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RESEARCH ARTICLE

Heavy Metal Contamination and Ecological Risk Assessment of Soils Around Mzedi Municipal Dumpsite, Blantyre, Malawi: Implications for Food Safety in Subsistence Farming Areas

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Abstract: Uncontrolled disposal of municipal solid waste is a growing environmental concern in developing countries, contributing to heavy metal accumulation in surrounding soils and water. This study assessed the concentrations, spatial distribution, and ecological risks of heavy metals around the Mzedi municipal dumpsite in Blantyre, Malawi. Composite soil samples were collected at 0 m, 50 m, 250 m, 400 m, and 650 m from the dumpsite, while surface water samples were taken from a nearby stream receiving runoff. Samples were analyzed for cadmium (Cd), zinc (Zn), copper (Cu), iron (Fe), manganese (Mn), lead (Pb), and cobalt (Co) using atomic absorption spectrophotometry. Contamination and risk levels were evaluated using the Contamination Factor (CF), Geo-accumulation Index (I_{geo}), Enrichment Factor (EF), and Potential Ecological Risk Index (PERI). Soil metal concentrations decreased with distance from the dumpsite in the order Fe > Mn > Zn > Cu > Pb > Cd > Co. Cadmium exhibited the highest contamination levels, with CF (70.00), I_{geo} (5.54), and EF (19.17) at 0 m indicating extremely polluted conditions and severe anthropogenic enrichment. PERI values ranged from 2,181 at 0 m to 117 at 650 m, shifting from very high to low ecological risk. Cadmium contributed > 96% of the total ecological risk, confirming it as the dominant contributor to ecological risk. In surface water, Cd (0.006–0.008 mg/L) and Pb (0.025–0.030 mg/L) exceeded WHO drinking water guidelines, confirming leachate-driven contamination of the adjacent stream. While crop metal concentrations were not directly measured, the elevated soil cadmium levels indicate potential for plant uptake and possible human exposure. However, without direct crop analysis, we cannot confirm the extent of food chain transfer, quantify dietary exposure, or assess compliance with food safety standards. This highlights the critical need for targeted crop monitoring studies to validate the inferred human health risks. This study provides the first comprehensive quantitative assessment of ecological risk at the Mzedi dumpsite using multiple contamination indices and robust statistical analysis. The findings support precautionary management measures, including restrictions on farming directly on the dumpsite, upgrading of waste disposal infrastructure, and community awareness programs.

Keywords: cadmium, ecological risk, heavy metals, Malawi, Mzedi dumpsite, PERI, soil contamination, surface water contamination

1 Introduction

Solid waste mismanagement is a growing environmental problem in many developing countries, particularly in sub-Saharan Africa, where open dumping is the most common waste disposal practice [1, 2]. Such unregulated dumping allows hazardous components of waste to interact with soil, water, and biota, leading to the accumulation of heavy metals and other toxic substances in the environment [3]. Unlike organic pollutants, heavy metals are non-biodegradable and tend to persist, accumulate, and bio magnify through food chains, posing long-term ecological and health risks. Their environmental mobility and persistence make them key indicators of anthropogenic pollution and ecosystem stress [4].

Heavy metals such as cadmium (Cd), zinc (Zn), copper (Cu), iron (Fe), manganese (Mn), lead (Pb) and cobalt (Co) occur naturally in soils but may reach toxic levels through anthropogenic activities, including waste dumping, industrial effluents and agricultural runoff. Municipal solid waste contains a complex mix of metals derived from discarded batteries, plastics, paint,

electronics and food waste, all of which can leach into soils through rainfall infiltration and surface runoff [5]. The accumulation of these metals in soil can alter soil chemistry, degrade fertility and introduce contaminants into crops grown nearby, thus affecting both ecological and agricultural sustainability [6].

Several studies have reported elevated concentrations of heavy metals around dumpsites in Africa and Asia [7] found that concentrations of metals like lead, zinc and copper exceeded permissible levels indicating strong anthropogenic input in Uyo, Nigeria. Similarly, Njagi et al. (2016) [8] studied Kadhodeki Dumpsite and found high levels of cadmium, lead and other toxic metals in both soil and water, emphasizing the danger posed to surrounding communities and the environment. The study noted that improper waste management practices contribute significantly to these elevated concentrations. Comparable trends were also observed in Iran's Anzali Wetland, where, Esmaeilzadeh et al. (2021) [9] noted substantial ecological risk from Cd and Zn contamination.

While waste management challenges in Blantyre, including informal and unregulated dumping, have been documented [10], research assessing the ecological consequences of such practices remains limited. The Mzedi Dumpsite, the primary waste disposal site for the Blantyre City Council since 1992, spans over 17 hectares, with roughly 3 hectares actively used for municipal waste disposal. As an open dumpsite without engineered liners or leachate control systems, waste interacts directly with surrounding soils and water [11].

To date, only one study has examined heavy metal contamination at Mzedi. Kalina and Tilley (2020) [10] conducted a mixed-methods investigation focusing on farmers' motivations and perceptions, with limited heavy metal analysis of four soil samples and three maize samples. Their study concluded that "the risk from heavy metals is relatively low" and that contamination levels were below WHO guidelines. However, their sampling design lacked the spatial resolution needed to characterize the full extent of contamination, their analysis did not employ established contamination indices (CF, Igeo, EF, PERI) for quantifying anthropogenic enrichment or ecological risk, and they did not assess surface water contamination. Furthermore,the limited sampling design and absence of contamination indices may have constrained the ability of the study to fully characterize ecological risk. Consequently, the true extent of contamination at Mzedi, including the spatial distribution of metals, the level of ecological risk, and the potential for surface water contamination, has not been comprehensively evaluated. Despite evidence that communities cultivate crops near or around dumpsites, there is a lack of empirical data on how these activities influence the transfer of contaminants into the food chain, soil fertility and overall ecosystem health. Consequently, there is a critical knowledge gap in integrating ecological risk assessment with agricultural practices near waste disposal sites in Malawi, which this study seeks to address.

