Journal of Geoscience and Environment Protection, 2025, 13(11), 286-314
https://www.scirp.org/journal/gep
ISSN Online: 2327-4344
ISSN Print: 2327-4336

Evaluation of Concentrations and Dispersion of Heavy Metals in Soils Surrounding Artisanal and Small-Scale Gold Mining in Chunya District, Mbeya

Fredrick P. Girenga, Nelson Mpumi, Ruth L. Moirana, Revocatus L. Machunda

Department of Environmental Science and Environmental Engineering, School of Materials, Energy, Water and Environmental Science, The Nelson Mandela African Institution of Science and Technology, Arusha, Tanzania
Email: fphinias@gmail.com

How to cite this paper: Girenga, F. P., Mpumi, N., Moirana, R. L., & Machunda, R. L. (2025). Evaluation of Concentrations and Dispersion of Heavy Metals in Soils Surrounding Artisanal and Small-Scale Gold Mining in Chunya District, Mbeya. *Journal of Geoscience and Environment Protection, 13,* 286-314.
https://doi.org/10.4236/gep.2025.1311015

Received: October 23, 2025
Accepted: November 23, 2025
Published: November 26, 2025

Abstract

Heavy metal contamination from Artisanal and Small-Scale Gold Mining (ASGM) is increasingly recognized as a global issue, impacting soil quality and public health. In Tanzania, while ASGM activities significantly bolster local economies, they also pose serious environmental risks. This study examined the levels and dispersion of heavy metals, specifically mercury (Hg), lead (Pb), arsenic (As), zinc (Zn), and cadmium (Cd) in the Chunya district. Soil samples were collected from both active and abandoned tailing heaps and analysed by Atomic Absorption Spectroscopy (AAS), with the results compared to the WHO/FAO (2008) guidelines for agricultural soils. The findings revealed alarming concentrations of Hg across all sampling points, ranging from 0.88 to 3.72 $mg{\cdot}kg^{-1}$. In contrast, 48 out of 51 sampling points exhibited higher Cd levels between 0.98 and 4.42 mg/kg, exceeding the safe limits of 0.5 $mg{\cdot}kg^{-1}$ for Hg and 0.8 $mg{\cdot}kg^{-1}$ for Cd. In contrast, the negative control site showed much lower levels (0.03 $mg{\cdot}kg^{-1}$ for Cd and 0.43 $mg{\cdot}kg^{-1}$ for Hg). A notable decrease in heavy metal concentrations was observed with increasing distance from the tailing heaps (0 m to 200 m). Soil pH and electrical conductivity significantly influenced the mobility of these contaminants, with higher concentrations found near lower tailing heaps. The elevated levels of Hg and Cd present substantial risks to human health and ecosystems, highlighting the urgent need for effective remediation strategies. Furthermore, the gold mining industry must innovate technologies that minimize heavy metal release during extraction processes to mitigate environmental harm.

Keywords

Heavy Metals, Tailing Heaps, Lateral Mobility, Permissible Limit, Environmental Risks, Human Health

1. Introduction

Artisanal and small-scale gold mining (ASGM) accounts for approximately 20% of global gold production, directly involving over 20 million miners and supporting the livelihoods of more than 100 million individuals worldwide (Hilson, 2002; Hilson & Maconachie, 2020). In Africa, ASGM plays a major role in rural economies, providing employment to around 10 million people and indirectly supporting over 60 million others (Grynberg & Singogo, 2021). In Tanzania, ASGM contributed 30% of the country's total gold output in 2021 (Maganga et al., 2023).

Despite its economic importance, ASGM generates large volumes of mine waste, known as tailings, which are often poorly managed (Mutemeri et al., 2024). These tailings contain hazardous heavy metals such as arsenic (As), chromium (Cr), lead (Pb), cadmium (Cd), zinc (Zn), and mercury (Hg). These metals are persistent in the environment and can accumulate in soil, water, plants, animals, and humans (Bradl, 2005; Violante et al., 2010). Long-term exposure to these contaminants is linked to serious health effects, including neurological damage, kidney dysfunction, and cancer (Nikmanesh et al., 2023; Vandana et al., 2022).

Previous studies have reported high concentrations of heavy metals in ASGM tailings. For instance, Tanzania displays increased cadmium levels (6.4 - 11 mg/kg), South Africa shows elevated zinc (8.9 - 65.7 mg/kg) concentrations, Ghana is characterized by high arsenic (8305 mg/kg), copper, zinc (177.56 mg/kg), and both South Africa and Ghana exhibit high lead levels (80 - 510 mg/kg). In comparison, Oman reports elevated chromium concentrations (486 mg/kg) (Fashola et al., 2016). Mercury, commonly used in gold extraction, is frequently found in elevated levels at ASGM sites in Tanzania, Ghana, and Ecuador (Gonçalves Jr. et al., 2017; Fikri et al., 2023). Other metals such as nickel (Ni), cobalt (Co), manganese (Mn), and iron (Fe) have also been detected in high concentrations near mining areas across Africa, Asia, and Latin America (Ogundele et al., 2021; Wiafe et al., 2022; Montalván-Olivares et al., 2021; Yabe et al., 2010).

A case study in Tendo and Aby Lagoon in Côte d'Ivoire on exposure of mercury from gold mining area revealed mean Hg concentrations in the sediments of Tendo and Aby lagoons to be 0.89 ± 0.26 $mg{\cdot}kg^{-1}$ and 0.70 ± 0.18 $mg{\cdot}kg^{-1}$, respectively. The minimum and maximum total Hg concentrations in the sediments from 25 stations were 0.04 and 3.56 $mg{\cdot}kg^{-1}$, respectively. This level of mercury contamination in lagoons during ASGM was reported to pose risks to the lagoon ecosystem and to the health of the population living near these lagoons (Claon et al., 2022).

Another case study conducted in Ibodi-Ijesa, Southwest Nigeria by Kyowe et al. (2024) assessed Index of heavy metal pollution and health risk assessment in rela-

tionship to AGSM, revealed low concentrations of copper (Cu), cobalt (Co), lead (Pb), and nickel (Ni), concentrations ranged from 80.17 to 100.11 $mg \cdot kg^{-1}$, 42.11 to 50.07 $mg \cdot kg^{-1}$, 30.93 to 54.00 $mg \cdot kg^{-1}$, and 35.30 to 44.20 $mg \cdot kg^{-1}$, respectively. Nickel (Ni), cadmium (Cd), and arsenic (As) were all below the allowable limit. Moreover, the Health Risk Index was greater than one, indicating possible health hazards for inhabitants.

Soil chemical properties like pH and electrical conductivity (EC) greatly affect heavy metal mobility (De Matos et al., 2001; Fijałkowski et al., 2012; Akbar et al., 2024).

Low pH makes metals more soluble and mobile, while high pH helps trap them through adsorption or precipitation (Bourg & Loch, 1995; Sintorini et al., 2021). Alghzawi et al. (2025) found that arsenic exhibits higher mobility in acidic mine-impacted soils, whereas in soils with neutral to slightly alkaline pH, arsenic is predominantly retained due to its association with iron oxides. This suggests that soil pH plays a critical role in controlling arsenic behavior and its environmental risk in mining areas (Zhuang et al., 2023).

Furthermore, Luan et al. (2022) demonstrated that cadmium exhibits enhanced migration rates in acidic soils compared to neutral pH conditions, suggesting an increased potential for dispersion in acidic environments.

Similarly, low EC supports metal retention in soil, but high EC increases competition from other ions, making metals more mobile and easier to spread. Jiang et al. (2021) observed that elevated electrical conductivity (EC) in non-ferrous metal tailings facilitated increased leaching of copper, zinc, and lead. Similarly, Gitari et al. (2018) reported that higher ionic strength promoted the mobilization of copper and zinc from tailings into pore water. In line with these findings, Kumkrong et al. (2022) demonstrated that soils exhibiting higher EC contained larger proportions of exchangeable metals, indicating enhanced metal mobility. These factors are especially important in mining-affected areas.

In Tanzania, ASGM is concentrated in regions such as Geita, Mara, Mbeya, Shinyanga, and Katavi (Kabamanya, 2025). Studies in these areas have confirmed elevated heavy metal levels in soil and water. However, most research has focused on identifying pollution hotspots without assessing how far the contamination spreads. This lack of spatial data limits our ability to evaluate environmental risks and design effective remediation strategies.

To address this gap, the present study aims to evaluate both the concentration levels and spatial distribution of heavy metals in soils surrounding artisanal and small-scale gold mining (ASGM) tailings in Tanzania. Soil samples will be systematically collected at incremental distances from the tailings sites and analysed for lead, cadmium, mercury, arsenic, and zinc using established laboratory procedures. Spatial distribution patterns will be delineated through geographic mapping coupled with rigorous statistical analyses. Metal concentrations are anticipated to peak near the tailings and diminish with distance, with more mobile metals such as cadmium and zinc dispersing farther, while less mobile, heavier metals like lead and arsenic remain concentrated near the contamination source (Wuana

& Okieimen, 2011; Violante et al., 2010). The outcomes of this study will enhance understanding of heavy metal pollution dynamics in ASGM environments, inform environmental risk assessments, and contribute to the development of remediation strategies aimed at safeguarding ecosystems and public health (Hilson, 2002; Hilson & Maconachie, 2020).

2. Materials and Methods

2.1. Study Areas

This research was carried out in Chunya District, situated within the Lupa Goldfield at coordinates 8˚33'23.69" S and 33˚26'1.88" E. Ranking as Tanzania's second largest goldfield after the Lake Victoria Goldfield, the Lupa Goldfield spans an area exceeding 3,000 km^2. Historical data reveal that during the colonial era, the region yielded approximately 30 tonnes of gold and 8 tonnes of silver (Mnali, 2001), with an additional 41.24 tonnes of gold extracted between 2015 and 2020 according to the Tanzania Mining Commission (TMC, 2021. The soils around the mining sites in the study area are mainly used for agricultural activities, particularly the cultivation of seasonal crops, including maize and common beans (Mnali, 2001). **Figure 1** shows the Chunya district and the five villages where this study was conducted.

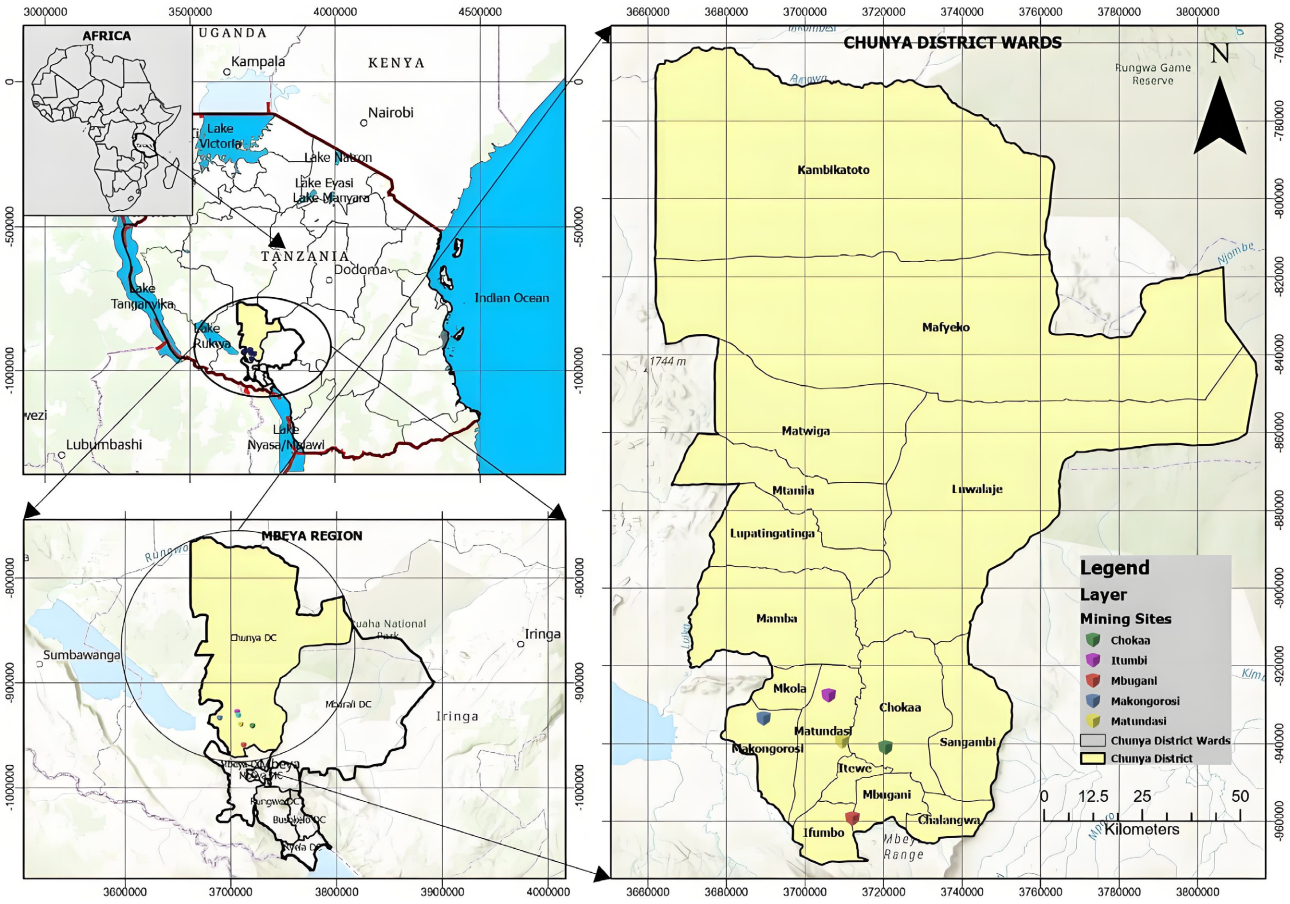

Figure 1. Location of the study area in Chunya District within the Lupa Goldfield, southwestern Tanzania. Sampling villages (Itumbi, Makongorosi, Mbugani, Chokaa, Matundasi).

