboso (2.4) and Prestea (2.2) landfills are moderately to heavily polluted, while Bogoso (1.3) is slightly polluted. Huni Valley (1.0) is currently at the precautionary warning threshold, indicating that protective measures must be implemented to prevent future soil degradation.

4) Geo-accumulation Index (I_{geo}) values ranged from −15.87 to 2.37, showing that while most metals represent unpolluted conditions, the Aboso landfill is moderately to strongly polluted with Lead ($I_{geo} = 2.37$).

5) The overall Pollution Load Index (PLI) exceeded the critical safety threshold of 1.0 only at the Abosso/Tarkwa site (2.54), while the remaining sites fell within safe limits.

6) The total environmental risk was highest at the Abosso and Tarkwa sites, driven by a combination of high spatial waste loading, elevated soil acidity, and severe heavy metal accumulation. Conversely, the Bogoso site presented the lowest calculated ecological risk due to its lower sampling density and localised tipping patterns.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

References

Adamcová, D., Radziemska, M., Ridošková, A., Bartoň, S., Pelcová, P., Elbl, J. et al. (2017). Environmental Assessment of the Effects of a Municipal Landfill on the Content and Distribution of Heavy Metals in *Tanacetum vulgare* L. *Chemosphere, 185,* 1011-1018. https://doi.org/10.1016/j.chemosphere.2017.07.060

Adamcová, D., Vaverková, M. D., Bartoň, S., Havlíček, Z., & Břoušková, E. (2016). Soil Contamination in Landfills: A Case Study of a Landfill in Czech Republic. *Solid Earth, 7,* 239-247. https://doi.org/10.5194/se-7-239-2016

Akoto, O., Nimako, C., Asante, J., & Bailey, D. (2016). Heavy Metals Enrichment in Surface Soil from Abandoned Waste Disposal Sites in a Hot and Wet Tropical Area. *Environmental Processes, 3,* 747-761. https://doi.org/10.1007/s40710-016-0183-x

Ali, S. M., Pervaiz, A., Afzal, B., Hamid, N., & Yasmin, A. (2014). Open Dumping of Municipal Solid Waste and Its Hazardous Impacts on Soil and Vegetation Diversity at Waste Dumping Sites of Islamabad City. *Journal of King Saud University-Science, 26,* 59-65. https://doi.org/10.1016/j.jksus.2013.08.003

Anon (2021). *Ghana Statistical Service [GSS], 2021 Population and Housing Census: District Demographic Census Report - Prestea Huni-Valley Municipality*. Ghana Statistical Service.

CCME (2001). *Canadian Soil Quality Guidelines for the Protection of Environmental and Human Health: Summary Table*. Canadian Council of Ministers of the Environment.

Chaer, I., El Cadi, A., Brigui, J., Ziat, K., & Khaddor, M. (2019). Evaluating Soil Quality at a Landfill: A Study Case from Morocco (Tangier). *Mediterranean Journal of Chemistry, 9,* 317-325. https://doi.org/10.13171/mjc94191119973mk

Dai, L., Wang, L., Liang, T., Zhang, Y., Li, J., Xiao, J. et al. (2019). Geostatistical Analyses and Co-Occurrence Correlations of Heavy Metals Distribution with Various Types of Land Use within a Watershed in Eastern Qinghai-Tibet Plateau, China. *Science of the Total Environment, 653,* 849-859. https://doi.org/10.1016/j.scitotenv.2018.10.386

Fosu, S., Gyimah, E., Boakye, F. A., & Stemn, E. (2023). Ecotoxicological Status and Health Risks Implication of Heavy Metals in Urban Soils of the A'koon and Brahabobom Communities Tarkwa—Ghana. *Ghana Mining Journal, 25,* 28-44.

Franzluebbers, A. J. (2002). Soil Organic Matter Stratification Ratio as an Indicator of Soil Quality. *Soil and Tillage Research, 66,* 95-106. https://doi.org/10.1016/s0167-1987(02)00018-1

Gbanie, S. P., Tengbe, P. B., Momoh, J. S., Medo, J., & Kabba, V. T. S. (2013). Modelling Landfill Location Using Geographic Information Systems (GIS) and Multi-Criteria Decision Analysis (MCDA): Case Study Bo, Southern Sierra Leone. *Applied Geography, 36,* 3-12. https://doi.org/10.1016/j.apgeog.2012.06.013

Hakanson, L. (1980). An Ecological Risk Index for Aquatic Pollution Control. A Sedimentological Approach. *Water Research, 14,* 975-1001. https://doi.org/10.1016/0043-1354(80)90143-8

Huang, J., Hu, Y., Zhang, R., Ma, R., & Wu, W. (2018). Spatial Distribution and Potential Ecological Risk Assessment of Heavy Metals in Agricultural Soils from a Rapidly Urbanised Area. *Environmental Pollution, 238,* 644-653.

Ismail, S., Ishak, C., Samah, M., Hatta, E., & Wahab, A. (2015). Soil Contamination from Non-Sanitary Waste Landfill in Langat Water Catchment Area, Malaysia. *Journal of Scientific Research and Reports, 7,* 480-493. https://doi.org/10.9734/jsrr/2015/15102

Karlen, D. L., Andrews, S. S., & Doran, J. W. (2001). Soil Quality: Current Concepts and Applications. *Advances in Agronomy, 74,* 1-40. https://doi.org/10.1016/s0065-2113(01)74029-1

Kjeldsen, P., Barlaz, M. A., Rooker, A. P., Baun, A., Ledin, A., & Christensen, T. H. (2002). Present and Long-Term Composition of MSW Landfill Leachate: A Review. *Critical Reviews in Environmental Science and Technology, 32,* 297-336. https://doi.org/10.1080/10643380290813462

Kwesi, E. A. A., Horror, L. C., & Annan, J. K. (2018). Provision of Sanitation Maps for Improving Waste Management and Sanitation at the District Level: Case Study in the Tarkwa-Nsuaem Districtity of Ghana. In *Conference Proceedings, 5th UMaT Biennial International Mining and Mineral Conference* (pp. 15-20). UMaT Press.