Beyond environmental contamination, the practice of cultivating food crops on and around municipal dumpsites represents an emerging food safety concern in many developing countries. Crops grown on contaminated soils can absorb heavy metals through their root systems and accumulate them in edible tissues. Continuous consumption of such crops may expose local populations to toxic metals including cadmium and lead, which have been associated with kidney dysfunction, neurological disorders and developmental effects [2]. In Malawi, where urban agriculture contributes significantly to household food security cultivation on or near waste disposal sites may create a potential pathway for contaminant transfer from soil to humans, although direct crop analysis is required to confirm this pathway. However, direct measurement of crop metal concentrations is needed to confirm the extent of this transfer, as plant uptake depends on factors including metal bioavailability, soil properties, and crop species.

The present study addresses the identified gaps by providing a comprehensive quantitative assessment of heavy metal contamination at the Mzedi dumpsite. Specifically, this study: (1) employs a robust sampling design with five distances and triplicate replicates; (2) applies multiple contamination indices (CF, I_{geo}, EF, PERI) to classify contamination and ecological risk; (3) includes surface water analysis to assess leachate-driven contamination of adjacent aquatic systems; (4) uses statistical analysis (ANOVA, Pearson correlation) to identify spatial patterns and source relationships; and (5) utilizes literature-based background values from Malawian soils for accurate normalization. This approach provides the first comprehensive ecological risk assessment at Mzedi and identifies cadmium as the dominant contributor to ecological risk, a finding that contrasts with the earlier conclusion of "relatively low" risk.

This study aims to assess the concentration, spatial variation and ecological risk of selected heavy metals (Cd, Pb, Cu, Zn, Co, Mn, and Fe) in soils in and around Mzedi municipal dumpsite in Blantyre, Malawi. By applying multiple contamination indices (CF, I_{geo}, EF, PERI), this

research provides a comprehensive assessment of soil pollution status and its potential ecological impact. The findings will contribute to the understanding of waste-derived contamination in southern Malawi and support the formulation of policies for improved solid waste management and environmental protection.

2 Materials and Methods

2.1 Study area

The study was conducted at the Mzedi municipal dumpsite, located in Kachere Township, Blantyre, Malawi. Solid waste collected around Blantyre is disposed at this site which is located some 5.5 km north of Limbe CBD, along the Blantyre-Zomba Road soon after Kachere Township. Mzedi dumpsite has a total area of about 17.3 hectares (including the buffer zone) out of which a total of 3.0 ha is currently being used for waste disposal purposes. (see Figure 1)

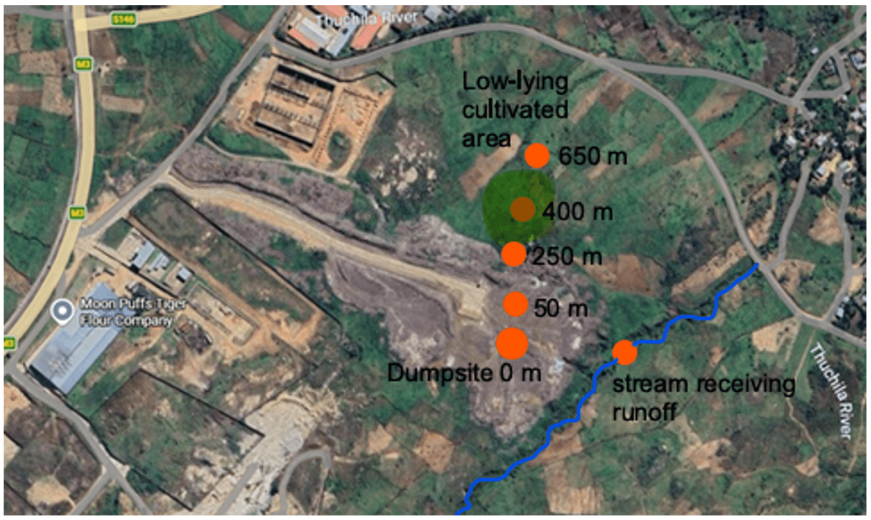

Figure 1 Satellite image of Mzedi dumpsite showing the radial sampling transect layout (Google Maps, 2026). Sampling points were established at 0 m (dumpsite center), 50 m, 250 m, 400 m, and 650 m along the southeastern transect. The 400 m point (highlighted) was situated in a low-lying cultivated area where surface runoff from the dumpsite accumulates during rainfall events. The stream receiving runoff flows along the southeastern edge of the dumpsite.

The dumpsite was established around 1992 and was designed as an open dumpsite where there are no mechanisms for the treatment of leachate and gaseous waste produced from the solid waste decomposition processes. Spreading and compaction of refuse at the dumpsite is done periodically by hired machinery in an effort to manage the available dumping space. The region experiences a tropical climate, with a rainy season (November – April) and a dry season (May – October) [11].

2.2 Sampling Methodology

2.2.1 Soil Sampling

Soil samples were collected at five radial distances (0 m, 50 m, 250 m, 400 m, and 650 m) radiating outward from the dumpsite center. The distances were selected to capture the spatial gradient of contamination from the source to peripheral areas. At each distance, three composite samples were obtained by mixing five subsamples collected from a depth of 0–20 cm using a stainless-steel auger. The subsamples were collected from random points within each radial distance to account for spatial heterogeneity. All samples were collected during the dry season to ensure consistency and comparability. The composite samples were transferred into clean, air-tight polyethylene bags, labeled accordingly, and transported to the laboratory for further analysis.