2.2. Sample Collection and Preparation

The soil sampling procedure used a hybrid sampling approach combining cluster and simple random sampling techniques (Pennock et al., 2007). Five villages Chokaa, Matundasi, Makongorosi, Itumbi, and Mbugani served as clusters, and in each village, a simple random sampling method was used to select two sites for this study. From each site, soil samples were collected at the tailing deposit (0 m), then at 50 m, 100 m, 150 m, and 200 m points along the transect line. At each point, three soil subsamples were collected using a soil auger at 0 - 30 cm, and these were used to constitute a single composite sample following the procedure described by Shapiro & Kranz (1992). Additionally, one negative control sample was collected 6 km away from any mining activity to provide a baseline for comparison. GPS coordinates for all sampling points were recorded using a Garmin ETREX 22 device to support accurate spatial referencing and mapping (Huising & Mesele, 2022). All samples were air-dried, homogenized, and sieved to remove debris and ensure uniform particle size before digestion as outlined in the procedure by Saha et al. (2017).

2.3. Determination of Soil pH and Electrical Conductivity

The procedure described by Sharma et al. (2004) was adopted, where ten grams of air-dry soil were placed in a 50 mL beaker, then 25 mL of deionized water for the ratio (1:2.5) was added to the beaker and mixed well using a mechanical shaker for 30 minutes. After leaving the suspension to settle for 15 minutes, EC and pH were measured using an EC meter and a pH meter, respectively. Between each EC and pH reading, the electrode was rinsed with distilled water, and standardization was done after every 25 samples.

2.4. Determination of Heavy Metal Concentration

The acid digestion protocol was employed to determine the concentration of heavy metals (Hseu, 2004). Ten grams of each sample were placed in a 250 ml conical flask, followed by the addition of 10 ml concentrated nitric acid (HNO_3).

The mixture was heated at 100˚C for 15 minutes to initiate organic matter breakdown, then cooled. Subsequently, 5 ml of concentrated hydrochloric acid (HCl) was added, and the solution was reheated for 30 minutes until brown fumes ceased, indicating completion of the initial digestion.

After cooling, 2 ml of distilled water and 3 ml of hydrogen peroxide (H_2O_2) were added to oxidize residual organic matter. If effervescence persisted, an additional 1 ml of H_2O_2 was added. The final digestion step involved adding 10 ml of concentrated HCl and heating until the volume was reduced to approximately 5 ml. The digested mixture was filtered, diluted to 100 ml with distilled water, and stored in acid-washed containers for analysis. Before the quantification of heavy metals in digested soil and tailings samples, the Atomic Absorption Spectrophotometer (AAS) was meticulously calibrated to ensure analytical accuracy and reproducibility. Calibration was conducted using certified standard solutions of the target ele-

ments—lead (Pb), mercury (Hg), cadmium (Cd), arsenic (As), and zinc (Zn)—prepared at predetermined concentrations. Mercury was quantified using Cold Vapour Atomic Absorption Spectrometry (CVAAS), while Graphite Furnace Atomic Absorption Spectrometry (GFAAS) was used for quantification of cadmium, zinc and lead, and Hydride generation AAS was used for quantification of arsenic.

Each standard solution was introduced into the respective AAS, and the corresponding absorbance values were recorded. The absorbance readings demonstrated a consistent and proportional increase with concentration, confirming the expected linearity of the calibration response.

To further validate the calibration procedure, a reagent blank (negative control digest) was incorporated to account for potential background interference. Additionally, verification standards were employed throughout the analytical run to monitor instrument stability and performance.

Subsequently, calibration curves for each metal were constructed by plotting absorbance against concentration. These curves served as the analytical benchmark, enabling the accurate determination of metal concentrations in unknown samples based on their absorbance values.

2.5. Data Analysis

Using R software, one-way ANOVA was used to analyze the data and Tukey's Test was used to separate the means.

3. Results

3.1. Itumbi Village

For Itumbi village site 1, the results indicate that the concentrations of cadmium (0.11 - 2.77 $mg{\cdot}kg^{-1}$) and mercury (1.25 - 0.43 $mg{\cdot}kg^{-1}$) in the soil were above the allowable limit (0.8 $mg{\cdot}kg^{-1}$ for Cd and 0.5 $mg{\cdot}kg^{-1}$ for Pb), while the remaining metals were below the allowable limit. The results also indicate a significant difference in Cd, Pb, and Zn concentrations between the 0 - 200 m distance, where a non-significant difference in concentration from 0 - 200 m distance was recorded for As ($p \leq 0.05$). The results also show a decrease in soil pH and EC with distance from 0 to 200 m (Table 1).

For the Itumbi site 2, a similar result was recorded, where the concentration of cadmium (0.21 - 3.78 $mg{\cdot}kg^{-1}$) and mercury (1.01 - 2.87 $mg{\cdot}kg^{-1}$) in the soils was above the allowable limit, while the remaining metals were below or within the allowable limit. A significant difference in heavy metal concentration from 0 to 200 m distance from the tailing deposit was recorded for Cd, Pb, and As, whereas a non-significant difference in concentration from 0 - 200 m was recorded for As ($p \leq 0.05$) (Table 2).

3.2. Makongorosi Village

For site 1, the results indicate that the concentrations of Cadmium (4.0 - 1.22 $mg{\cdot}kg^{-1}$) and Mercury (2.66 - 1.29 $mg{\cdot}kg^{-1}$) in the soil were above the allowable

Table 1. Mean concentrations (±SD) of Cd, Pb, Hg, As, and Zn, along with soil pH and electrical conductivity (EC), measured at the Itumbi village site 1 in Chunya District, Tanzania. WHO (2008) permissible limits are shown for comparison.

Distance	Concentration of metals						
	Cd (mg/kg)	Pb (mg/kg)	Hg (mg/kg)	As (mg/kg)	Zn (mg/kg)	pH	EC µS cm^{-1}
0 m	2.70 ± 0.53a	40.12 ± 0.53a	2.41 ± 0.53a	0.78 ± 0.53a	14.51 ± 0.54a	7.8 ± 0.6	930 ± 51.09
50 m	1.80 ± 0.55ab	39.09 ± 0.55a	1.94 ± 0.55a	0.72 ± 0.55a	13.82 ± 0.55ab	7.6 ± 0.6	95 ± 1
100 m	1.46 ± 0.53b	33.19 ± 0.48b	1.92 ± 0.55a	0.64 ± 0.35a	12.87 ± 0.54b	6.9 ± 0.5	31 ± 1
150 m	1.36 ± 0.55b	30.48 ± 0.57c	1.32 ± 1.53ab	0.63 ± 0.31a	9.62 ± 0.53c	6.4 ± 0.6	27 ± 1
200 m	0.11 ± 0.05c	25.04 ± 0.47d	1.25 ± 0.54ab	0.31 ± 0.5a	6.00 ± 0.54d	6.4 ± 0.5	24 ± 1
-Ve control	0.03 ± 0.01c	20.24 ± 0.57e	0.43 ± 0.22b	0.02 ± 0.01a	4.74 ± 0.57d	5.2 ± 0.57	1 ± 0.5
p-value	5.75e−05	3.61e−14	0.0061	0.165	8.9e−11	0.00123	41e−15
Allowable limit (WHO)	**0.8**	**100**	**0.5**	**20**	**200**	**7.5**	**1000**

Table 2. Mean concentrations (±SD) of Pb, Hg, Cd, As, and Zn, as well as soil pH and electrical Conductivity (EC) was measured at Itumbi village site 2 in Chunya District, Tanzania. WHO (2008) guideline values are included for reference.

Distance	Concentration of metals						
	Cd (mg/kg)	Pb (mg/kg)	Hg (mg/kg)	As (mg/kg)	Zn (mg/kg)	pH	EC µS cm^{-1}
0 m	3.78 ± 0.51a	41.33 ± 0.54a	2.87 ± 0.52a	0.86 ± 0.44a	16.43 ± 0.54a	6.13 ± 0.55	950 ± 1
50 m	1.67 ± 0.54b	40.47 ± 0.54a	2.29 ± 0.42ab	0.73 ± 0.42a	15.90 ± 0.54a	6.00 ± 0.50	80 ± 1
100 m	1.35 ± 0.42b	30.89 ± 0.54b	2.01 ± 0.54ab	0.68 ± 0.41a	10.45 ± 0.54b	6.00 ± 0.50	34 ± 1
150 m	1.34 ± 0.53b	28.42 ± 0.57c	1.42 ± 0.53bc	0.50 ± 0.22a	8.33 ± 0.56c	5.80 ± 0.50	30 ± 1
200 m	0.21 ± 0.05c	28.34 ± 0.55c	1.01 ± 0.52bc	0.45 ± 0.21a	5.98 ± 0.53d	5.70 ± 0.50	25 ± 1
-Ve control	0.03 ± 0.005c	20.24 ± 0.57d	0.43 ± 0.22c	0.02 ± 0.005a	4.74 ± 0.57d	5.20 ± 0.57	1 ± 0.5
p-value	1.5e−06	4.05e−14	0.00043	0.0882	1.19e−11		
Allowable limit (WHO)	**0.8**	**100**	**0.5**	**20**	**200**	**7.5**	**1000**

limit for Cd and Hg, respectively. This was contrary to other metals whose concentrations were within the allowable limit. The results also indicate a significant difference in Cd, Pb, Zn, and Hg concentrations between the 0 – 200 m distance, where a non-significant difference in concentration from 0 – 200 m distance was recorded for As ($p \leq 0.05$). The results also show a decrease in soil pH and EC with distance from 0 to 200m (Table 3).

For site 2, a similar result was recorded where the concentration of Cadmium (1.33 - 3.76 $mg{\cdot}kg^{-1}$) and Mercury (1.26 - 2.66 $mg{\cdot}kg^{-1}$) in the soils was above the allowable limit, while the concentration of other metals was below or within the allowable limit. A significant decrease in heavy metal concentration from 0 to 200 m distance from the tailing deposit was recorded for Cd, Pb, and Hg, whereas a non-significant decrease in concentration from 0 - 200 m was recorded for As at $p \leq 0.05$. There was also a decrease in the average pH and EC with an increase in distance from 0 - 200 m (Table 4).

Table 3. Mean concentrations (±SD) of Pb, Hg, Cd, As, and Zn, as well as soil pH and electrical Conductivity (EC) was measured at the Makongorosi village site 1 in Chunya District, Tanzania. WHO (2008) guideline values are included for reference.

Distance	Concentration of metals						
	Cd (mg·kg^{-1})	Pb (mg·kg^{-1})	Hg (mg·kg^{-1})	As (mg·kg^{-1})	Zn (mg·kg^{-1})	pH	EC µS cm^{-1}
0 m	4.00 ± 0.50a	36.80 ± 0.51a	2.66 ± 0.52a	0.86 ± 0.50a	16.52 ± 0.51a	8.0 ± 0.50	2801 ± 1
50 m	2.64 ± 0.51b	33.09 ± 0.52b	2.11 ± 0.53ab	0.66 ± 0.50a	12.19 ± 0.51b	6.5 ± 0.50	31 ± 1
100 m	2.02 ± 0.52bc	29.89 ± 0.49c	1.59 ± 0.51abc	0.50 ± 0.30a	11.92 ± 0.39bc	6.4 ± 0.50	20 ± 1
150 m	1.78 ± 0.48bc	27.27 ± 1.03d	1.57 ± 0.53abc	0.47 ± 0.33a	11.35 ± 0.55bc	6.0 ± 0.50	5 ± 1
200 m	1.22 ± 0.47cd	23.60 ± 1.45e	1.29 ± 0.52bc	0.36 ± 0.30a	10.66 ± 0.47c	6.0 ± 0.50	2 ± 1
-Ve control	0.03 ± 0.01d	20.24 ± 0.57f	0.43 ± 0.22c	0.02 ± 0.01a	4.74 ± 0.57d	5.2 ± 0.57	1 ± 0.5
p-value	4.67e−06	3.95e−12	0.0024	0.179	1.06e−10		
Allowable limit (WHO)	**0.8**	**100**	**0.5**	**20**	**200**	**7.5**	**1000**

Table 4. Mean concentrations (±SD) of Pb, Hg, Cd, As, and Zn, as well as soil pH and electrical Conductivity (EC) was measured at the Makongorosi village site 2 in Chunya District, Tanzania. WHO (2008) guideline values are included for reference.

