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COMPARATIVE CHARACTERIZATION OF LEAD AND OTHER HEAVY METAL CONTAMINATION IN ORE AND TAILINGS: ENVIRONMENTAL HEALTH RISKS IN SMALL-SCALE MINING COMMUNITIES IN ZAMFARA, NIGERIA, AND GEITA, TANZANIA

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ABSTRACT

Artisanal and Small-scale Mining (ASM) is tailings, a vital livelihood activity in Zamfara State, Nigeria, and Geita Region, Tanzania. However, ASM often involves hazardous practices, leading to immediate health risks and environmental contamination. We conducted a study to urgently assess the concentration levels of lead and other heavy metals in ore and tailings, highlighting the need for immediate action.

A preliminary assessment in mining and residential areas focused on understanding the local context of ASM. The community, which played a crucial role in this study, was actively engaged and trained on heavy metal risks and safer mining practices. A total of 16 ore and 4 tailings samples were collected from mining sites and analyzed for heavy metals using X-ray fluorescence (XRF) spectrometry and atomic absorption spectrometry (AAS).

Heavy metal concentrations were higher in Zamfara than in Geita. Lead was the dominant metal in Zamfara, while copper dominated in Geita. In Zamfara, tailings had a mean lead concentration of 391,571.67 mg/kg (Pb > As > Cu >

Zn > Ni > Cr), and ores had 15,019.1 mg/kg of lead (Pb > As > Cu > Zn > Ni > Cr). Geita, tailings had 760.4 mg/kg of copper (Cu > Zn > As > Ni > Cr > Pb), and ores had 299.03 mg/kg of copper (Cu > Zn > As > Ni > Cr > Pb). Tailings contained higher metal concentrations than ores.

Higher metal concentrations in tailings pose serious environmental and health risks, highlighting the urgent need for effective management. This includes proper tailings handling, monitoring, safer mining practices, soil remediation, stronger regulations, and increased community awareness.

KEYWORDS

Lead; other heavy metal; Ore; Tailing; Small-Scale Mining Communities

1. INTRODUCTION

Artisanal and Small-Scale Mining (ASM) is a significant economic activity in many developing countries, providing livelihoods for millions of people. In Zamfara State, Nigeria, and Geita Region, Tanzania, ASM has become an essential source of income and employment, particularly in rural communities where alternative economic opportunities are scarce. However, ASM is often conducted with rudimentary tools and informal processing methods, leading to serious environmental contamination and health risks. The improper handling of ores and tailings results in the release of hazardous heavy metals, including lead, mercury, cadmium, arsenic, and other toxic elements into surrounding environment (Jeevanandam, 2025). These contaminants pose long-term threats to miners, nearby communities, water sources, and ecosystems, with children and pregnant women being particularly vulnerable to exposure.

While ASM supports over 500,000 miners in Nigeria (Nnaji et al., 2016), its environmental impacts remain underexplored especially across regions. In Zamfara, a 2010 lead poisoning crisis revealed the severe risks of processing lead-rich gold ore (MSF, 2010b). Toxic dust contaminated soil and water, causing hundreds of child fatalities. Mercury use in ore processing further worsens pollution (WHO, 2016), highlighting the urgent need for environmental monitoring in ASM zones.

In Geita Region, heavy metals like chromium, copper, and lead exceed safety limits, posing risks to soil and food safety (Mgendi et al., 2020). Zamfara's extreme lead contamination and Geita's mixed metal exposure make both regions valuable case studies for ASM-related pollution.

The source of lead contamination in northern Nigeria has been directly linked to artisanal gold mining, particularly during the surge in gold prices around 2009-2010. Artisanal mining and processing in Zamfara have been associated with both chronic environmental contamination and acute lead poisoning, which has been an ongoing issue in the region for decades (Benedicta et al., 2023). Soils in contaminated Zamfara villages have shown lead levels up to 185,000 ppm, with ore averaging 89,500 ppm (Bartrem et al., 2014). These levels are linked to manual ore processing with mercury and basic crushing techniques. These methods release fine, lead-rich dust into homes, soil, and water.

Despite the economic significance of ASM, there remains a critical gap in understanding its long-term environmental and health impacts. While existing research addresses economic, social, and occupational hazards, site-specific studies that integrate geochemical assessments, heavy metal contamination data, and health exposure risks remain scarce. Additionally, research on the direct health effects of heavy metal exposure on miners and vulnerable populations, such as children and pregnant women, is still limited.