In the laboratory, the soil samples were air-dried at room temperature for 72 hours to remove moisture. The dried samples were then ground using a mortar and pestle to obtain homogenized material and sieved through a 2 mm mesh to remove coarse debris, stones, and organic matter.

The sieved samples were stored in clean, labeled polyethylene bags prior to digestion for heavy metal analysis.

2.2.2 Water Sampling

Surface water samples were collected from a stream that receives direct runoff from the Mzedi dumpsite. The stream flows along the southeastern edge of the dumpsite and passes through adjacent agricultural land and Moto Village. Triplicate water samples were collected at a point approximately 50 meters downstream of the dumpsite boundary. All samples were collected during the dry season to ensure consistency with soil sampling.

One liter of water was collected from each sampling point using pre-cleaned polyethylene bottles. The bottles were cleaned by soaking in 10% nitric acid for 24 hours and rinsed twice with deionized water prior to use. Samples were collected in triplicate at the sampling point. Upon collection, water samples were preserved immediately by acidification to pH < 2 with concentrated HNO_3 to prevent metal precipitation and microbial activity. The samples were stored in ice-filled coolers during transport to the laboratory, following standard procedures recommended by the American Public Health Association [12].

2.3 Quantification of Heavy Metals

2.3.1 Soil Sample Digestion

Soil samples were digested using a suitable acid digestion method to extract heavy metals. Approximately 1.0 g of each sieved soil sample was accurately weighed and transferred into a digestion tube. A mixture of 10 ml of concentrated nitric acid (HNO_3, 70%) and 5 ml of perchloric acid ($HClO_4$, 70%) was added to each sample. The samples were digested on a hot plate at 150°C for 3 hours in a fume cupboard until white fumes were observed, indicating complete digestion. The digested samples were allowed to cool to room temperature, after which the digests were filtered through Whatman No. 42 filter paper into 50 mL volumetric flasks. The filtrate was diluted to the mark with deionized water (18.2 MΩ·cm resistivity). The digested samples were then stored in clean, labelled polyethylene bottles at 4°C until analysis. All digestions were performed in triplicate to ensure accuracy and reproducibility.

2.3.2 Water Sample Digestion

Water samples were digested following the standard method for heavy metal analysis. In this method, 25 ml of each preserved water sample was measured into a digestion beaker. Then, 10 ml of concentrated nitric acid (HNO_3, 69%) was added, and the mixture was evaporated on a hot plate in a fume cupboard until the brown fumes disappeared, leaving white fumes. The residue was allowed to cool, after which 50 ml of deionized water was added, and the solution was concentrated by further evaporation to approximately 25 ml. Subsequently, another 25 ml of deionized water was added to make the final volume up to 50 ml. The digested samples were filtered through Whatman No. 42 filter paper into clean, labeled polyethylene bottles and stored at 4°C until analysis. All digestions were performed in triplicate.

2.3.3 Heavy Metal Determination

The concentrations of cadmium (Cd), zinc (Zn), copper (Cu), iron (Fe), manganese (Mn), lead (Pb), and cobalt (Co) in digested soil and water samples were determined using a flame Atomic Absorption Spectrophotometer (AAS, Agilent Technologies, USA). The AAS was calibrated daily using standard solutions prepared from certified stock solutions. Calibration curves were constructed using a minimum of five standard concentrations for each metal, and the analysis was performed only when the coefficient of determination (R^2) of the calibration curve was greater than 0.99.

2.4 Statistical Analysis

Descriptive statistics, correlation analysis, and contamination indices were computed using Microsoft Excel and Python. A one-way analysis of variance (ANOVA) at a 0.05 significance level was applied to identify significant differences in heavy metal concentrations among the sampling distances around the dumpsite.

Microsoft Excel was used to prepare charts, tables, and spatial variation plots. The results were subsequently used to assess contamination levels and potential ecological risks through the application of Contamination Factor (CF), Geo-accumulation Index (I_{geo}), Enrichment Factor (EF), and Potential Ecological Risk Index (PERI). All data are presented as mean ± standard deviation, and statistical significance was set at $p < 0.05$ for all analyses.

2.5 Quality assurance and control

All glassware was washed with detergent, rinsed with deionized water, and soaked in 10% nitric acid before use. Reagent blanks and certified reference materials (CRM) were used to validate analytical accuracy. Recovery rates for most metals ranged between 90% and 105%, and results were considered acceptable as per standard analytical guidelines [9].

2.6 Ethics Statement

This study involved the collection of soil and surface water samples and did not involve human participants, animals, or protected biological materials. Therefore, ethical approval was not required.

2.7 Contamination and risk assessment indices

To establish reliable background concentrations, this study drew upon two recent Malawian baseline investigations. For Cd, Pb, Co, and Mn, background values were adopted from Mlangeni et al. (2022) (Cd = 0.044 mg/kg, Pb = 11 mg/kg, Co = 14 mg/kg, Mn = 601 mg/kg). For Cu, Zn, and Fe, baseline values were obtained from Dzinjalamala et al. (2024) (Cu = 60.4 mg/kg, Zn = 190 mg/kg, Fe = 6,552 mg/kg).

Both studies were conducted within the same broader geological region, the African savanna of southern Malawi which is characterized by highly weathered tropical soils, predominantly lateritic in nature. The use of these complementary background datasets ensures that the contamination indices calculated in this study are appropriately calibrated to local geochemical conditions, thereby enhancing the accuracy and reliability of the ecological risk assessment.