Distance	Concentration of metals						
	Cd (mg·kg^{-1})	Pb (mg·kg^{-1})	Hg (mg·kg^{-1})	As (mg·kg^{-1})	Zn (mg·kg^{-1})	pH	EC µS cm^{-1}
0 m	3.76 ± 0.53a	38.21 ± 0.46a	1.61 ± 0.52a	1.21 ± 0.92a	17.71 ± 0.54a	7.6 ± 0.5	2850 ± 1
50 m	2.87 ± 0.54ab	30.08 ± 0.53b	1.43 ± 0.54a	0.78 ± 0.10b	12.29 ± 0.54b	7.0 ± 1.0	30 ± 1
100 m	1.90 ± 0.53bc	28.34 ± 0.53c	1.34 ± 0.53a	0.60 ± 0.05b	11.55 ± 0.54b	6.7 ± 1.0	28 ± 1
150 m	1.80 ± 0.56bc	27.78 ± 0.55c	1.23 ± 0.54a	0.23 ± 0.15c	11.0 ± 0.54bc	6.0 ± 1.0	5 ± 1
200 m	1.33 ± 0.52cd	25.82 ± 0.78d	1.1 ± 0.56a	0.22 ± 0.21c	9.67 ± 0.54c	5.9 ± 1.0	3.5 ± 1
-Ve control	0.03 ± 0.01d	20.24 ± 0.57e	0.43 ± 0.22a	0.02 ± 0.01c	4.74 ± 0t.57d	5.2 ± 0.57	1 ± 0.5
p-value	1.66e−05	3e−12	0.145	7.26e−08	5.63e−08		
Allowable limit (WHO)	**0.8**	**100**	**0.5**	**20**	**200**	**7.5**	**1000**

3.3. Mbugani Village

The results for site 1 indicate that all tested heavy metals recorded higher concentrations between 0 - 200 m compared to the negative control point. The results also indicate that Cadmium (Cd) was above the allowable limit (4.3 - 1.43 mg/kg), while for Hg the distance from 0 - 150 m recorded concentrations above the allowable limit (2.62 - 0.88 mg/kg) except for the 200 m distance from the tailing deposit, whose concentration was slightly below the allowable limit of 0.43 mg/kg. This was contrary to other metals whose concentrations for distances between 0 - 200 m were within the allowable limit. The results also indicate a significant difference in Cd, Pb, Zn, and Hg concentrations between the 0 - 200 m distance, whereas a non-significant difference in concentration from 0 - 200 m distance was recorded for As. The results also show a decrease in soil pH and EC with distance from 0 to 200 m (Table 5).

For site 2, a similar result was recorded where the concentration of Cadmium

(1.63 - 4.42 mg·kg^{-1}) and Mercury (1.17 - 3.72 mg·kg^{-1}) in the soils was above the allowable limit, while the concentration of other metals was below or within the allowable limit. A significant decrease in heavy metal concentration from 0 to 200m distance from the tailing deposit was recorded for all tested heavy metals at ($p \leq 0.05$) (Table 6).

Table 5. Mean concentrations (±SD) of Pb, Hg, Cd, As, and Zn, as well as soil pH and Electrical Conductivity (EC), measured at Mbugani village site 1 in Chunya District, Tanzania. WHO (2008) guideline values are included for reference.

Distance	Concentration of metals						
	Cd (mg·kg^{-1})	Pb (mg·kg^{-1})	Hg (mg·kg^{-1})	As (mg·kg^{-1})	Zn (mg·kg^{-1})	pH	EC (µS cm^{-1})
0 m	4.3 ± 0.54a	36.04 ± 0.55a	2.62 ± 0.42a	1.24 ± 0.45a	22.46 ± 0.53a	8.0 ± 0.5	140 ± 1
50 m	3.11 ± 0.38b	31.08 ± 0.54b	1.94 ± 0.05b	1.24 ± 0.27a	16.69 ± 0.28b	7.0 ± 0.5	3 ± 1
100 m	2.33 ± 0.11bc	22.82 ± 0.57c	1.72 ± 0.17b	0.56 ± 0.14b	16.22 ± 0.38b	7.0 ± 0.5	3 ± 1
150 m	1.89 ± 0.23cd	19.29 ± 0.54d	1.34 ± 0.17bc	0.32 ± 0.04b	15.27 ± 1.08bc	6.0 ± 0.5	3 ± 1
200 m	1.43 ± 0.24d	17.20 ± 0.57d	0.88 ± 0.22cd	0.27 ± 0.04b	13.99 ± 1.34c	6.0 ± 0.5	3 ± 1
-Ve control	0.03 ± 0.005e	11.33 ± 1.89e	0.43 ± 0.22d	0.02 ± 0.01b	4.74 ± 0.57d	5.2 ± 0.57	1 ± 0.5
p-value	2.16e−08	4.05e−12	1.34e−06	5.67e−05	1.65e−10		
Allowable limit (WHO)	**0.8**	**100**	**0.5**	**20**	**200**	**7.5**	**1000**

Table 6. Mean concentrations (±SD) of Pb, Hg, Cd, As, and Zn, as well as soil pH and Electrical Conductivity (EC), measured at Mbugani village site 1 in Chunya District, Tanzania. WHO (2008) guideline values are included for reference.

	Concentration of metals						
	Cd (mg·kg^{-1})	Pb (mg·kg^{-1})	Hg (mg·kg^{-1})	As (mg·kg^{-1})	Zn (mg·kg^{-1})	pH	EC (µS cm^{-1})
0 m	4.42 ± 0.55a	37.52 ± 0.53a	3.72 ± 0.47a	1.56 ± 0.53a	14.51 ± 0.54a	7.5 ± 0.5	300 ± 0.1
50 m	4.00 ± 0.49a	28.76 ± 0.58b	3.01 ± 0.48ab	0.92 ± 0.01ab	13.82 ± 0.55ab	6.6 ± 0.5	10 ± 1.0
100 m	3.23 ± 0.57ab	24.54 ± 0.57c	2.02 ± 0.47bc	0.82 ± 0.43ab	12.87 ± 0.54b	6.6 ± 0.5	7 ± 1.0
150 m	2.43 ± 0.54bc	21.03 ± 0.54d	1.72 ± 0.57c	0.47 ± 0.05b	9.62 ± 0.53c	6.4 ± 0.5	6 ± 1.0
200 m	1.63 ± 0.49c	15.87 ± 0.48e	1.17 ± 0.44cd	0.34 ± 0.05b	6.00 ± 0.54d	6.0 ± 0.5	6 ± 1.0
-Ve control	0.03 ± 0.01d	12.67 ± 0.51f	0.43 ± 0.22d	0.02 ± b0.01	4.74 ± 0.57d	5.2 ± 0.57	1 ± 0.5
p-value	1.09e−06	7.44e−15	1.51e−05	0.00164	8.9e−11		
Allowable limit (WHO)	**0.8**	**100**	**0.5**	**20**	**200**	**7.5**	**1000**

3.4. Chokaa Village

The results indicate that the concentration of Cd and Hg was above the allowable limit (1.07 - 4.24 mg/kg) and (1.17 - 3.39 mg/kg) for Cd and Hg, respectively. This was contrary to other metals whose concentrations for distances between 0 - 200 m were within the allowable limit. The results also indicate a significant difference at $p \leq 0.05$ in Cd, Pb, Zn, and Hg concentrations between the 0 - 200 m distance. The results also show a decrease in soil pH and EC with distance from 0 to 200 m (Table 7).

For site 2, similar to site 1, it was recorded that the concentration of Cadmium (1.61 - 4.24 mg/kg^{-1}) and Mercury (1 - 2.31 mg/kg^{-1}) in the soils was above the allowable limit, while the concentration of other metals was within the allowable limit. A significant decrease in heavy metal concentration from 0 to 200m distance from the tailing deposit was recorded for all tested heavy metals ($p \leq 0.05$) (Table 8).

Table 7. Mean concentrations (±SD) of Pb, Hg, Cd, As, and Zn, as well as soil pH and Electrical Conductivity (EC), measured at Chokaa village site 1 in Chunya District, Tanzania. WHO (2008) guideline values are included for reference.

Distance	Concentration of heavy metals						
	Cd (mg·kg^{-1})	Pb (mg·kg^{-1})	Hg (mg·kg^{-1})	As (mg·kg^{-1})	Zn (mg·kg^{-1})	pH	EC (µS cm^{-1})
0 m	4.24 ± 0.57a	32.60 ± 0.54a	3.39 ± 0.54a	1.43 ± 0.99a	22.06 ± 0.47a	8.3 ± 0.50	1056 ± 1.0
50 m	2.54 ± 0.49b	32.01 ± 0.53a	2.45 ± 0.56ab	1.38 ± 0.24ab	20.19 ± 0.54b	6.8 ± 0.50	70 ± 1.0
100 m	2.19 ± 0.58bc	27.34 ± 0.52b	2.18 ± 0.47ab	0.51 ± 0.27abc	13.03 ± 0.54c	6.8 ± 0.50	41 ± 1.0
150 m	1.61 ± 0.48bc	27.02 ± 0.51b	1.92 ± 0.59b	0.29 ± 0.03abc	10.18 ± 0.51d	6.5 ± 0.50	30 ± 1.0
200 m	1.07 ± 0.48cd	20.83 ± 0.54c	1.17 ± 0.54bc	0.23 ± 0.04bc	8.64 ± 0.47d	6.5 ± 0.50	28 ± 1.0
-Ve control	0.03 ± 0.01d	12.77 ± 0.51d	0.43 ± 0.22c	0.02 ± 0.01c	4.74 ± 0.57e	5.2 ± 0.57	1 ± 0.5
p-value	3.87e−06	4.91e−14	0.000199	0.00494	1.59e−13		
Allowable limit (WHO)	**0.8**	**100**	**0.5**	**20**	**200**	**7.5**	**1000**

Table 8. Mean concentrations (±SD) of Pb, Hg, Cd, As, and Zn, as well as soil pH and Electrical Conductivity (EC), measured at the Chokaa village site 2 in Chunya District, Tanzania. WHO (2008) guideline values are included for reference.

Distance	Concentration of metals						
	Cd (mg·kg^{-1})	Pb (mg·kg^{-1})	Hg (mg·kg^{-1})	As (mg·kg^{-1})	Zn (mg·kg^{-1})	pH	EC (µS cm^{-1})
0 m	4.24 ± 0.56a	35.98 ± 0.79a	2.31 ± 0.44a	1.83 ± 0.48a	20.27 ± 0.54a	7.4 ± 0.5	1200 ± 1
50 m	2.75 ± 0.47b	28.67 ± 0.52b	1.82 ± 0.58ab	1.74 ± 0.47a	18.34 ± 0.47b	7.2 ± 0.5	50 ± 1
100 m	2.19 ± 0.59b	26.34 ± 0.53c	1.38 ± 0.56abc	1.52 ± 0.57ab	14.24 ± 0.51c	6.6 ± 0.5	39 ± 1
150 m	1.83 ± 0.57b	25.17 ± 0.54cd	1.23 ± 0.49abc	1.35 ± 0.48ab	12.08 ± 0.55d	6.53 ± 1.04	31 ± 1
200 m	1.61 ± 0.48b	23.56 ± 0.57d	1 ± 0.46bc	0.43 ± 0.05bc	9.21 ± 0.54e	6.0 ± 0.5	26 ± 1
-Ve control	0.03 ± 0.01c	20.24 ± 0.57e	0.43 ± 0.22c	0.02 ± 0.01c	4.74 ± 0.57f	5.2 ± 0.57	1 ± 0.5
p-value	7.24e−06	1.21e−11	0.00642	0.000607	1.05e−12		
Allowable limit (WHO)	**0.8**	**100**	**0.5**	**20**	**200**	**7.5**	**1000**

3.5. Matundasi Village

The results indicate that the concentrations of Cd and Hg were above the allowable limits (2.85 - 0.89 mg·kg^{-1}) and (1.98 - 1.53 mg·kg^{-1}), respectively. There was a significant difference in all tested metal concentrations between the 0 – 200 m distance. The results also show a decrease in soil pH and EC with an increase in distance from 0 to 200m (Table 9).

Similarly, site 2 recorded higher concentrations of Cd and Hg (3.65 - 0.98 mg/kg) and (2.43 - 1.60 mg/kg), respectively, which were above the allowable limit, while the concentration of other tested metals was within the allowable limit. A significant decrease in heavy metal concentration from 0 to 200 m distance from the tailing deposit was recorded for all tested heavy metals at ($p \leq 0.05$). There was also a decrease in soil pH with an increase in distance from the tailing deposit (Table 10).

Table 9. Mean concentrations (±SD) of Pb, Hg, Cd, As, and Zn, as well as soil pH and Electrical Conductivity (EC), measured at the Matundasi village site 1 in Chunya District, Tanzania. WHO (2008) guideline values are included for reference.

Distance	Concentration of metals						
	Cd (mg·kg^{-1})	Pb (mg·kg^{-1})	Hg (mg·kg^{-1})	As (mg·kg^{-1})	Zn (mg·kg^{-1})	pH	EC (µS cm^{-1})
0 m	2.85 ± 0.13a	34.99 ± 0.54a	1.98 ± 0.54a	1.62 ± 1.0a	22.06 ± 0.53a	8.2 ± 0.5	77 ± 1
50 m	2.3 ± 2.3b	31.96 ± 0.57b	1.78 ± 0.47a	1.50 ± 0.22ab	18.59 ± 0.55b	8.0 ± 0.5	45 ± 1
100 m	1.9 ± 1.9bc	27.53 ± 0.51c	1.68 ± 0.49a	1.07 ± 0.2abc	15.85 ± 0.52c	8.0 ± 0.5	36 ± 1
150 m	1.65 ± 1.65c	19.43 ± 0.47d	1.55 ± 0.30ab	0.7 ± 0.1abc	13.65 ± 0.54d	7.0 ± 0.5	33 ± 1
200 m	0.98 ± 0.98d	18.72 ± 0.74d	1.53 ± 0.57ab	0.38 ± 0.08bc	10.94 ± 0.52e	6.0 ± 0.5	25 ± 1
-Ve control	0.03 ± 0.03e	16.24 ± 1.27e	0.43 ± 0.22b	0.02 ± 0.005c	4.74 ± 4.74f	5.2 ± 0.57	1 ± 0.5
p-value	6.87e−10	1.97e−12	0.0165	0.00367	8.76e−13		
Allowable limit (WHO)	**0.8**	**100**	**0.5**	**20**	**200**	**7.5**	**1000**

Table 10. Mean concentrations (± SD) of Pb, Hg, Cd, As, and Zn, as well as soil pH and Electrical Conductivity (EC), measured at Matundasi village site 2 in Chunya District, Tanzania. WHO (2008) guideline values are included for reference.