This study specifically investigates: (1) the concentration levels of lead and other heavy metals in ore and tailings from ASM sites in Zamfara and Geita, (2) the differences in contamination levels between the two regions, and (3) the potential environmental and health risks associated with these findings. By analyzing contamination levels and comparing trends across these regions, this research seeks to fill critical knowledge gaps and provide scientific evidence to support intervention strategies and safer mining practices. Understanding contamination patterns will provide essential data for environmental management policies, regulatory frameworks, and health interventions to protect mining communities from long-term exposure to toxic heavy metals. By providing the first comparative assessment of these two regions, this research contributes to a deeper understanding of ASM-related contamination, informing targeted interventions and environmental policies.

Ultimately, this study contributes to the broader discussion on sustainable ASM practices, ensuring that economic benefits do not come at the cost of environmental and public health deterioration.

2. MATERIALS AND METHODS

2.1 Preliminary assessment

A preliminary assessment was conducted in three villages in Zamfara State (Abare, Dareta, and Bagega) and two villages in Geita Region (Mgusu and Msasa) to understand the local context of artisanal small-scale mining (ASM). The study focused on Dareta, Abare, and Bagega villages due to their high number of children enrolled in the lead poisoning treatment program run by MSF and the suspected soil contamination with heavy metals. These villages were also chosen for their relative accessibility in terms of security and road conditions, as Zamfara is a compromised security zone that limits access to other areas. Mgusu and Msasa villages were included due to better road access compared to other remote or hazardous locations where sample collection was challenging. The local mining leaders in these villages agreed to participate and allowed sample collection. Furthermore, to ensure that local communities were informed of the study, as well as to encourage collaboration and community engagement while strengthening credibility, meetings were conducted with miners and local leaders to discuss ASM-related issues. Community and mining leaders participated in planning and lead hazard awareness training before the assessment. Miners and ore processors received targeted education on the dangers of lead, mercury, and silica dust, as well as on safer practices, including forming safety committees to oversee the reduction of exposure and environmental contamination from ASM activities.

2.2 Ethical Considerations

This study complied with ethical standards for environmental and community-based research. While formal ethical approval was not required, informed consent was obtained from miners, community members, and local leaders before participation in training sessions and discussions. Sample collection was conducted with the permission of local authorities and mining site leaders.

No invasive procedures were performed, and the study posed no direct risks to participants. Ethical guidelines for environmental research were strictly followed to ensure respect for local communities and minimize any potential environmental impact.

2.2 Ore and tailings sample collection

A systematic sampling effort was conducted across active four mining sites and four formal processing sites, resulting in the collection of 16 ore samples (8 Tanzania and 8 Nigeria) and 4 tailings samples (2 Tanzania and 2 Nigeria). Each village provided four ore samples from local mining operations and one tailings sample, following a structured pattern: Two samples were collected from underground mining, two from open-pit mining, and one tailings sample from the nearest processing site. This approach enabled the evaluation of lead and other heavy metal concentrations, allowing comparisons between the ore and tailings. Only 16 ore and 4 tailings samples were collected, limited by security and access challenges. Some mining leaders in other areas refused participation, and inactive mining sites were inaccessible because of compromised security and roads no longer in use. The focus on active mining sites was due to these logistical challenges.

In the first village (Abare and Dareta), samples were labeled as 1UG1, 1UG2, 1OP1, 1OP2, and 1TL. Due to their geographic proximity, these two villages were treated as a single unit. In Bagega, Zamfara State samples were labeled as 2UG1, 2UG2, 2OP1, 2OP2, and 2TL; in Mgusu, Geita Region they were designated as 3UG1, 3UG2, 3OP1, 3OP2, and 3TL; and in Msasa, Geita Region samples were marked as 4UG1, 4UG2, 4OP1, 4OP2, and 4TL.

The first ore samples were collected from the initial underground mining hole at a depth of at least 20 meters, while the second ore samples were taken approximately 30 meters away, maintaining the same depth. The third and fourth ore samples were obtained from functional open-pit mines, each at a depth of 5 meters, with the fourth sample sourced from a separate pit 30 meters from the third. Tailings samples were gathered from the nearest processing site. Each sample weighed around 0.25 kg and was placed in transparent plastic bags for transport to the Min MSF laboratory in Anka LGA for analysis.