The degree of soil contamination was evaluated using multiple pollution indices identical to those adopted from related studies [15, 16]. The equations are given below:

(1) Contamination Factor (CF):

$$CF = \frac{C_i}{C_{\text{background}}}$$

where C_i is the concentration of metal *i* in the sample, and $C_{\text{background}}$ is its background value Background concentrations for heavy metals were derived from local Malawian studies.

(2) Geo-accumulation Index (I_{geo}):

$$I_{\text{geo}} = \log_2 \left(\frac{C_i}{1.5 B_i} \right)$$

where B_i is the background concentration and 1.5 is a correction factor for natural variation. The Igeo values were classified according to Muller (1969) [17] as shown in Table 1.

Table 1 Geo-accumulation Pollution Classes

I_{geo} Value	Class	Pollution Intensity
$I_{geo} \leq 0$	0	Unpolluted
$0 < I_{geo} < 1$	1	Unpolluted to moderately polluted
$1 < I_{geo} < 2$	2	Moderately polluted
$2 < I_{geo} < 3$	3	Moderately to strongly polluted
$3 < I_{geo} < 4$	4	Strongly polluted
$4 < I_{geo} < 5$	5	Strongly to extremely polluted
$I_{geo} \geq 5$	6	Extremely polluted

(3) Enrichment Factor (EF):

$$EF = \frac{(C_i/Fe)_{\text{sample}}}{(C_i/Fe)_{\text{background}}}$$

EF greater than 1 indicates varying degrees of contamination, with higher values indicating higher levels of contamination compared to background levels. Enrichment factors are classified as shown in Table 2.

(4) Potential Ecological Risk Index (PERI):

$$E_r = T_r \times CF$$

Table 2 Enrichment Factor Classification

EF Value	Enrichment Category
$EF < 1$	No enrichment
$1 \leq EF < 3$	Minor enrichment
$3 \leq EF < 5$	Moderate enrichment
$5 \leq EF < 10$	Moderately severe enrichment
$10 \leq EF < 25$	Severe enrichment
$25 \leq EF < 50$	Very severe enrichment
$EF \geq 50$	Extremely severe enrichment

where T_r is the metal's toxic-response factor (Cd = 30, Pb = 5, Cu = 5, Cr = 2, Zn = 1, Co = 5, Mn = 1, Fe = 1).

$$RI = \sum E_r$$

The E_r values and PERI values were classified according to Hakanson (1980) [18] as shown in Table 3:

Table 3 Classification of Er and PERI [18]

E_r Value	Ecological Risk Level	PERI (RI) Value	Ecological Risk Level
$E_r < 40$	Low ecological risk	$RI < 150$	Low ecological risk
$40 \leq E_r < 80$	Moderate ecological risk	$150 \leq RI < 300$	Moderate ecological risk
$80 \leq E_r < 160$	Considerable ecological risk	$300 \leq RI < 600$	Considerable ecological risk
$160 \leq E_r < 320$	High ecological risk	$RI \geq 600$	Very high ecological risk
$E_r \geq 320$	Very high ecological risk	–	–

3 Results

3.1 Heavy metal concentrations in soil

Figure 2 shows the concentrations of heavy metals (Cd, Zn, Cu, Fe, Mn, Pb, Co) in soil at varying distances from Mzedi dumpsite (0 m, 50 m, 250 m, 400 m, 650 m). From Table 4, all metals showed highest concentrations at 0 m (Cd: 3.08 mg/kg; Zn: 705.80 mg/kg; Cu: 316.18 mg/kg; Pb: 80.00 mg/kg). Cd, Cu, and Pb decreased by 95%, 98%, and 82%, respectively, from 0 m to 650 m. Fe and Mn showed relatively stable concentrations across all distances, reflecting their dominant lithogenic origin.

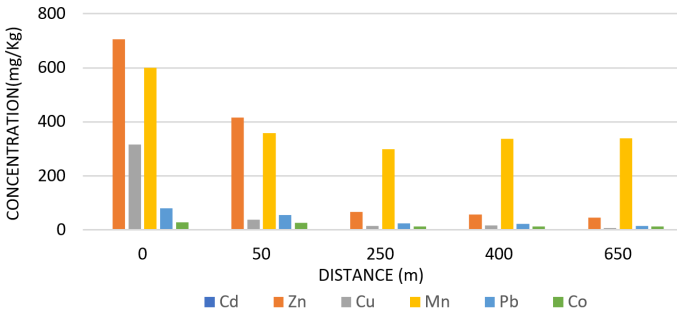

Figure 2 Concentrations of heavy metals (Cd, Zn, Cu, Fe, Mn, Pb, Co) in soil at varying distances from Mzedi dumpsite

Table 4 Mean ± SD of Heavy Metal Concentrations (mg/kg) in Soil Samples Collected at Varying Distances from Mzedi Dumpsite, Blantyre

Distance (m)	Cd (mg/kg)	Zn (mg/kg)	Cu (mg/kg)	Fe (mg/kg)	Mn (mg/kg)	Pb (mg/kg)	Co (mg/kg)
0	3.08 ± 0.74	705.80 ± 84.91	316.18 ± 66.29	23,916.98 ± 3,449.23	600.12 ± 63.39	80.00 ± 27.58	28.18 ± 0.74
50	2.58 ± 2.09	416.75 ± 348.81	38.40 ± 1.91	21,383.10 ± 5,027.95	359.15 ± 64.21	55.50 ± 43.84	26.50 ± 3.04
250	0.75 ± 0.00	67.54 ± 0.38	14.12 ± 1.38	11,417.20 ± 294.37	299.82 ± 48.05	24.75 ± 1.77	13.10 ± 0.00
400	1.18 ± 0.04	57.25 ± 25.78	17.50 ± 3.39	12,524.57 ± 730.19	337.60 ± 65.48	22.25 ± 6.01	12.92 ± 1.03
650	0.15 ± 0.00	46.32 ± 38.56	6.72 ± 2.86	15,420.18 ± 5,722.37	339.50 ± 47.31	14.25 ± 3.89	12.92 ± 0.67
WHO	0.3	-	2	3	0.5	0.1	0.05
EU	1.5		140		0.5	150	
MBS	0.01	15	2	3	1.5	0.05	

3.2 Statistical Analysis: One-Way ANOVA

Table 5 shows the One-Way ANOVA results for Heavy Metal Concentrations in Soil Samples at Different Distances from Mzedi Dumpsite, Blantyre.