Distance	Concentration of metals						
	Cd (mg·kg^{-1})	Pb (mg·kg^{-1})	Hg (mg·kg^{-1})	As3 (mg·kg^{-1})	Zn (mg·kg^{-1})	pH	EC (µS cm^{-1})
0 m	3.65 ± 0.58a	24.66 ± 0.53a	2.43 ± 0.59a	1.76 ± 0.49a	27.74 ± 0.53a	7.8 ± 0.5	130 ± 1.0
50 m	2.98 ± 0.47ab	22.66 ± 0.55b	2.23 ± 0.49a	1.53 ± 0.56ab	26.01 ± 0.48b	7.7 ± 0.5	95 ± 1
100 m	2.77 ± 0.54ab	20.29 ± 0.52c	1.97 ± 0.57a	0.83 ± 0.42abc	24.46 ± 0.51c	6.8 ± 0.5	47.33 ± 1
150 m	1.97 ± 0.44bc	18.98 ± 0.57c	1.64 ± 0.49ab	0.63 ± 0.32bc	17.47 ± 0.54d	6.4 ± 0.5	32 ± 1
200 m	0.98 ± 0.41cd	16.24 ± 0.54d	1.60 ± 0.47ab	0.15 ± 0.06c	12.45 ± 0.54e	6.0 ± 0.5	22 ± 1
-Ve control	0.03 ± 0.01d	15.77 ± 1.27d	0.43 ± 0.22b	0.02 ± 0.01c	4.74 ± 0.57f	5.2 ± 0.57	1 ± 0.5
p-value	3.68e−06	1.6e−08	0.00416	0.000408	6.54e−15		
Allowable limit (WHO)	**0.8**	**100**	**0.5**	**20**	**200**	**7.5**	**1000**

Concentrations of Pb at the tailing heap (0 m and 200 m)

At the tailing deposit site (0 m), the concentration of Pb ranged from 24.66 mg/kg at Matundasi site 2 to 41.33 mg/kg at Itumbi village site 2. The results also

show that for most sites, there was a small difference in the concentration of Pb (Figure 2).

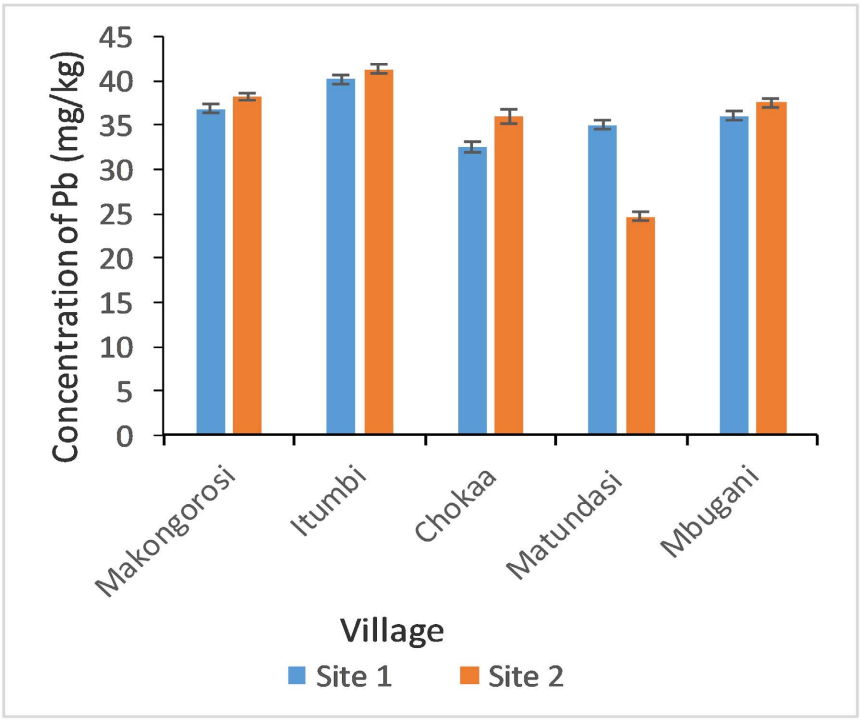

Figure 2. Concentration of lead (Pb) at 0 m from the tailings across different villages (Makongorosi, Itumbi, Chokaa, Matundasi, and Mbugani) for Site 1 and Site 2.

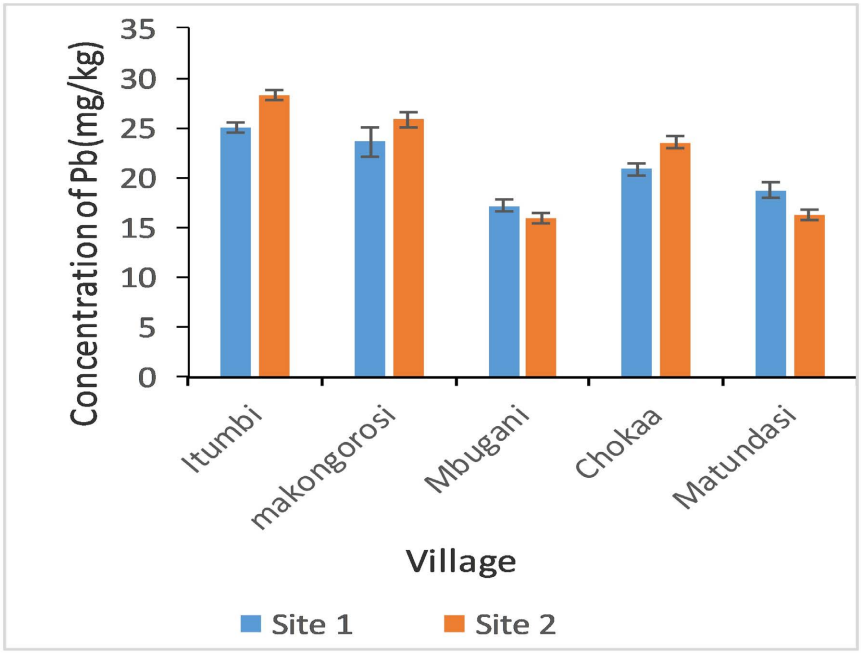

Figure 3. Concentration of lead (Pb) at 200 m from the tailings across different villages (Makongorosi, Itumbi, Chokaa, Matundasi, and Mbugani) for Site 1 and Site 2.

At 200 m (Figure 3), the lowest Pb concentration was recorded in Mbugani village site 2 (15.87 mg/kg), while the highest concentration was recorded in Itumbi village site 2 (28.34 mg/kg) (Figure 3). The results show a significant decrease in Pb concentration from 0m to 200m ($p \leq 0.05$).

Concentrations of Cd at the tailing heap (0) and 200 m

At 0 m (Figure 4), the concentration of Cd ranged from 2.7 to 4.42 mg/kg, where the lowest concentration was recorded in Itumbi village site 1, while the highest was recorded in Mbugani village site 2. However, a small difference was recorded (Graph 4) in the concentration of Cd for most of the studied sites.

At 200 m (Figure 5), the lowest Cd concentration was recorded in Itumbi village site 1 (0.11 mg/kg), while the highest concentration was recorded in Mbugani village site 2 (1.63 mg/kg). The results show a significant decrease in Pb concentration from 0 m to 200m ($p \leq 0.05$).

Concentration of Hg at the tailing heap (0 m) and 200 m

The results indicate that the lowest concentration of Hg at 0 m (Figure 6) was recorded at the Makongorosi site 2 (1.61 mg/kg), while the highest concentration was recorded at the Mbugani village site 2 (3.72 mg/kg) (Figure 6), the concentration of which was above the allowable limit. The results indicate a small range of Hg concentrations among the studied sites, with the lowest value recorded at Mbugani Village Site 1 (0.88 mg/kg) and the highest at Chokaa Village Site 2 (1 mg/kg) (Figure 7). The results show a significant decrease in Hg concentration from 0 m to 200 m for all sites.

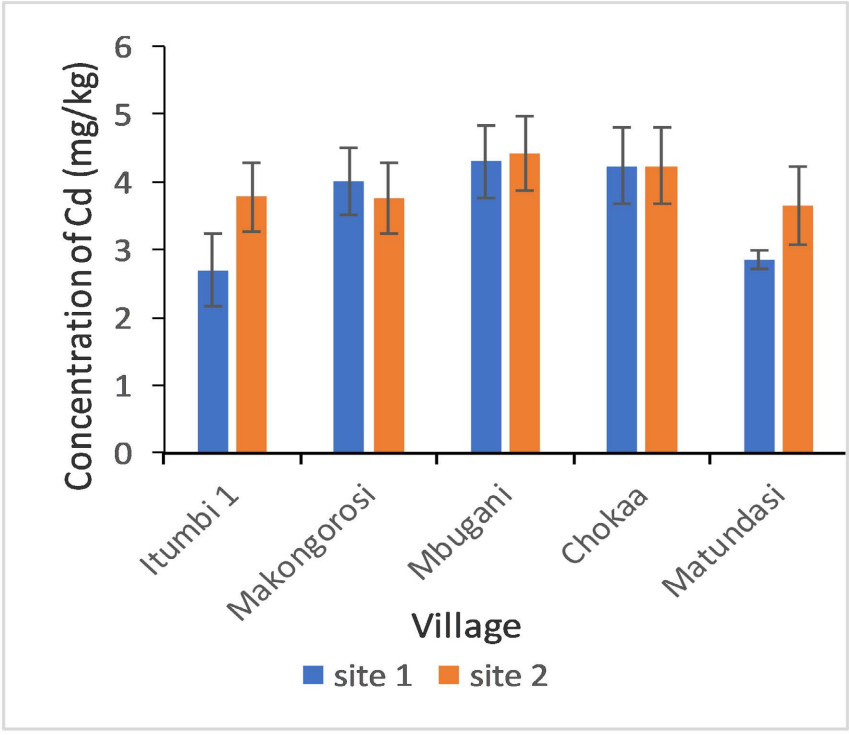

Figure 4. Concentration of Cadmium (Cd) at 0 m from the tailings across different villages (Makongorosi, Itumbi, Chokaa, Matundasi, and Mbugani) for Site 1 and Site 2.

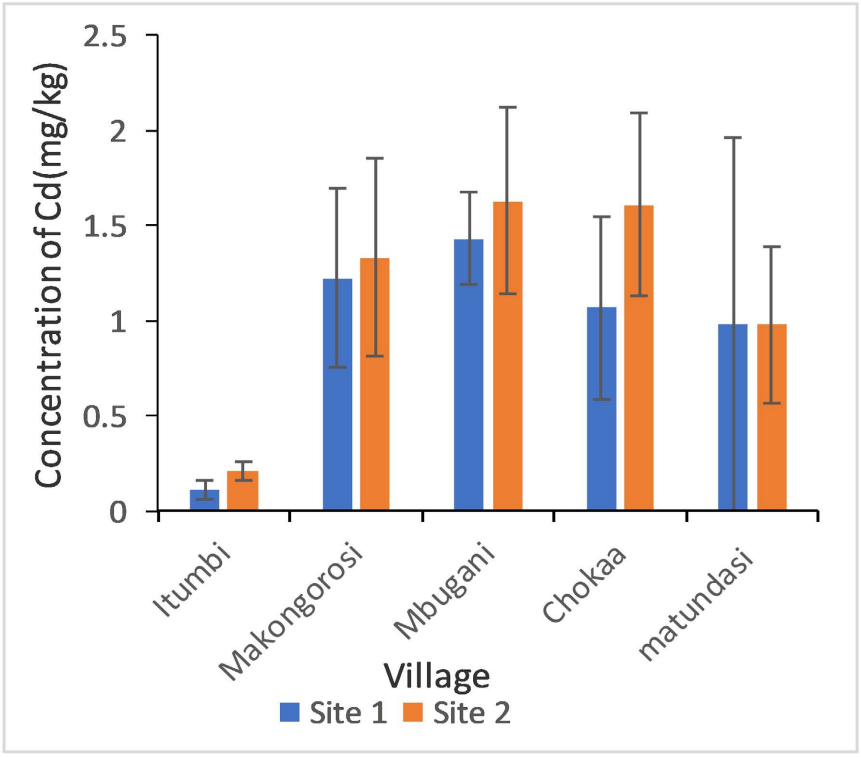

Figure 5. Concentration of Cadmium (Cd) at 200 m from the tailings across different villages (Makongorosi, Itumbi, Chokaa, Matundasi, and Mbugani) for Site 1 and Site 2.