The sampling depths were selected based on the maximum extraction levels for each mining method: 20 m for underground pits and 5 m for open pits. This approach ensures that samples accurately reflect the most contaminated zones where ore and tailings are concentrated. These depths correspond with expected contamination gradients, as the deeper layers in underground mining typically accumulate higher contaminant levels due to prolonged exposure and reduced dilution. In contrast, shallower depths in open-pit mining may be more influenced by surface-related contamination.

2.4 Ore and tailings sample Analysis

The analysis aimed to quantify lead and other heavy metals, including nickel, chromium, arsenic, zinc, copper, and manganese, based on their potential impact on environmental and human health. The analysis utilized Field Portable X-ray XRF in accordance with EPA SW-846 Test Method 6200. The handheld XRF instrument was calibrated following EPA Method 6200 guidelines. Calibration was verified daily using certified standard reference materials (SRMs), such as NIST 2710, USGS, RCR, and Sio_2 or equivalent, to ensure energy stability and measurement accuracy. A fundamental parameters (FP) model was used, with slope and intercept adjusted to match the certified values within ±20%. Instrument blanks and method blanks were run regularly to check for contamination, and calibration checks were repeated after every 20 samples. A percent difference (%D) between measured and certified values was kept within acceptable limits to maintain data integrity and comparability. Results were expressed in milligrams per kilogram (mg/kg).

Sampling in the Geita region followed standardized procedures to ensure data quality and reliability. Samples were analyzed at the SGS Environmental Laboratory in Mwanza using Atomic Absorption Spectrophotometry (AAS). The calibration of the AAS was carried out following a rigorous protocol to guarantee accurate and consistent measurements. The instrument was allowed to warm up according to the manufacturer's guidelines, and the appropriate hollow cathode lamp was installed and aligned for maximum intensity. Wavelength calibration was performed by setting the instrument to the correct analytical line for each element, followed by slit width adjustment for optimal resolution. Calibration was conducted using high-purity metal stock solutions to prepare a series of standards, which were measured to construct a calibration curve. This curve was verified with a quality control standard to confirm linearity and accuracy, and all data were properly documented.

For sample preparation, ore and tailings were air-dried for 72 hours, ground to <75 µm, sieved, and homogenized. Acid digestion using a 3:1 mixture of HNO_3 and HCl, following EPA Method 3050B, ensured complete metal extraction. The digest was heated to 95°C for 2 hours, then filtered and diluted prior to analysis. Analytical precision was maintained through the use of duplicate analyses (10% of samples), certified reference materials (CRMs), and blanks. Contamination was minimized by employing acid-cleaned tools, disposable gloves, pre-cleaned sample bags, and acid-washed glassware throughout the process.

2.5 Statistical analysis

The statistical analysis was conducted using Microsoft Excel to evaluate differences in heavy metal concentrations between sample groups. A t-test under 95% confidence level was applied to determine whether variations in ore and tailings contamination levels and differences between Zamfara and Geita were statistically significant. The choice of the t-test was based on the study's focus on comparing two independent groups (ore vs. tailings, and Zamfara vs. Geita). The t-test is well-suited for analyzing differences between two means, making it an appropriate method for this dataset. While ANOVA is often used for comparisons involving multiple groups, it was not necessary for this study, as the analysis focused solely on two-group comparisons. Given the relatively small sample size, the t-test provided sufficient statistical power while controlling for Type I errors.

To further assess the magnitude of differences between sites, Cohen's d effect sizes were calculated. Confidence intervals were calculated, but small sample sizes and variability led to negative lower bounds, which are not meaningful for this type of data. To maintain statistical rigor and interpretability, Cohen's d was chosen as the primary measure of effect size. This approach ensures a clearer understanding of differences between sites.

A standardized approach was applied for heavy metal concentrations below the detection limit (LOD) by assigning the LOD value as the minimum concentration in statistical calculations. This method minimizes bias, ensures data consistency, and provides a conservative estimate of contamination levels, which is crucial for environmental and health risk assessments. Given that only a small portion of the dataset was below the LOD, this approach did not significantly affect overall trends.