Table 5 One-Way ANOVA results

Metal	*F*-statistic	*p*-value
Cd	4.78	0.02
Zn	3.33	0.06
Cu	5.92	0.01
Fe	2.52	0.11
Mn	1.52	0.27
Pb	5.43	0.01
Co	9.17	0

3.3 Correlation Analysis Between Heavy Metals

Table 6 shows the Pearson correlation coefficients between heavy metals in soil samples around Mzedi dumpsite.

Table 6 Pearson Correlation Coefficients

Metal	Cd	Zn	Cu	Fe	Mn	Pb	Co
Cd	1.00	0.94	0.75	0.86	0.75	0.97	0.95
Zn	0.94	1.00	0.89	0.94	0.90	0.99	0.96
Cu	0.75	0.89	1.00	0.76	0.99	0.87	0.73
Fe	0.86	0.94	0.76	1.00	0.80	0.91	0.96
Mn	0.75	0.90	0.99	0.80	1.00	0.86	0.75
Pb	0.97	0.99	0.87	0.91	0.86	1.00	0.96
Co	0.95	0.96	0.73	0.96	0.75	0.96	1.00

3.4 Contamination Factor (CF)

Figure 3 shows the contamination Factors (CF) for heavy metals at varying distances from Mzedi dumpsite. Cd showed the highest CF at 0 m (70.00), decreasing to 3.41 at 650 m—a 95% reduction from extreme contamination at the source to considerable contamination at the periphery. Cu and Pb CF decreased from 5.24 to 0.11 and 7.27 to 1.30, respectively. Zn CF decreased from 3.71 at 0 m to 0.24 at 650 m. Fe and Mn remained near background levels (CF < 2) at all distances, indicating minimal anthropogenic enrichment.

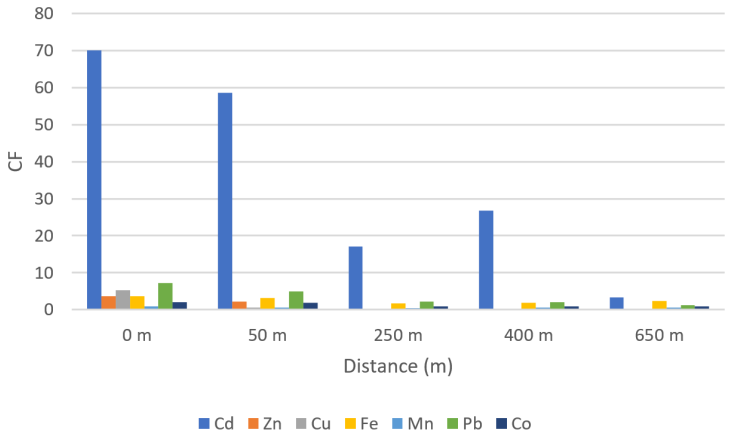

Figure 3 Contamination Factors (CF) for heavy metals at varying distances from Mzedi dumpsite

3.5 Geo-accumulation Index (Igeo)

Figure 4 shows the geo-accumulation Index (I_{geo}) values for heavy metals at different distances from Mzedi dumpsite. Cd ranged from extremely polluted at 0 m (I_{geo} = 5.54) to moderately to strongly polluted at 650 m (I_{geo} = 2.18). Pb ranged from strongly to extremely

polluted at 0 m (I_{geo} = 3.22) to strongly polluted at 650 m (I_{geo} = 3.16). All other metals were classified as unpolluted to moderately polluted ($I_{geo} < 1$) across all distances, confirming that Cd and Pb are the primary contaminants of concern.

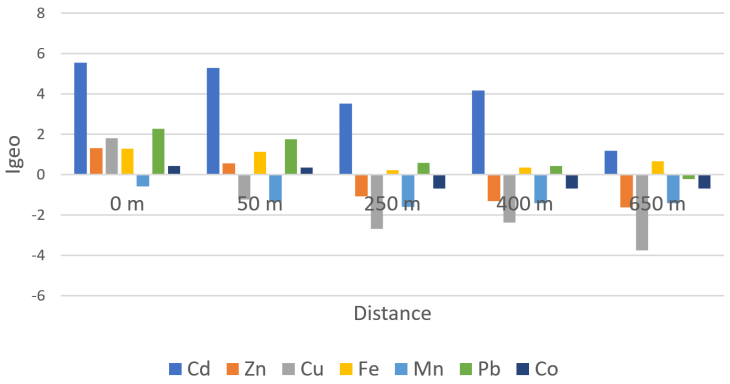

Figure 4 Geo-accumulation Index (I_{geo}) values for heavy metals at different distances from Mzedi dumpsite

3.6 Enrichment Factor (EF)

Figure 5 shows the enrichment Factor (EF) values for heavy metals at different distances from Mzedi dumpsite. Cd showed severe anthropogenic enrichment at 0 m (EF = 19.17), remaining in the severe enrichment category at 400 m (EF = 14.02). Pb and Zn showed minor enrichment (EF < 3) across all distances. Cu showed moderate enrichment at 0 m (EF = 4.23) decreasing to minor enrichment at 650 m (EF = 1.52). Fe and Mn exhibited EF values < 2 at all distances, confirming their natural background origin.