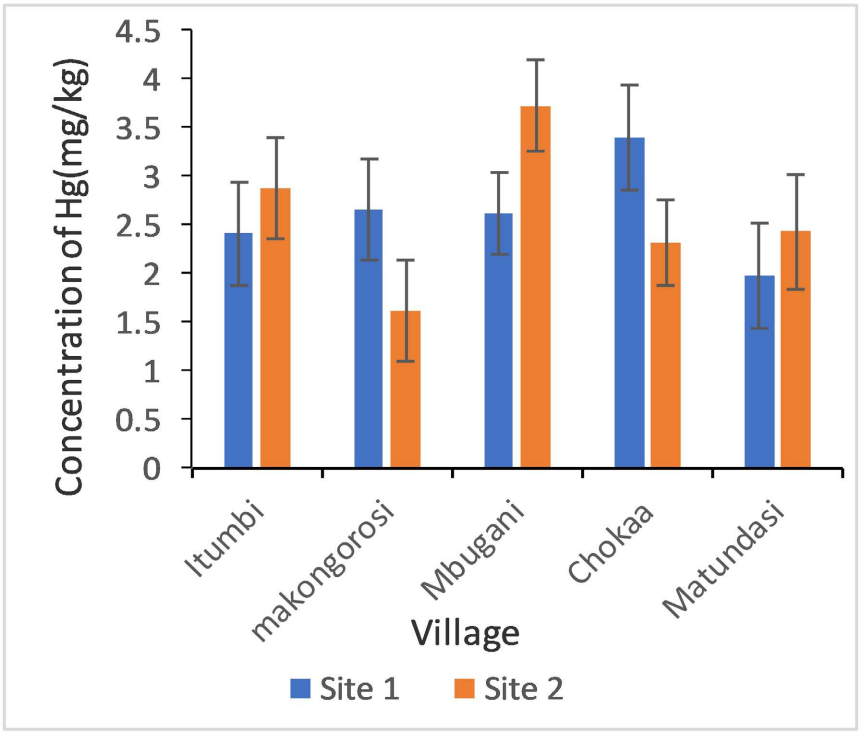

Figure 6. Concentration of Mercury (Hg) at 0 m from the tailings across different villages (Makongorosi, Itumbi, Chokaa, Matundasi, and Mbugani) for Site 1 and Site 2.

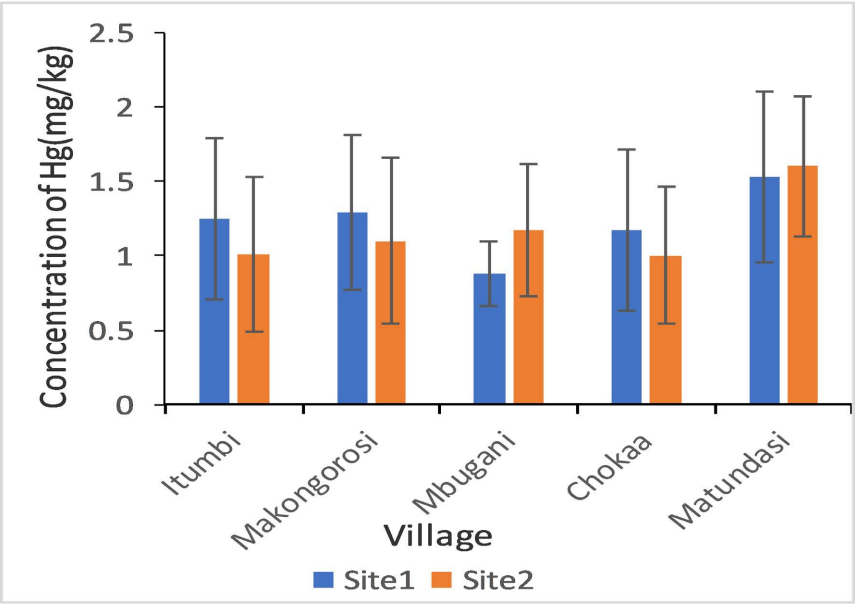

Figure 7. Concentration of Mercury (Hg) at 200 m from the tailings across different villages (Makongorosi, Itumbi, Chokaa, Matundasi, and Mbugani) for Site 1 and Site 2.

Concentrations of As at the tailing heap (0 m) and 200 m

The concentration of As at the tailing heap (Figure 8) ranged from 0.78 mg/kg to 1.83 mg/kg, where all concentrations were within the allowable limit. The highest concentration was recorded in Chokaa village, while the lowest concentration was recorded in Itumbi village.

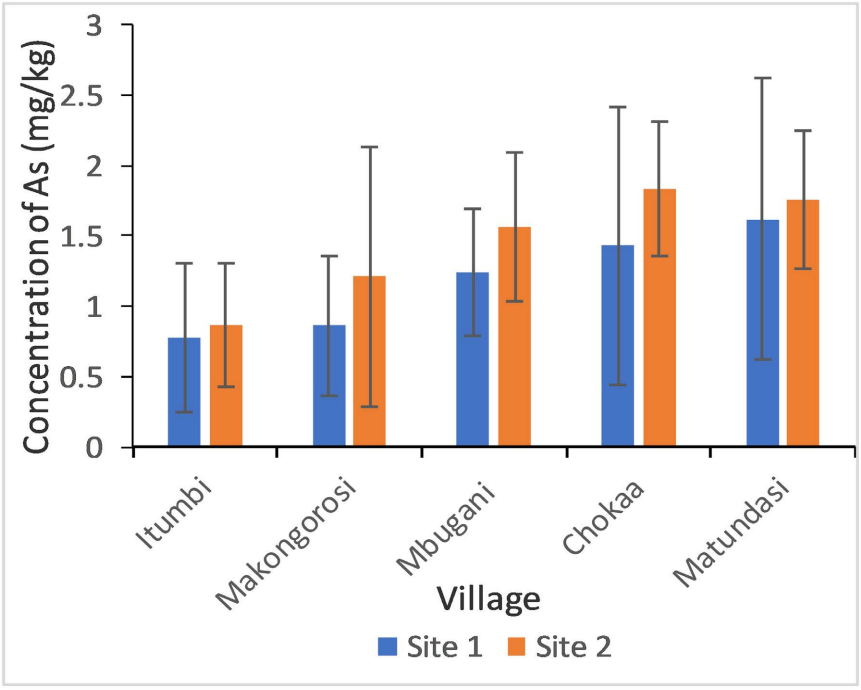

Figure 8. Concentration of arsenic (As) at 0 m from the tailings across different villages (Makongorosi, Itumbi, Chokaa, Matundasi, and Mbugani) for Site 1 and Site 2.

At 200 m, the lowest As concentration was recorded in Matundasi village site 1 (0.15 mg/kg) while the highest concentration was recorded in Itumbi village site 2 (0.45 mg/kg) (Figure 9). The results show a significant decrease in Pb

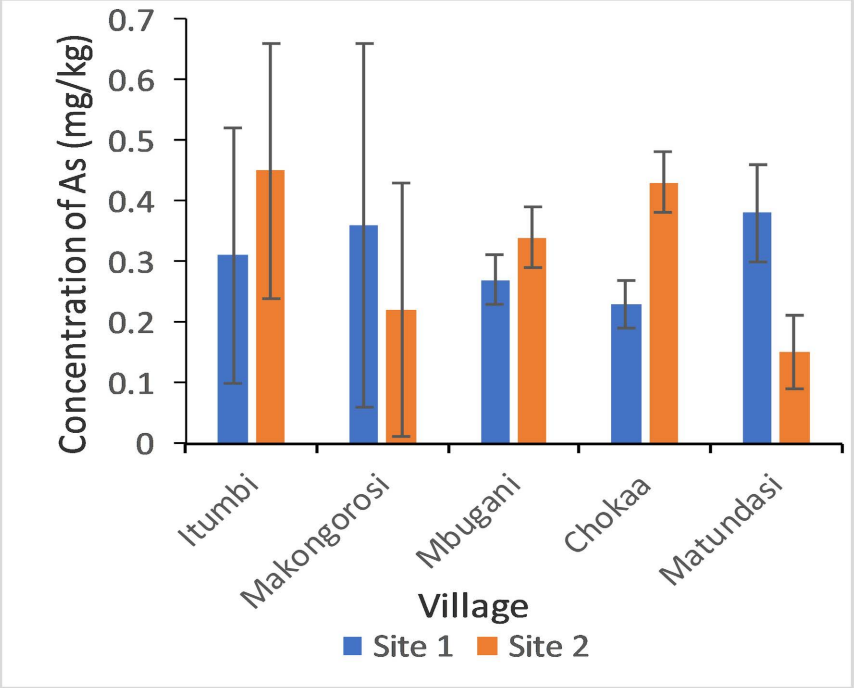

Figure 9. Concentration of Arsenic (As) at 200 m from the tailings across different villages (Makongorosi, Itumbi, Chokaa, Matundasi, and Mbugani) for Site 1 and Site 2.

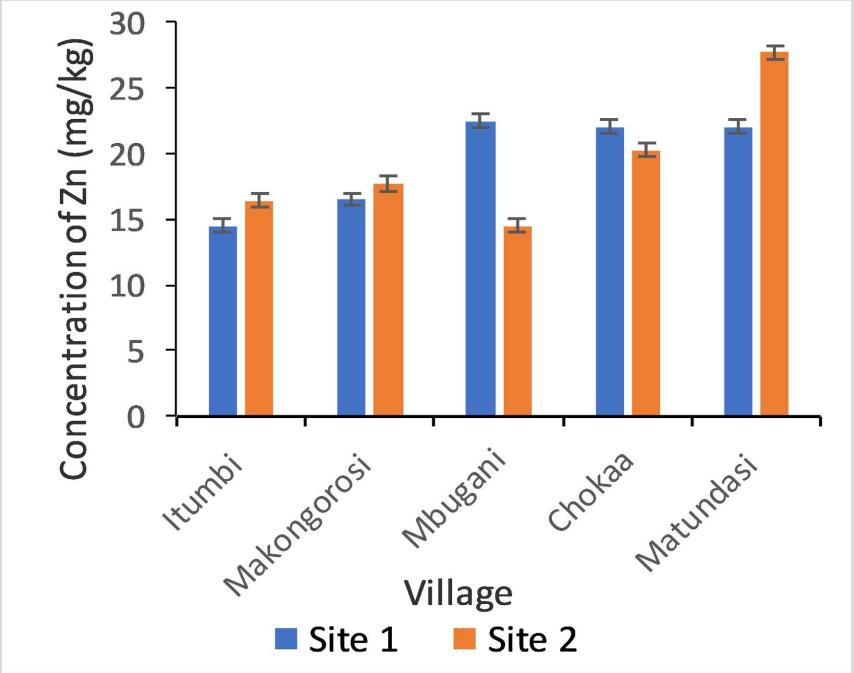

Figure 10. Concentration of Zinc (Zn) at 0 m from the tailings across different villages (Makongorosi, Itumbi, Chokaa, Matanda's, and Mbugani) for Site 1 and Site 2.

concentration from 0 m to 200 m.

Concentrations of Zn at the tailing heap (0 m) and 200 m

At 0 m, both site 1 from Mbugani village and site 2 from Itumbi village recorded the lowest concentration of Zn (14.51 mg/kg), while the highest concentration of Zn was recorded in Matundasi village site 2 (27.74 mg/kg) (Figure 10). The results show a wide range of differences in the Zn concentration at the tailing deposit site for the studied sites.

At 200 m, the lowest Zn concentration was recorded in Itumbi 1 village site (5.98 mg/kg), while the highest concentration was recorded in Mbugani village site 1 (13.99 mg/kg) (Figure 11). The results show a significant decrease in Pb concentration from 0 m to 200 m for all sites.

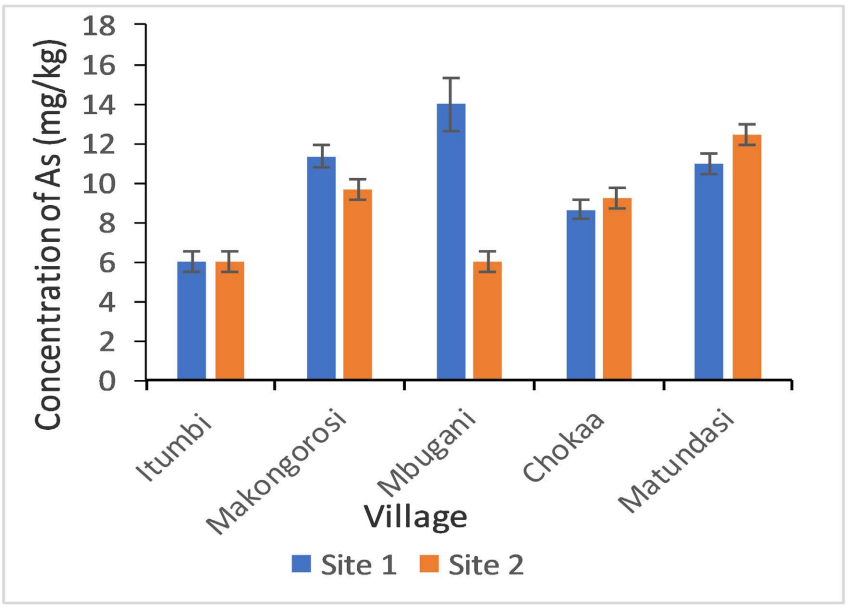

Figure 11. Concentration of Zinc (Zn) at 200 m from the tailings across different villages (Makongorosi, Itumbi, Chokaa, Matundasi, and Mbugani) for Site 1 and Site 2.