3. RESULTS AND DISCUSSION

Table 1 and 2 present the summary results of characterization of lead and other heavy metal contamination in ore and tailings for four villages in Zamfara State, Nigeria and Geita Region, Tanzania

TABLE 1: Characterization of lead and other heavy metals contamination in ore for site 1 (Abare and Dareta) and site 2 (Bagega) in Zamfara State

	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg
ID	**Pb**	**As**	**Cu**	**Zn**	**Cr**	**Ni**
SITE 1						
1UGI	31589.1	9289.8	6533.7	216.5	167.4	214.1
1UG2	30911.22	8231.64	5565.64	209.21	154.7	205.03
1OP1	3469.22	7762.01	736.94	64.72	68.83	101.61
1OP2	6856.79	7192.39	1286.18	132.25	139.81	161.27
Average	18206.58	8118.95	3530.62	155.66	132.69	170.51
SDV	15127.3	888.70	2944.04	71.61	44.04	51.40
Range	3469.22-31589.09	7192.39-9289.75	736.94-6533.73	64.72-216.46	68.83-167.4	101.61-214.12
SITE 2						
2UGI	18653.04	8129.34	3472.11	152.42	141.9	179.16
2UG2	22430.01	8057.12	4527.37	189.98	148.2	191.45
2OP1	3222.66	5553.75	539.1	50.49	55.32	89.45
2OP2	3020.64	5337.61	465.74	40.55	< LOD	91.43
Average	11831.59	6769.45	2251.08	108.36	86.36	137.88
SDV	10175.21	1531.39	2064.84	74.27	71.46	55.01
Range	3020.64-18653.04	5337.61-8129.34	465.74-4527.37	40.55-189.98	LOD-148.2	89.45-191.45

TABLE 2: Characterization of lead and other heavy metals contamination in ore for site 3 (Mgusu) and site 4 (Msasa) in Geita Region

	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg
ID	**Pb**	**As**	**Cu**	**Zn**	**Cr**	**Ni**
SITE 3						
3UGI	21.9	37.7	232.3	22.2	16.1	32.9
3UG2	23	38.9	236.9	22.9	16.5	33.8
3OP1	12.7	26.9	205.5	17.6	12.8	30.3
3OP2	< LOD	23.1	198.4	14.4	< LOD	< LOD
Average	14.4	31.65	218.275	19.275	11.35	24.25
SDV	10.65	7.84	19.16	4.01	7.75	16.23
Range	LOD-23	23.1-38.9	198.4-236.9	14.4-22.9	LOD-16.5	LOD-33.8
SITE 4						
4UGI	24.3	5581.3	845.3	321.6	124.8	71.3
4UG2	23.1	41.5	241.9	23.1	16.9	34.7
4OP1 4OP2	18.5	31.4	221.8	21.3	15.4	31.9
	15	28.7	210.1	18.6	< LOD	30.6
Average	20.225	1420.725	379.775	96.15	39.275	42.125
SDV	4.29	2773.72	310.63	150.31	57.53	19.53
Range	15-24.3	28.7-5581.3	210.1-845.3	18.6-321.6	LOD-124.8	30.6-71.3

Table 1 indicates that lead was the most toxic heavy metal in Zamfara, with a maximum concentration of 31,589.09 mg/kg, the highest among analyzed metals. Chromium had the lowest concentration at 44.04 mg/kg. In Geita, Table 2 shows that copper had the highest concentration at 236.9 mg/kg, while Pb, Cr, and Ni were the lowest. Both sites showed increasing heavy metal levels with mining depth, being higher in underground mining locations.

3.1 Ore Characterization at Sites 1 and 2 in Zamfara State

Lead and Copper contamination

At Site 1, lead levels ranged from 3,469.22 to 31,589.09 mg/kg, averaging 18,206.58 ± 15,127.31 mg/kg, while at Site 2, levels ranged from 3,020.64 to 22,430.01 mg/kg, averaging 11,831.59 ± 10,175.22 mg/kg. All values exceeded the WHO soil limit of 100 mg/kg.