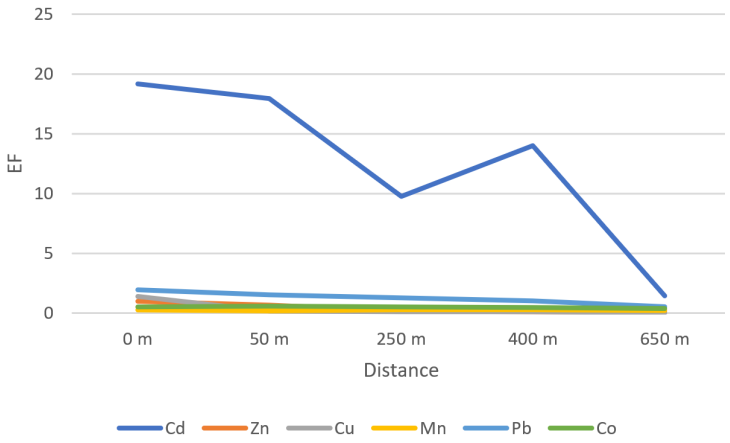

Figure 5 Enrichment Factor (EF) values for heavy metals at different distances from Mzedi dumpsite

3.7 Potential Ecological Risk Index (PERI)

Table 7 shows the PERI Values for Heavy Metals at Different Distances.

Table 7 PERI Values for Heavy Metals at Different Distances

Distance	Cd	Zn	Cu	Fe	Mn	Pb	Co	PERI (RI)
0 m	2,100.00	3.71	26.18	3.65	1.00	36.36	10.07	2,181.00
50 m	1,759.09	2.19	3.18	3.26	0.60	25.23	9.46	1,803.00
250 m	511.36	0.36	1.17	1.74	0.50	11.25	4.68	531.10
400 m	804.55	0.30	1.45	1.91	0.56	10.11	4.61	823.50
650 m	102.27	0.24	0.56	2.35	0.56	6.48	4.61	117.10

3.8 Heavy Metal Concentrations in Water

Table 8 shows the Heavy Metal Concentrations in Water.

Table 8 Heavy Metal Concentrations in Water

Sample	Cd (mg/L)	Zn (mg/L)	Cu (mg/L)	Fe (mg/L)	Mn (mg/L)	Pb (mg/L)	Co (mg/L)
Sample 1	0.008	0.450	0.035	0.520	0.120	0.025	0.015
Sample 2	0.006	0.520	0.042	0.580	0.135	0.034	0.018
Sample 3	0.007	0.480	0.038	0.490	0.110	0.028	0.012
WHO	0.003	3	2	0.3	0.1	0.01	-
EU	0.005	5	2.0	0.2	< 0.05	0.01	-
MBS	0.01	15	2	3	1.5	0.05	-

4 Discussion

The spatial distribution of heavy metals around Mzedi dumpsite suggests a clear point-source influence, with concentrations generally decreasing with distance, likely due to dilution, adsorption, and attenuation processes governed by soil properties and leachate migration. This gradient appears to reflect a combination of anthropogenic inputs and natural geochemical controls within the surrounding lateritic soils.

Cadmium (Cd) appears to be the most critical contaminant. Concentrations at the dumpsite center (3.08 mg/kg) exceeded MBS, WHO, and EU guideline values by 308-, 10-, and 2-fold, respectively, and remained elevated even at 650 m (exceeding MBS by 15-fold). This pattern suggests relatively high mobility and persistence in the soil environment, which may be linked to weak sorption and higher solubility compared to other metals [19]. In contrast, Zn and Cu showed strong enrichment at the source (705.80 mg/kg and 316.18 mg/kg) but decreased rapidly with distance, suggesting stronger attenuation through adsorption and precipitation mechanisms. Pb (80.00 mg/kg) remained elevated across the transect, which may reflect its low solubility and strong affinity for soil particles, potentially linked to batteries and electronic waste sources [20]. Co showed moderate spatial variability, while Fe and Mn exhibited high but relatively stable concentrations, which likely reflects dominant lithogenic control associated with tropical soil weathering processes.

ANOVA results suggest significant spatial variation for Cd, Cu, Pb, and Co ($p < 0.05$), while Zn shows a borderline response ($p = 0.06$), and Fe and Mn appear to show no significant variation. This pattern may indicate that Cd, Pb, Cu, and Co are more strongly influenced by anthropogenic inputs, whereas Fe and Mn are largely controlled by natural background geochemistry. Pearson correlation analysis further indicates strong positive associations among Zn, Pb, Cd, and Co ($r = 0.95$–0.99), which may suggest a shared source linked to mixed municipal waste and leachate transport processes [7, 8, 20]. Correlations involving Fe may reflect its role as a major soil matrix component that facilitates adsorption and co-precipitation of trace metals rather than indicating an external source [2, 20].

Multi-index contamination assessment consistently suggests Cd as the dominant contaminant of concern. CF values indicate extreme contamination for Cd (70.00), while Pb, Cu, and Zn show lower but still elevated enrichment near the source. Cd remains considerably contaminated even at 650 m (CF = 3.41), suggesting persistence beyond the immediate dumpsite zone. The geo-accumulation index (I_{geo}) indicates that Cd ranged from extremely polluted at the source ($I_{geo} = 5.54$) to moderately to strongly polluted at 650 m ($I_{geo} = 2.18$), whereas other metals tend to fall within unpolluted ranges beyond 50 m. Similarly, enrichment factor (EF) results suggest severe anthropogenic enrichment for Cd (EF = 19.17 at 0 m; 14.02 at 400 m), while Pb, Zn, and Cu generally show minor enrichment and Fe and Mn remain close to background levels.