4. Discussion

4.1. Soil pH and Electrical Conductivity

The combined influence of soil pH and electrical conductivity (EC) governs how heavy metals move from the tailings toward surrounding soils. Close to the tailings (0 - 50 m), EC is very high (up to about 2800 μS cm^{-1}) and pH is neutral to slightly alkaline (≈7 - 8) (refer to Table 1 and Table 2**).** According to Nordstrom et al. (2015), tailing heaps often have high pH (alkaline) and high Electrical Conductivity (EC) levels due to the specific chemical reagents used during mineral processing and the natural mineral composition of the ore. Under these conditions, the abundance of dissolved salts promotes ion exchange and desorption, allowing lead (Pb), cadmium (Cd), zinc (Zn), and mercury (Hg) to enter the soil water and migrate laterally. However, as water flows and percolates through the soil profile, soluble salts are leached out and EC rapidly decreases to below 40 μS

cm^{-1} at 200 m. At the same time, pH declines to weakly acidic values of about 5.5 - 6.5. Acidification favours the adsorption of metal cations onto clays and iron or manganese oxides or their precipitation as stable minerals, which sharply lowers their dissolved concentrations.

This two-stage process—initial mobilization followed by immobilization—explains the statistically significant drop in heavy-metal concentrations with distance observed at all sites. The mechanism is consistent with laboratory and field findings reported by Violante et al. (2010), who demonstrated that decreasing pH promotes adsorption of Pb, Zn, and Cd on soil minerals and thereby reduces their mobility; by Grobelak and Kowalska (2020), who showed that acidification and loss of soluble salts limit heavy-metal movement and bioavailability; and by Kumkrong et al. (2022), who found that high electrical conductivity in gold and silver tailings accelerates the early leaching of Cd and Zn, while the sharp decline in EC downstream limits further migration. Similar conclusions were drawn by Gitari et al. (2018), who observed that lower pH and lower ionic strength downstream of abandoned copper-mine tailings led to natural attenuation of toxic metals, and by Jiang et al. (2021), who confirmed that acidic conditions and reduced EC enhance the fixation of heavy metals and reduce their leaching potential.

Collectively, these studies support the present findings that neutral to alkaline, saline tailings facilitate the release of heavy metals near the source. As soils become less saline and slightly acidic with distance, natural immobilization processes significantly restrict the migration of heavy metals.

For instance, at the Makongorosi site 1, Pb concentrations decrease from approximately 36 $mg{\cdot}kg^{-1}$ at pH 8 and EC 2800 $\mu S\ cm^{-1}$ at the tailings point to 24 $mg{\cdot}kg^{-1}$ at 200 m, where pH drops to 6 and EC to 2 $\mu S\ cm^{-1}$. Chokaa exhibits a similar trend, with Cd declining from 4 $mg{\cdot}kg^{-1}$ at pH 8.3 and EC 1056 $\mu S\ cm^{-1}$ near the source to 1 $mg{\cdot}kg^{-1}$ at 200 m, where pH and EC are 6.5 and 28 $\mu S\ cm^{-1}$, respectively.

4.2. Concentration and Dispersion of Lead (Pb)

The results indicate that the Pb concentration between 0 - 200 m for all sampling points was within the permissible limits set by environmental guidelines, such as the WHO/FAO standard of 100 mg/kg for agricultural soils (WHO (2008)). This result is consistent with the study by Kaaya et al. (2025), who reported low concentrations of Pb in Geita mining sites in Tanzania, which could cause negligible health risks. This lead concentration found in the study area is lower than the elevated concentrations reported in both South Africa and Ghana (80 - 510 mg/kg).

Pb is known to have low mobility in soil; hence, elevated concentrations are expected at point sources of contamination, which are tailing deposits (Shu et al., 2014; Martín et al., 2014; Rodríguez et al., 2009). The results show a significant decrease in Pb concentration with the decrease in soil pH and electrical conductivity; for instance, the concentration of Pb at the tailing heap (0 m) was 41.33 ±

0.54 mg/kg while the soil pH and electrical conductivity were 6.13 and 950 μS cm^{-1}, respectively. The concentration decreased to 28.34 ± 0.55 mg/kg at 200 m when soil pH and electrical conductivity reduced to 5.7 and 25 μS cm^{-1} in Itumbi village site 2 (**Table 2**).

Potentially, Pb poses a serious health risk to both adults and children when it is at high concentrations; it is associated with impaired fertility and complicated pregnancy, cardiovascular diseases, impaired kidney function, high blood pressure, and neurodevelopmental effects (WHO, 2011). Also, Gimmler et al. (2002) and Abdulkareem et al. (2015) revealed that exposure to high Pb concentrations is linked to numerous health and environmental issues, such as renal, neurological, and developmental effects (Haque et al., 2021), soil pollution, and phytotoxicity.

4.3. Concentration and Dispersion of Cadmium (Cd)

The study recorded higher concentrations of Cd than the permissible limit (0.8 $mg{\cdot}kg^{-1}$) for most of the studied sites, whereby the highest value was 4.42 $mg{\cdot}kg^{-1}$, while the lowest concentration was 0.11 $mg{\cdot}kg^{-1}$. This concentration is, however, slightly below the Tanzania general reported increasing concentration of Cd (6.4 - 11 mg/kg) in mining areas (Fikri et al., 2023).

However, the result is consistent with area-specific studies such as Kaaya et al. (2025), who reported a higher concentration of Cd in *Ifugandi* (13.67 $mg{\cdot}kg^{-1}$) *and Bululu* (20.13 $mg{\cdot}kg^{-1}$) Gold mining sites in Tanzania. Another study by Kaggwa et al. (2024) reported potentially higher concentrations of Cd in tailing heaps (e.g., a mean of 11.83 ± 3.01 mg/kg at Nyarugusu-Geita, Tanzania) and the concentration reduced to 0.553 - 0.770 mg/L in mining drainages. Similarly, the lateral mobility of Cd was found to be governed by soil pH and electrical conductivity; for instance, in Matundasi village site 1, the concentration at the tailing heap (0 m) was 2.85 $mg{\cdot}kg^{-1}$ while soil pH and electrical conductivity were 8.2 and 77 μS cm^{-1} respectively, whereas at 200 m, the concentration reduced to 0.98 $mg{\cdot}kg^{-1}$ while soil pH and electrical conductivity also reduced to 6.0 and 25 μS cm^{-1} respectively (**Table 9**).

When compared to other heavy metals such as Pb and Cu, Cd exhibits high relative mobility, often found in acid-extractable fractions in the soil, increasing the risk of contamination. This has been confirmed by this study, where higher concentrations of Cd above the permissible limit (0.8 mg/kg) were even found at the furthest distance (200 m) from the tailing heap. A study by Merrington and Alloway (1994) indicated that more than 4.2 kg Cd/a was being transferred from the tailing heaps via the streams in the form of dissolved load.

Higher concentrations of Cd in the soil pose human health and environmental risks (Ahmad et al., 2021; De Vries et al., 2007). Studies refer to Cd as an important environmental and industrial toxicant that has a very long half-life, ranging from 10 to 35 years. It is a multi-organ, multi-system poison that actively migrates through soil–plant systems (Wang et al., 2021a). Various studies have highlighted

the human health risks of exposure to Cd, which include an increased risk of cancers, such as bladder, prostate, kidney, pancreatic, and breast cancers (Qing et al., 2021; Tchounwou et al., 2012).

On the nervous system, Cd exposure is thought to contribute to the onset of central nervous system (CNS)-related disorders, such as Parkinson's disease (PD), Alzheimer's disease (AD), amyotrophic lateral sclerosis (ALS), Huntington's disease (HD), and multiple sclerosis (MS).

4.4. Concentration and Dispersion of Mercury (Hg)

The results indicate that the concentration of Hg at all sampling points was higher than the permissible limit (0.5 mg/kg). The highest value recorded was 3.72 mg/kg, while the lowest concentration was 0.88 mg/kg. The results indicate higher mobility of Hg from the tailing heap (0 m) to the soils, whereby higher concentrations above the allowable limits were even recorded at the furthest distance (200 m) from the heap. This result is consistent with various studies that have been conducted in Tanzania, which have reported concentration levels in soils and tailings ranging from 1.7 to 53.8 mg/kg (Taylor et al., 2005; Herman & Kihampa, 2015; Sanga et al., 2023). The result is also in line with the findings by Gonçalves Jr. et al. (2017) and Fikri et al. (2023), who justified that since mercury is commonly used in gold extraction, it is frequently found in elevated levels at ASGM sites in Tanzania, Ghana, and Ecuador.

Other metals such as nickel (Ni), cobalt (Co), manganese (Mn), and iron (Fe) have also been detected in high concentrations near mining areas across Africa, Asia, and Latin America (Ogundele et al., 2021; Wiafe et al., 2022; Montalván-Olivares et al., 2021; Yabe et al., 2010).

Higher concentrations of Hg are reported because the metal is used mainly for the processing of primary gold quartz veins and supergene gold mineralizations. Gravimetric material flow analyses show that 70% - 80% of the Hg is lost to the atmosphere during processing, and 20% - 30% is lost to tailings, soils, stream sediments, and water. For instance, for every 1 g Au produced, 1.2 - 1.5 g Hg are lost to the environment (Maglambayan et al., 2005).

Mercury mobility in soil is reported to vary greatly, from very low in soils with high organic matter and sulfur too high in sandy soils, and depends on its chemical form, soil properties like pH, organic matter, and sulfur content, and environmental factors such as redox potential (Šípková et al., 2016; Boszke et al., 2008; Skyllberg, 2012).

Mercury tends to immobilize in the upper soil layers due to its affinity for soil minerals and organic matter, forming stable complexes that can reduce its potential to move to groundwater.

Higher concentrations of Hg in the environment above the permissible limit cause significant environmental and health risks (Kim et al., 2016). For instance, in human health, Hg has become one of the most serious problems threatening human subsistence (Clarkson, 2002; Tsuji et al., 2003). Mercury (Hg) is recog-

nized as one of the most harmful metals with potential impacts on human health due to its volatility, its long life in the atmosphere, and its tendency to accumulate in living organisms (Yu et al., 2016). Human poisoning can result from both short-term and prolonged exposure to mercury (Carocci et al., 2013).

4.5. Concentration and Dispersion of Arsenic (As)

The results indicate that the concentration levels of As at all sampling points were within the permissible limit of 20 mg/kg. The highest concentration was 1.83 mg/kg (**Table 8**), while the lowest concentration was 0.15 mg/kg (**Table 10**). This result is contrary to the study by Kaaya et al. (2025), who reported higher concentrations of As, i.e., 6.17 ± 4.41 mg/kg in Nyarugusu and 63.8 ± 53.2 mg/kg in Lwamgasa, both mining sites from Geita District in Tanzania. This result also indicates that As levels are extremely far below the reported elevated concentrations of As in Ghana (8305 mg/kg) (Gonçalves Jr. et al., 2017).

The low levels of arsenic in the study area can be attributed to the presence of little arsenic-rich ores, such as arsenopyrite (Garelick et al., 2008; Majzlan et al., 2014). Additionally, limited oxidation and leaching activities of sulfide minerals can account for the low levels of As in the environment (Lengke et al., 2009).

The lateral mobility of arsenic is variable and often relatively low, but it can increase significantly under certain conditions. For instance, in highly acidic and highly alkaline conditions, arsenic exhibits higher mobility, with greater movement observed in acidic environments, while in neutral pH conditions (pH ≈ 7), As is more stable and less mobile (Campbell & Nordstrom, 2014; Patel et al., 2023). Water flow and contact time enhance leaching, while factors like organic matter and certain mineral compositions can either increase or decrease mobility (Carrillo-González et al., 2006).

According to Wang et al. (2021b), arsenic was listed first among substances toxic to human health by the Agency for Toxic Substances and Disease Registry (ATSDR) from the Department of Health of the United States, and thus was recognized as an important carcinogen.

Higher concentrations of arsenic in the mining sites and soils are associated with serious environmental and health problems, including cancers, cardiovascular diseases, neurological damage, and skin lesions in humans (Chen et al., 2009; Singh et al., 2007). It contaminates soil and water through waste products, potentially harming ecosystems and local communities. The effects depend on the arsenic species, dose, and duration of exposure (Patel et al., 2023; Singh et al., 2007).

4.6. Concentration and Dispersion of Zinc (Zn)

The results indicate that the concentration levels of Zn for all sampling points were within the permissible limit (200 mg/kg). The highest concentration of Zn was 27.74 mg/kg (**Table 10**), while the lowest concentration was 5.98 mg/kg (**Table 2**). This result is consistent with other studies conducted in other Tanzanian gold mining sites and tailing heaps, where the concentration is at higher levels

(e.g., 101.9 ± 20.6 mg/kg) than surrounding soils (e.g., 68.67 mg/kg (Machiwa, 2003). Another study by Pkemoi (2024) reported a Zn mean concentration of 54.17 - 118.07 mg/kg at the tailings. The concentrations of Zn in the study area are consistent with elevated concentrations reported in South Africa, showing (8.9 - 65.7 mg/kg), where levels for both areas fall within the permissible limits (below 200 $mg{\cdot}kg^{-1}$).

The low concentration of Zn in the study sites can be attributed to the nature of the gold ore composition, whereby if the ore is not rich in zinc, the tailings will naturally have low zinc content (Rodríguez et al., 2009). However, leaching occurring under acidic conditions can lead to the dissolution of zinc from the ore, making it more mobile and causing it to be washed out of the mine and tailings (Sethurajan et al., 2017; Shu et al., 2001). On the other hand, a lower concentration of Zn in the soils can be attributed to the soil pH, where the study sites are dominated by neutral to alkaline conditions, where Zn is least mobile.

According to Gangloff et al. (2006), zinc mobility in soil is generally low, as it is tightly held by soil particles and organic matter. Zn movement is largely controlled by soil pH (least mobile in neutral to alkaline soils, while highly mobile in acidic conditions).