Kwesi, E. A. A., Sablah, E. Lawerty, J. K and Amankwah, R. K. (2021). Site Screening for Landfill Development at the District Level: Case Study in the Prestea Huni-Valley Districtity of Ghana. *Ghana Journal of Technology, 5,* 70-81.

Lehmann, J., Bossio, D. A., Kögel-Knabner, I., & Rillig, M. C. (2020). The Concept and Future Prospects of Soil Health. *Nature Reviews Earth & Environment, 1,* 544-553. https://doi.org/10.1038/s43017-020-0080-8

Lin, X., Zhang, Q., Zhou, L., Wang, H., Liu, H., Huang, Y., & Wu, L. (2021). Differences in Heavy Metal Contents of Farmland Soils with Different Matrices Development and pH. *Environment and Ecology, 3,* 83-88.

Martínez-Guijarro, R., Paches, M., Romero, I., & Aguado, D. (2019). Enrichment and Contamination Level of Trace Metals in the Mediterranean Marine Sediments of Spain. *Science of the Total Environment, 693,* Article 133566. https://doi.org/10.1016/j.scitotenv.2019.07.372

Memoli, V., Esposito, F., Panico, S. C., De Marco, A., Barile, R., & Maisto, G. (2019). Evaluation of Tourism Impact on Soil Metal Accumulation through Single and Integrated Indices. *Science of the Total Environment, 682,* 685-691. https://doi.org/10.1016/j.scitotenv.2019.05.211

Mohiuddin, K. M., Ogawa, Y., Zakir, H. M., Otomo, K., & Shikazono, N. (2011). Heavy Metals Contamination in Water and Sediments of an Urban River in a Developing Country. *International Journal of Environmental Science & Technology, 8,* 723-736. https://doi.org/10.1007/bf03326257

Mukhopadhyay, S., Chakraborty, S., Bhadoria, P. B. S., Li, B., & Weindorf, D. C. (2020). Assessment of Heavy Metal and Soil Organic Carbon by Portable X-Ray Fluorescence Spectrometry and Nixpro™ Sensor in Landfill Soils of India. *Geoderma Regional, 20,* e00249. https://doi.org/10.1016/j.geodrs.2019.e00249

Nezhad, K., Tahsin, M., Tabatabaii, S., & Gholami, A. (2015). Geochemical Assessment of Steel Smelter-Impacted Urban Soils, Ahvaz, Iran. *Journal of Geochemical Exploration, 152,* 91-109. https://doi.org/10.1016/j.gexplo.2015.02.005

Odom, F., Gikunoo, E., Arthur, E. K., Agyemang, F. O., & Mensah-Darkwa, K. (2021). Stabilization of Heavy Metals in Soil and Leachate at Dompoase Landfill Site in Ghana. *Environmental Challenges, 5,* Article 100308. https://doi.org/10.1016/j.envc.2021.100308

Odukoya, A. M. (2015). Contamination Assessment of Toxic Elements in the Soil within and around Two Dumpsites in Lagos, Nigeria. *Ife Journal of Science, 17,* 351-361.

Pramila, R., & Ramesh, K. V. (2011), Biodegradation of Low-Density Polyethylene (LDPE) by Fungi Isolated from Municipal Landfill Area. *Journal of Microbiology and Biotechnology, 1,* 131-136.

Seshie, V. I., Obiri-Danso, K., & Miezah, K. (2020). Municipal Solid Waste Characterisation and Quantification as a Measure towards Effective Waste Management in the Takoradi Sub-Metro, Ghana. *Ghana Mining Journal, 20,* 86-98. https://doi.org/10.4314/gm.v20i2.10

Swati, Ghosh, P., & Thakur, I. S. (2017). An Integrated Approach to Study the Risk from Landfill Soil of Delhi: Chemical Analyses, *in Vitro* Assays and Human Risk Assessment. *Ecotoxicology and Environmental Safety, 143,* 120-128. https://doi.org/10.1016/j.ecoenv.2017.05.019

Wahsha, M., Nadimi-Goki, M., Fornasier, F., Al-Jawasreh, R., Hussein, E., & Bini, C. S. (2017). Microbial Enzymes as an Early Warning Management Tool for Monitoring Mining Site Soils. *Catena, 148,* 40-45.

Wuana, R. A., & Okieimen, F. E. (2011). Heavy Metals in Contaminated Soils: A Review of Sources, Chemistry, Risks and Best Available Strategies for Remediation. *ISRN Ecology, 2011,* 1-20. https://doi.org/10.5402/2011/402647

Xu, D., Gao, B., Chen, S., Peng, W., Zhang, M., Qu, X. et al. (2019). Release Risk Assessment of Trace Metals in Urban Soils Using *In-Situ* DGT and DIFS Model. *Science of the Total Environment, 694,* Article 133624. https://doi.org/10.1016/j.scitotenv.2019.133624

Zhang, H., Zhou, X., Wang, L., Wang, W., & Xu, J. (2018). Concentrations and Potential Health Risks of Strontium in Drinking Water from Xi'an, Northwest China. *Ecotoxicology and Environmental Safety, 164,* 181-188. https://doi.org/10.1016/j.ecoenv.2018.08.017