The Potential Ecological Risk Index (PERI) suggests very high ecological risk at the dumpsite center (2,181.0), largely driven by Cd, which appears to contribute more than 90% of the total risk due to its high toxicity coefficient (Tr = 30). Although risk appears to decrease with distance, relatively elevated values appear at 400 m (823.5). Field observations showed that the 400 m sampling point was located in a low-lying cultivated area where the terrain sloped towards the site, allowing surface runoff from the dumpsite to accumulate during rainfall events. These topographic conditions likely promoted the redistribution and localized accumulation of leachate-derived contaminants, explaining the elevated ecological risk observed at this location despite its greater distance from the dumpsite. At 650 m, risk levels appear substantially reduced (117.1), suggesting attenuation of contamination influence with distance.

Surface water results indicate that the dumpsite may be contributing to adjacent aquatic contamination. Cd (0.006–0.008 mg/L) and Pb (0.025–0.034 mg/L) exceed WHO and EU

guideline values, suggesting potential ecological and human health concerns [21, 22]. Fe and Mn also exceed recommended thresholds in some samples, while Zn, Cu, and Co remain within acceptable limits. These patterns suggest possible transport of contaminants through leachate infiltration and runoff processes.

Overall, the integrated evidence from spatial trends, statistical analysis, and contamination indices (CF, Igeo, EF, and PERI) consistently suggests that Cd is the most important contaminant of concern at Mzedi dumpsite. This contrasts with earlier assessments that reported low risk [16], which may be attributed to limited sampling density and absence of normalized contamination indices. The observed persistence of Cd in both soil and water systems, combined with agricultural activities within 20–100 m of the site, may indicate a potential pathway for food-chain transfer [5, 8, 20]. These findings therefore suggest the need for targeted mitigation measures, including buffer zone enforcement, improved waste management practices, and continued monitoring of soil and water quality.

4.1 Implications for Agriculture, Food Safety and Environmental Management

The integrated findings from soil, water, and ecological risk assessments collectively confirm that Mzedi dumpsite exerts a multicompartmental influence on the surrounding environment, with profound implications for agriculture, food safety, aquatic ecosystems, and environmental management. In terms of irrigation and agricultural water use, the stream receiving dumpsite runoff contains cadmium (0.006–0.008 mg/L) and lead (0.025–0.034 mg/L) that exceed FAO irrigation water quality guidelines (0.01 and 0.005 mg/L, respectively), rendering this water unsuitable for longterm irrigation a critical concern in Malawi where untreated surface water is commonly used for dry season vegetable and maize cultivation, potentially introducing metals into soils and crops through direct deposition and root uptake [23], as documented across Africa where wastewater-irrigated vegetables in Nigeria [5] and Ghana [24] contained lead and cadmium exceeding permissible limits, posing significant health risks to consumers.

For aquatic ecosystem health, cadmium concentrations (0.006–0.008 mg/L) exceed WHO guidelines for aquatic life protection (0.005 mg/L), and lead levels (0.025–0.034 mg/L) surpass European Inland Fisheries Advisory Commission (EIFAC) guidelines (0.01–0.02 mg/L), indicating chronic stress on freshwater biota, with studies from Nigeria [25] and South Africa [26] linking such contamination to reduced biodiversity and altered community structure. Furthermore, the non-biodegradable nature of cadmium and lead facilitates bioaccumulation and biomagnification through aquatic food chains [27, 28]. While fish samples were not collected in this study, evidence from comparable African contexts [29–31] has documented fish from contaminated waters accumulating metals above FAO/WHO consumption limits. This suggests that similar bioaccumulation may occur in the stream receiving Mzedi runoff, a particular concern in Malawi where fish are a dietary protein staple. The observed water concentrations (Cd: 0.006–0.008 mg/L; Pb: 0.025–0.034 mg/L) exceed thresholds associated with bioaccumulation in these studies, warranting future fish sampling to validate this inference.

Regarding agriculture and food safety, elevated cadmium, lead, zinc, and copper in cultivated soils particularly the active maize fields within contaminated zones, raise direct food chain concerns, as maize's extensive root system facilitates uptake of bioavailable metals, especially cadmium, which translocates to grains even at low soil concentrations, consistent with the strong spatial gradient and PERI dominance of cadmium; empirical African studies reinforce this, with maize from the Iringa dumpsite in Tanzania containing lead exceeding FAO/WHO limits by threefold and posing significant carcinogenic risks [32], while Nigerian studies [33] discouraged maize cultivation on dumpsiteadjacent soils due to lifetime cancer risks, and research from Ghana [34] and Uganda [35] documented cadmium and lead in vegetables far above safe limits, with cadmium and lead showing the highest translocation factors to edible portions; Additionally, the phytotoxicity of excess copper and zinc, along with potential synergistic toxic effects from mixed contaminants, threatens soil fertility and crop productivity over time. While direct dietary exposure data were not collected in this study, the elevated soil concentrations particularly cadmium, raise concern about potential chronic dietary exposure via the soil–plant–human pathway, with subsistence farming communities being most vulnerable. However, confirmation of this pathway requires direct measurement of metal concentrations in locally cultivated crops and, ultimately, human biomonitoring studies [34, 35].

From an environmental management perspective, the integrated evidence, spatial soil gradients, water exceedances, and consistently high ecological risk indices (CF, I_{geo}, EF, PERI), demonstrates that contamination is active and ongoing, not historical, necessitating urgent

interventions: establishment of engineered landfill systems to minimize leachate generation; immediate restriction of agricultural activities in high-risk zones; integrated monitoring of soil and water compartments; application of phytoremediation or soil stabilization only as supplementary measures without source control; and public awareness programs to warn communities against cultivating crops or using untreated water in contaminated areas. Ultimately, sustainable management requires a coordinated multisectoral approach combining environmental regulation, agricultural land-use control, and public health protection, given the interconnected nature of soil contamination, water pollution, and potential food chain transfer, with the consistently stringent Malawi Bureau of Standards (MBS) guidelines underscoring the need for locally relevant yet protective thresholds to address the persistent cadmiumdriven risks that permeate all compartments of this waste-impacted landscape.