High levels of zinc in the environment have been associated with altering soil and aquatic microbial diversity, and can thus affect the bioavailability and absorption of other metals as well (Hussain et al., 2022). In humans, exposure to excessive zinc levels leads to toxicity; this toxicity is, however, a treatable and non-life-threatening condition. Several symptoms cause distress to human activities and lifestyle, including fever, breathing difficulty, nausea, chest pain, and cough (Hussain et al., 2022; Balch et al., 2011). In plant nutrition, excessive Zn levels are associated with decreased soil fertility and potential toxicity to plants (Van and Nga, 2024).

5. Conclusion

The study has highlighted elevated concentrations of mercury (Hg) and cadmium (Cd) in soil within a 0 - 200 m lateral distance from tailing heaps, surpassing permissible limits. In contrast, levels of lead (Pb), arsenic (As), and zinc (Zn) remain within acceptable ranges. The concentration of heavy metals significantly decreases with distance from the source due to dispersion from the source. Soil pH and electrical conductivity influence the dispersion of these heavy metals. Hg and Cd pose significant environmental and health risks, with Hg being extremely harmful and Cd linked to human cancer. To mitigate these risks, effective remediation and management strategies are necessary to reduce metal accumulation in ecosystems. Environmentally sustainable strategies such as Phyto-remediation, microbial remediation, nanotechnology, advanced hybrid biological methods (Nano bioremediation), and modified chemical immobilization techniques need to be incorporated in the remediation of Hg and Cd in the study area. Additionally, other cutting-edge technologies such as treeID need to be incorporated in the

process to facilitate the identification and use of trees as a low-cost, sustainable and ecologically sound solution to the remediation of heavy metal-contaminated soil.

Conflicts of Interest

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

References

Abdulkareem, J. H., Abdulkadir, A., & Abdu, N. (2015). Vertical Distribution of Lead (pb) in Farmlands around Contaminated Goldmine in Zamfara State, Northern Nigeria. *African Journal of Agricultural Research, 10,* 4975-4989. https://doi.org/10.5897/ajar2015.10068

Ahmad, W., Alharthy, R. D., Zubair, M., Ahmed, M., Hameed, A., & Rafique, S. (2021). Toxic and Heavy Metals Contamination Assessment in Soil and Water to Evaluate Human Health Risk. *Scientific Reports, 11,* Article No. 17006. https://doi.org/10.1038/s41598-021-94616-4

Akbar, Z., Akbar, W. A., Irfan, M., Rahim, H. U., Khan, U., Saleem, A. et al. (2024). Comparative Effects of Organic and Inorganic Amendments on Heavy Metal Co-Contaminated Soil Remediation, Reducing Heavy Metal Bioavailability and Enhancing Nutrient Accessibility for Maize Growth. *Land Degradation & Development, 35,* 4741-4753. https://doi.org/10.1002/ldr.5254

Alghzawi, M. I. Z. (2025). *Investigating the Transformations of Arsenic and Toxic Metal (Loid)s Speciation and the Impact on Arsenic Bioaccessibility in Particulate Matter from Mine Tailings Sites Distributed in Different Climates.* Master's Thesis, The University of Arizona.

Balch, J. F., Stengler, M., & Young-Balch, R. (2011). *Prescription for Natural Cures: A Self-Care Guide for Treating Health Problems with Natural Remedies Including Diet, Nutrition, Supplements, and Other Holistic Methods.* Turner Publishing Company.

Boszke, L., Kowalski, A., Astel, A., Barański, A., Gworek, B., & Siepak, J. (2008). Mercury Mobility and Bioavailability in Soil from a Contaminated Area. *Environmental Geology, 55,* 1075-1087. https://doi.org/10.1007/s00254-007-1056-4

Bourg, A. C. M., & Loch, J. P. G. (1995). Mobilization of Heavy Metals as Affected by pH and Redox Conditions. In W. Salomons, & W. M. Stigliani (Eds.), *Biogeodynamics of Pollutants in Soils and Sediments* (pp. 87-102). Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-642-79418-6_4

Bradl, H. B. (2005). *Sources and Origins of Heavy Metals.* In *Interface Science and Technology* (Vol. 6, pp. 1-27). Elsevier.

Campbell, K. M., & Nordstrom, D. K. (2014). Arsenic Speciation and Sorption in Natural Environments. *Reviews in Mineralogy and Geochemistry, 79,* 185-216. https://doi.org/10.2138/rmg.2014.79.3

Carocci, A., Rovito, N., Sinicropi, M. S., & Genchi, G. (2013). Mercury Toxicity and Neurodegenerative Effects. In D. Whitacre (Eds.), *Reviews of Environmental Contamination and Toxicology* (pp. 1-18). Springer International Publishing. https://doi.org/10.1007/978-3-319-03777-6_1

Carrillo-González, R., Šimůnek, J., Sauvé, S., & Adriano, D. (2006). Mechanisms and Pathways of Trace Element Mobility in Soils. *Advances in Agronomy, 91,* 111-178. https://doi.org/10.1016/s0065-2113(06)91003-7

Chen, Y., Parvez, F., Gamble, M., Islam, T., Ahmed, A., Argos, M. et al. (2009). Arsenic Exposure at Low-To-Moderate Levels and Skin Lesions, Arsenic Metabolism, Neurological Functions, and Biomarkers for Respiratory and Cardiovascular Diseases: Review of Recent Findings from the Health Effects of Arsenic Longitudinal Study (HEALS) in Bangladesh. *Toxicology and Applied Pharmacology, 239,* 184-192. https://doi.org/10.1016/j.taap.2009.01.010

Claon, S. J., Kouassi, S. K., Arsène M'bassidje, S., Séri, L. K., Kouadio, L. K., & Djaman, J. A. (2022). Exposure of Mercury from Gold Ming Area: A Case Study in Tendo and Aby Lagoon in Côte d'Ivoire. *Journal of Environmental Protection, 13,* 613-627. https://doi.org/10.4236/jep.2022.139039

Clarkson, T. W. (2002). The Three Modern Faces of Mercury. *Environmental Health Perspectives, 110,* 11-23. https://doi.org/10.1289/ehp.02110s111

de Matos, A. T., Fontes, M. P. F., da Costa, L. M., & Martinez, M. A. (2001). Mobility of Heavy Metals as Related to Soil Chemical and Mineralogical Characteristics of Brazilian Soils. *Environmental Pollution, 111,* 429-435. https://doi.org/10.1016/s0269-7491(00)00088-9

de Vries, W., Römkens, P. F. A. M., & Schütze, G. (2007). Critical Soil Concentrations of Cadmium, Lead, and Mercury in View of Health Effects on Humans and Animals. In W. de Vries, P. F. A. M. Römkens, & G. Schütze (Eds.), *Reviews of Environmental Contamination and Toxicology* (pp. 91-130). Springer. https://doi.org/10.1007/978-0-387-69163-3_4

Fashola, M., Ngole-Jeme, V., & Babalola, O. (2016). Heavy Metal Pollution from Gold Mines: Environmental Effects and Bacterial Strategies for Resistance. *International Journal of Environmental Research and Public Health, 13,* Article 1047. https://doi.org/10.3390/ijerph13111047

Fijałkowski, K., Kacprzak, M., Grobelak, A., & Placek, A. (2012). The Influence of Selected Soil Parameters on the Mobility of Heavy Metals in Soils. *Inżynieria i Ochrona środowiska, 15,* 81-92.

Fikri, E., Firmansyah, Y. W., Afifah, A. S., & Fauzi, M. (2023). The Existence of Artisanal Small-Scale Gold Mining in Indonesia: The Impact of Public Health and Environmental Sustainability: A Narrative Review. *Journal of Environmental Health, 15,* 99. https://doi.org/10.20473/jkl.v15i2.2023.99-108

Gangloff, W. J., Westfall, D. G., Peterson, G. A., & Mortvedt, J. J. (2006). Mobility of Organic and Inorganic Zinc Fertilizers in Soils. *Communications in Soil Science and Plant Analysis, 37,* 199-209. https://doi.org/10.1080/00103620500403200

Garelick, H., Jones, H., Dybowska, A., & Valsami-Jones, E. (2008). Arsenic Pollution Sources. In H. Garelick, H. Jones, A. Dybowska, & E. Valsami-Jones (Eds.), *Reviews of Environmental Contamination and Toxicology* (pp. 17-60). Springer. https://doi.org/10.1007/978-0-387-79284-2_2

Gimmler, H., Carandang, J., Boots, A., Reisberg, E., & Woitke, M. (2002). Heavy Metal Content and Distribution within a Woody Plant during and after Seven Years Continuous Growth on Municipal Solid Waste (MSW) Bottom Slag Rich in Heavy Metals. *Journal of Applied Botany*, 76, 203-217.

Gitari, W. M., Thobakgale, R., & Akinyemi, S. A. (2018). Mobility and Attenuation Dynamics of Potentially Toxic Chemical Species at an Abandoned Copper Mine Tailings Dump. *Minerals, 8,* 64. https://doi.org/10.3390/min8020064

Gonçalves Jr., A. C., Nacke, H., Schwantes, D., Campagnolo, M. A., Miola, A. J., Tarley, C. R. T. et al. (2017). Adsorption Mechanism of Chromium (III) Using Biosorbents of *Jatropha curcas* L. *Environmental Science and Pollution Research, 24,* 21778-21790.

https://doi.org/10.1007/s11356-017-9749-z

Grobelak, A., & Kowalska, A. (2020). Heavy Metal Mobility in Soil under Futuristic Climatic Conditions. In *Climate Change and Soil Interactions* (pp. 437-451). Elsevier.

Grynberg, R., & Singogo, F. K. (2021). The ASGM Sector in Africa: Lessons from China. In R. Grynberg, & F. K. Singogo (Eds.), *African Gold: Production, Trade and Economic Development* (pp. 49-109). Springer International Publishing. https://doi.org/10.1007/978-3-030-65995-0_3

Herman, A., & Kihampa, C. (2015). Heavy Metals Contamination in Soils and Water in the Vicinity of Small Scale Gold Mines at Londoni and Sambaru, Singida Region, Tanzania. *International Journal of Environmental Monitoring and Analysis, 3,* 397-403. https://doi.org/10.11648/j.ijema.20150306.13

Hilson, G. (2002). Small-scale Mining in Africa: Tackling Pressing Environmental Problems with Improved Strategy. *The Journal of Environment & Development, 11,* 149-174. https://doi.org/10.1177/10796502011002003

Hilson, G., & Maconachie, R. (2020). Artisanal and Small-Scale Mining and the Sustainable Development Goals: Opportunities and New Directions for Sub-Saharan Africa. *Geoforum, 111,* 125-141. https://doi.org/10.1016/j.geoforum.2019.09.006

Hseu, Z. (2004). Evaluating Heavy Metal Contents in Nine Composts Using Four Digestion Methods. *Bioresource Technology, 95,* 53-59. https://doi.org/10.1016/j.biortech.2004.02.008

Huising, J. E., & Mesele, S. A. (2022). *Protocol for Field Survey: Guidelines for Field Surveyors on Soil Sample Collection and Field Assessment of Agricultural Lands in Africa.* IITA, 55 p.

Hussain, S., Khan, M., Sheikh, T. M. M., Mumtaz, M. Z., Chohan, T. A., Shamim, S. et al. (2022). Zinc Essentiality, Toxicity, and Its Bacterial Bioremediation: A Comprehensive Insight. *Frontiers in Microbiology, 13,* Article 900740. https://doi.org/10.3389/fmicb.2022.900740

Jiang, L., Sun, H., Peng, T., Ding, W., Liu, B., & Liu, Q. (2021). Comprehensive Evaluation of Environmental Availability, Pollution Level and Leaching Heavy Metals Behavior in Non-Ferrous Metal Tailings. *Journal of Environmental Management, 290,* Article ID: 112639. https://doi.org/10.1016/j.jenvman.2021.112639

Kaaya, N. I., Vegi, M. R., & Macheyeki, A. S. (2025). Health Risks of Geogenic Contaminants in Gold Mining Areas in Geita, Tanzania. *Journal of Trace Elements and Minerals, 12,* Article ID: 100222. https://doi.org/10.1016/j.jtemin.2025.100222

Kabamanya, E. A. (2025). *The Politics of Artisanal and Small-Scale Gold Mining (ASGM) in Tanzania in the 21st Century.* Master's Thesis, Syracuse University.

Kaggwa, A., Byamugisha, D., Omara, T., & Ntambi, E. (2024). Assessment of Potentially Toxic Elements and Their Risks in Water and Sediments of Kitengure Stream, Buhweju Plateau, Uganda. *Earth, 5,* 743-760. https://doi.org/10.3390/earth5040039

Kim, K., Kabir, E., & Jahan, S. A. (2016). A Review on the Distribution of Hg in the Environment and Its Human Health Impacts. *Journal of Hazardous Materials, 306,* 376-385. https://doi.org/10.1016/j.jhazmat.2015.11.031

Kumkrong, P., Dy, E., Tyo, D. D., Jiang, C., Gedara Pihilligawa, I., Kingston, D. et al. (2022). Investigation of Metal Mobility in Gold and Silver Mine Tailings by Single-Step and Sequential Extractions. *Environmental Monitoring and Assessment, 194,* Article No. 423. https://doi.org/10.1007/s10661-022-10054-3

Kyowe, H. A., Awotoye, O. O., Oyekunle, J. A. O., & Olusola, J. A. (2024). Index of Heavy Metal Pollution and Health Risk Assessment with Respect to Artisanal Gold Mining Op-

erations in Ibodi-Ijesa, Southwest Nigeria. *Journal of Trace Elements and Minerals, 9,* Article ID: 100160. https://doi.org/10.1016/j.jtemin.2024.100160

Lengke, M. F., Sanpawanitchakit, C., & Tempel, R. N. (2009). The Oxidation and Dissolution of Arsenic-Bearing Sulfides. *The Canadian Mineralogist, 47,* 593-613. https://doi.org/10.3749/canmin.47.3.593

Luan, Y., Xu, J., Zhou, J., Wang, H., Han, F., Wang, K. et al. (2022). Migration and Removal of Labile Cadmium Contaminants in Paddy Soils by Electrokinetic Remediation without Changing Soil pH. *International Journal of Environmental Research and Public Health, 19,* Article 3812. https://doi.org/10.3390/ijerph19073812

Machiwa, J. (2003). Metal Concentrations in Sediment and Fish of Lake Victoria near and Away from Catchments with Gold Mining Acctivities. *Tanzania Journal of Science, 29,* 43-54. https://doi.org/10.4314/tjs.v29i2.18377

Maganga, S. P., Mdee, O. J., Kombe, G. G., & Ntalikwa, J. W. (2023). Situational Analysis of Gold Processing Practices at Artisanal and Small-Scale Gold Mining in Tanzania. *Tanzania Journal of Engineering and Technology, 42,* 27-43.

Maglambayan, V. B., Murao, S., Corpus, T. J. C., Sera, K., Futatsugawa, S., & Tsuji, M. (2005). Mercury Contamination Associated with Small-Scale Gold Mining in the Upper Ambalanga River, Benguet, Philippines, from River Sediment Sampling. In *Community and State Interests in Small-Scale Mining: Sharing Experiences from the Asia-Pacific Region*. Philippine Sustainable Development Network Foundation, Inc. (PSDN).

Majzlan, J., Plášil, J., Škoda, R., Gescher, J., Kögler, F., Rusznyak, A. et al. (2014). Arsenic-rich Acid Mine Water with Extreme Arsenic Concentration: Mineralogy, Geochemistry, Microbiology, and Environmental Implications. *Environmental Science & Technology, 48,* 13685-13693. https://doi.org/10.1021/es5024916

Martn, F., Simn, M., Garca, I., Romero, A., & Gonzlez, V. (2014). Pollution of Pb in Soils Affected by Pyrite Tailings: Influence of Soil Properties. In M. C. Hernandez-Soriano (Ed.), *Environmental Risk Assessment of Soil Contamination*. InTech Open. https://doi.org/10.5772/57270

Merrington, G., & Alloway, B. J. (1994). The Transfer and Fate of Cd, Cu, Pb and Zn from Two Historic Metalliferous Mine Sites in the U.K. *Applied Geochemistry, 9,* 677-687. https://doi.org/10.1016/0883-2927(94)90027-2

Mnali, S. (2001). Assessment of Heavy Metal Pollution in the Lupa Gold Field, SW Tanzania. *Tanzania Journal of Science, 27,* 15-22. https://doi.org/10.4314/tjs.v27i2.18343

Montalván-Olivares, D. M., Santana, C. S., Velasco, F. G., Luzardo, F. H. M., Andrade, S. F. R., Ticianelli, R. B. et al. (2021). Multi-Element Contamination in Soils from Major Mining Areas in Northeastern of Brazil. *Environmental Geochemistry and Health, 43,* 4553-4576. https://doi.org/10.1007/s10653-021-00934-x

Mutemeri, N., de Tomi, G., Naré, C., Bellois, G., Weldegiorgis, F. S., & Taquiri, J. (2024). *ASGM Tailings Management and Reprocessing Governance: Global Trends.*

Nikmanesh, Y., Mohammadi, M. J., Yousefi, H., Mansourimoghadam, S., & Taherian, M. (2023). The Effect of Long-Term Exposure to Toxic Air Pollutants on the Increased Risk of Malignant Brain Tumors. *Reviews on Environmental Health, 38,* 519-530. https://doi.org/10.1515/reveh-2022-0033

Nordstrom, D. K., Blowes, D. W., & Ptacek, C. J. (2015). Hydrogeochemistry and Microbiology of Mine Drainage: An Update. *Applied Geochemistry, 57,* 3-16. https://doi.org/10.1016/j.apgeochem.2015.02.008

Ogundele, L. T., Oluwajana, O. A., Ogunyele, A. C., & Inuyomi, S. O. (2021). Heavy Metals, Radionuclides Activity and Mineralogy of Soil Samples from an Artisanal Gold Mining

Site in Ile-Ife, Nigeria: Implications on Human and Environmental Health. *Environmental Earth Sciences, 80,* Article No. 202. https://doi.org/10.1007/s12665-021-09494-w

Patel, K. S., Pandey, P. K., Martín-Ramos, P., Corns, W. T., Varol, S., Bhattacharya, P. et al. (2023). A Review on Arsenic in the Environment: Contamination, Mobility, Sources, and Exposure. *RSC Advances, 13,* 8803-8821. https://doi.org/10.1039/d3ra00789h

Pennock, D., Yates, T., & Braidek, J. (2007). Soil Sampling Designs. *Soil Sampling and Methods of Analysis, 2,* 1-14.

Pkemoi, E. (2024). *Assessment of Radio-Ecological Hazardous and Toxic Heavy Metal Contamination Associated with Artisanal Gold Mining in West Pokot County.* Master's Thesis, University of Nairobi.

Qing, Y., Yang, J., Zhu, Y., Li, Y., Zheng, W., Wu, M. et al. (2021). Dose-Response Evaluation of Urinary Cadmium and Kidney Injury Biomarkers in Chinese Residents and Dietary Limit Standards. *Environmental Health, 20,* Article No. 75. https://doi.org/10.1186/s12940-021-00760-9

Rodríguez, L., Ruiz, E., Alonso-Azcárate, J., & Rincón, J. (2009). Heavy Metal Distribution and Chemical Speciation in Tailings and Soils around a Pb-Zn Mine in Spain. *Journal of Environmental Management, 90,* 1106-1116. https://doi.org/10.1016/j.jenvman.2008.04.007

Saha, J. K., Selladurai, R., Coumar, M. V., Dotaniya, M. L., Kundu, S., & Patra, A. K. (2017). Collection and Processing of Polluted Soil for Analysis. In J. K. Saha, R. Selladurai, M. V. Coumar, M. L. Dotaniya, S. Kundu, & A. K. Patra (Eds.), *Soil Pollution—An Emerging Threat to Agriculture* (137-153). Springer Singapore. https://doi.org/10.1007/978-981-10-4274-4_6

Sanga, T. R., Maseka, K. K., Ponraj, M., Tungaraza, C., Mng'ong'o, M. E., & Mwakalapa, E. B. (2023). Accumulation and Distribution of Mercury in Agricultural Soils, Food Crops and Associated Health Risks: A Case Study of Shenda Gold Mine-Geita Tanzania. *Environmental Challenges, 11,* Article ID: 100697. https://doi.org/10.1016/j.envc.2023.100697

Sethurajan, M., Huguenot, D., Jain, R., Lens, P. N. L., Horn, H. A., Figueiredo, L. H. A. et al. (2017). Leaching and Selective Zinc Recovery from Acidic Leachates of Zinc Metallurgical Leach Residues. *Journal of Hazardous Materials, 324,* 71-82. https://doi.org/10.1016/j.jhazmat.2016.01.028

Shapiro, C. A., & Kranz, W. L. (1992). Comparison of Auger and Core Soil Sampling Methods to Determine Soil Nitrate under Field Conditions. *Journal of Production Agriculture, 5,* 358-362. https://doi.org/10.2134/jpa1992.0358

Sharma, S. K., Dahiya, S. S., & Kapoor, A. K. (2004). Soil pH and Electrical Conductivity. *Soil Analysis, 140,* 1-151.

Shu, W. S., Ye, Z. H., Lan, C. Y., Zhang, Z. Q., & Wong, M. H. (2001). Acidification of Lead/zinc Mine Tailings and Its Effect on Heavy Metal Mobility. *Environment International, 26,* 389-394. https://doi.org/10.1016/s0160-4120(01)00017-4

Singh, N., Kumar, D., & Sahu, A. P. (2007). Arsenic in the Environment: Effects on Human Health and Possible Prevention. *Journal of Environmental Biology, 28,* 359.

Sintorini, M. M., Widyatmoko, H., Sinaga, E., & Aliyah, N. (2021). Effect of Ph on Metal Mobility in the Soil. *IOP Conference Series: Earth and Environmental Science, 737,* Article ID: 012071. https://doi.org/10.1088/1755-1315/737/1/012071

Šípková, A., Száková, J., Hanč, A., & Tlustoš, P. (2016). Mobility of Mercury in Soil as Affected by Soil Physicochemical Properties. *Journal of Soils and Sediments, 16,* 2234-2241. https://doi.org/10.1007/s11368-016-1420-7

Skyllberg, U. (2012). Chemical Speciation of Mercury in Soil and Sediment. *Environmental Chemistry and Toxicology of Mercury*, 219-258. https://doi.org/10.1002/9781118146644.ch7

Taylor, H., Appleton, J. D., Lister, R., Smith, B., Chitamweba, D., Mkumbo, O. et al. (2005). Environmental Assessment of Mercury Contamination from the Rwamagasa Artisanal Gold Mining Centre, Geita District, Tanzania. *Science of the Total Environment, 343,* 111-133. https://doi.org/10.1016/j.scitotenv.2004.09.042

Tchounwou, P. B., Yedjou, C. G., Patlolla, A. K., & Sutton, D. J. (2012). Heavy Metal Toxicity and the Environment. In A. Luch (Ed.), *Molecular, Clinical and Environmental Toxicology* (pp. 133-164). Springer Basel. https://doi.org/10.1007/978-3-7643-8340-4_6

Tsuji, J. S., Williams, P. R. D., Edwards, M. R., Allamneni, K. P., Kelsh, M. A., Paustenbach, D. J. et al. (2003). Evaluation of Mercury in Urine as an Indicator of Exposure to Low Levels of Mercury Vapor. *Environmental Health Perspectives, 111,* 623-630. https://doi.org/10.1289/ehp.5717

Van, H., Hoang, V. H., Nga, L. T. Q., & Nguyen, V. Q. (2024). Effects of Zn Pollution on Soil: Pollution Sources, Impacts and Solutions. *Results in Surfaces and Interfaces, 17,* Article ID: 100360. https://doi.org/10.1016/j.rsurfi.2024.100360

Vandana, Priyadarshanee, M., Mahto, U., & Das, S. (2022). Mechanism of Toxicity and Adverse Health Effects of Environmental Pollutants. In S. Das, & H. R. Dash (Eds.), *Microbial Biodegradation and Bioremediation* (pp. 33-53). Elsevier. https://doi.org/10.1016/b978-0-323-85455-9.00024-2

Violante, A., Cozzolino, V., Perelomov, L., Caporale, A. G., & Pigna, M. (2010). Mobility and Bioavailability of Heavy Metals and Metalloids in Soil Environments. *Journal of Soil Science and Plant Nutrition, 10,* 268-292. https://doi.org/10.4067/s0718-95162010000100005

Wang, M., Bera, G., Mitra, K., Wade, T. L., Knap, A. H., & Phillips, T. D. (2021a). Tight Sorption of Arsenic, Cadmium, Mercury, and Lead by Edible Activated Carbon and Acid-Processed Montmorillonite Clay. *Environmental Science and Pollution Research, 28,* 6758-6770. https://doi.org/10.1007/s11356-020-10973-z

Wang, M., Chen, Z., Song, W., Hong, D., Huang, L., & Li, Y. (2021b). A Review on Cadmium Exposure in the Population and Intervention Strategies against Cadmium Toxicity. *Bulletin of Environmental Contamination and Toxicology, 106,* 65-74. https://doi.org/10.1007/s00128-020-03088-1

WHO (World Health Organization) (2008). *Guidelines for Drinking Water Quality: Incorporating the First and Second Agenda Volume Recommendations.* WHO Press.

WHO (World Health Organization) (2011). *Guidelines for Drinking Water Quality.* WHO Press.

WHO/FAO (World Health Organization/Food and Agriculture Organization) (2008). *Codex Alimentarius Commission, General Standard for Contaminants and Toxins in Food and Feed (CXS 193-1995, Amended 2008).* Joint FAO/WHO Food Standards Programme.

Wiafe, S., Awuah Yeboah, E., Boakye, E., & Ofosu, S. (2022). Environmental Risk Assessment of Heavy Metals Contamination in the Catchment of Small-Scale Mining Enclave in Prestea Huni-Valley District, Ghana. *Sustainable Environment, 8,* Article ID: 2062825. https://doi.org/10.1080/27658511.2022.2062825

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

Yabe, J., Ishizuka, M., & Umemura, T. (2010). Current Levels of Heavy Metal Pollution in Africa. *Journal of Veterinary Medical Science, 72,* 1257-1263. https://doi.org/10.1292/jvms.10-0058

Yu, J., Yue, B., Wu, X., Liu, Q., Jiao, F., Jiang, X. et al. (2016). Removal of Mercury by Adsorption: A Review. *Environmental Science and Pollution Research, 23,* 5056-5076. https://doi.org/10.1007/s11356-015-5880-x

Zhuang, F., Huang, J., Li, H., Peng, X., Xia, L., Zhou, L. et al. (2023). Biogeochemical Behavior and Pollution Control of Arsenic in Mining Areas: A Review. *Frontiers in Microbiology, 14,* Article 1043024. https://doi.org/10.3389/fmicb.2023.1043024