5 Conclusion and Recommendations

5.1 Conclusion

This comprehensive study of Mzedi dumpsite in Blantyre, Malawi, reveals severe heavy metal contamination particularly cadmium, with concentrations at the dumpsite center showing extreme enrichment (CF = 70.00, Igeo = 5.54, EF = 19.17) and contributing >96% of the very high ecological risk (PERI = 2,181), which declines to low risk at 650 m (PERI = 117). Surface water analysis confirmed active leachate transport, with cadmium (0.006–0.008 mg/L) and lead (0.025–0.030 mg/L) exceeding WHO drinking water guidelines. The present study demonstrates substantially higher ecological risk than previously reported, primarily due to the inclusion of contamination indices and ecological risk assessment approaches. The contamination pattern coupled with active maize cultivation on and around the dumpsite, creates a potential food chain pathway for toxic metals, supported by similar African studies documenting crop contamination and health risks. Urgent recommendations include: formal prohibition of farming within a 250-meter buffer zone, upgrade to a sanitary landfill with leachate control, community awareness programs, regular environmental monitoring, and provision of safe water alternatives. This first comprehensive quantitative assessment establishes cadmium as the priority contaminant requiring immediate multi-sectoral intervention to prevent further environmental degradation and human exposure.

5.2 Future Research Recommendations

To build upon the baseline data established in this study, several critical research priorities emerge. First, comprehensive crop monitoring studies should directly measure heavy metal concentrations, particularly cadmium, given its dominance in the ecological risk assessment, in maize, vegetables, and other crops cultivated on and around the dumpsite, including analysis of metal bioavailability and bioconcentration factors to confirm the extent of food chain contamination and provide a robust basis for public health risk assessment. Second, long-term temporal and seasonal monitoring studies are essential to investigate how the tropical climate's distinct wet and dry seasons influence metal mobility, leachate generation, and plant uptake, thereby enabling prediction of future contamination trends and informing adaptive mitigation strategies.

Third, sequential extraction procedures should be employed to determine metal speciation and bioavailability, as total metal concentrations may overestimate actual risks if metals are strongly bound to soil particles, and understanding speciation would improve risk assessments and guide remediation selection. Fourth, epidemiological and dietary exposure studies including biomonitoring of heavy metal levels in local populations and assessment of health outcomes should be conducted to provide direct evidence of public health risks associated with consuming contaminated crops and water, supporting targeted interventions. Fifth, given the absence of engineered liners, groundwater quality investigations are urgently needed to assess leachate migration and potential contamination of drinking water sources. Finally, building on the work of Kalina and Tilley (2020) [10], critical social science research should explore how communities conceptualize waste-related risks, identify culturally appropriate risk communication strategies, and understand the socio-economic factors driving subsistence farming on contaminated land, ultimately identifying pathways for sustainable livelihood alternatives. By integrating these multidisciplinary investigations spanning environmental chemistry, toxicology, hydrogeology, and social science, future research can transform the current inferential risk assessments into empirically grounded evidence, guiding effective remediation, land-use planning, and public health protection measures at Mzedi dumpsite and similar waste-impacted environments across Malawi and sub-Saharan Africa.

5.3 Limitations of the study

Several methodological constraints should be acknowledged when interpreting the findings of this study. First, the absence of direct heavy metal measurements in locally cultivated crops (such as maize and leafy vegetables) means that the inferred food safety and human health risks remain inferential rather than empirically confirmed, as actual plant uptake is governed by complex factors including metal bioavailability, soil pH, organic matter content, and agronomic practices; future research should prioritize crop analysis to quantify contaminant transfer from soil to the food chain. Second, the study's cross-sectional design captures only a single time point, precluding assessment of seasonal or long-term trends in metal mobility and bioavailability, which are influenced by rainfall, temperature, and soil moisture variations necessitating long-term monitoring to determine whether contamination is increasing, stable, or declining.

Third, the analysis relied on total metal concentrations rather than bioavailable fractions, potentially overestimating ecological and health risks if metals are strongly bound to soil particles; sequential extraction procedures should be incorporated in future studies to determine metal speciation and true bioavailability. Fourth, human health outcomes and direct dietary exposure assessments were not conducted, meaning that public health implications are based on environmental data and established toxicological knowledge rather than direct epidemiological evidence. Fifth, surface water sampling was confined to a single downstream location (though triplicate samples improved analytical reliability), limiting the characterization of spatial variability along the stream network and contaminant dispersion dynamics; future studies should incorporate multiple upstream and downstream points to better capture transport and dilution patterns. Despite these limitations, this study establishes crucial baseline data on the spatial distribution and ecological risk of heavy metals at Mzedi dumpsite, unequivocally identifying cadmium as the priority contaminant demanding urgent environmental and public health interventions.

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Author Contributions

Vincent Gwengwe: Conceptualization, Methodology, Writing-Original Draft, Investigation, Data Collection, Writing-Review; **Ephraim Vunain**: Data Curation, Visualization, Supervision, Formal Analysis. The final manuscript was read and approved by all authors.

Data Availability

The data supporting the findings of this study are available within the article.

Ethical Statement

All authors have read, understood, and complied as applicable with the statement on "Ethical responsibility of Authors" as found in the Instructions for Authors.

Conflicts of Interest

The authors declare no conflicts of interest.

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