Similarly, at Site 1, copper levels ranged from 736.94 to 6,533.73 mg/kg, averaging 3,530.62 ± 2,944.04 mg/kg, while Site 2 ranged from 465.74 to 4,527.37 mg/kg, averaging 2,251.08 ± 2,064.84 mg/kg, all above the WHO threshold. Lower levels were recorded in sample 1OP1 at Site 1 (least 5m depth) and sample 2OP2 at Site 2 (30 meters away). The t-test results show no significant difference in lead ($p = 0.255$) or copper ($p = 0.252$) concentrations between sites. However, Cohen's d effect sizes indicate a moderate effect for both lead ($d = 0.49$) and copper ($d = 0.50$), suggesting a moderate but meaningful difference between the two sites

Zinc and Chromium contamination

At Site 1, zinc levels ranged from 164.72 to 316.46 mg/kg, averaging 255.66 ± 71.61 mg/kg, with 50% below the WHO limit of 300 mg/kg. Chromium ranged from 68.83 to 167.4 mg/kg, averaging 132.69 ± 44.04 mg/kg, with 75% exceeding the WHO limit of 100 mg/kg.

At Site 2, zinc ranged from 140.55 to 289.98 mg/kg, averaging 208.36 ± 74.27 mg/kg, all below the WHO limit. Chromium ranged from below detection to 148.2 mg/kg, averaging 86.36 ± 51.90 mg/kg, with 50% exceeding the WHO limit. Lower levels were observed in sample 1OP1 at Site 1 and sample 2OP2 at Site 2. The t-test shows no significant difference in zinc ($p = 0.197$) or chromium ($p = 0.156$) concentrations. However, Cohen's d effect sizes indicate a moderate effect for zinc ($d = 0.65$) and a large effect for chromium ($d = 0.96$), suggesting that while zinc differences between sites are moderate, the difference in chromium concentrations is more substantial.

Arsenic and Nickel contamination

At Site 1, arsenic levels ranged from 7,762.01 to 9,289.75 mg/kg, averaging 8,118.95 ± 888.71 mg/kg, while Site 2 ranged from 5,337.61 to 8,057.12 mg/kg, averaging 6,769.46 ± 1,531.39 mg/kg. All values far exceeded the WHO limit of 20 mg/kg.

At Site 1, nickel levels ranged from 101.61 to 214.12 mg/kg, averaging 170.51 ± 51.40 mg/kg, while Site 2 ranged from 89.45 to 191.45 mg/kg, averaging 137.87 ± 55.01 mg/kg, all above the WHO limit of 50 mg/kg. The third ore samples at both sites showed lower concentrations. The t-test indicates no significant differences in arsenic ($p = 0.089$) or nickel ($p = 0.210$) levels. However, Cohen's d effect sizes indicate a large effect for arsenic ($d = 1.08$) and a moderate effect for nickel ($d = 0.61$), suggesting that while the difference in arsenic concentrations between sites is substantial, the difference in nickel concentrations is moderate.

Manganese* and *Iron contamination

At Site 1, manganese levels ranged from 637.16 to 858.57 mg/kg, averaging 738.71 ± 91.56 mg/kg, while Site 2 ranged from 493.86 to 731.11 mg/kg, averaging 633.73 ± 115.35 mg/kg. The t-test ($p = 0.102$) indicates no significant difference. However, Cohen's d effect size indicates a large effect for manganese ($d = 1.01$), suggesting a substantial difference between sites despite the lack of statistical significance.

At Site 1, iron levels ranged from 12,793.14 to 162,595.53 mg/kg, averaging 85,355.55 ± 83,277.04 mg/kg, while Site 2 ranged from 12,591.9 to 141,285.92 mg/kg, averaging 74,942.53 ± 71,662.27 mg/kg. Statistical analysis ($p = 0.428$) shows no significant difference between sites. Cohen's d effect size for iron ($d = 0.13$) suggests a small effect, indicating minimal variation in iron concentrations between the two sites.

3.2 Ore Characteristics for Sites 3 and 4 in Geita Region

Lead and Copper contamination

At Site 3, lead levels ranged from below the limit of detection (LOD) to 23 mg/kg, averaging 14.4 ± 10.66 mg/kg, all below Tanzania's 200 mg/kg and WHO's 100 mg/kg limits. Copper ranged from 198.4 to 236.9 mg/kg, averaging 218.28 ± 19.16 mg/kg, with 75% exceeding Tanzania's 200 mg/kg limit and all surpassing the WHO threshold.

At Site 4, lead levels ranged from 15 to 24.3 mg/kg, averaging 20.225 ± 4.29 mg/kg, all below regulatory limits. Copper ranged from 210.1 to 845.3 mg/kg, averaging 379.78 ± 310.63 mg/kg, exceeding both limits.

Samples 3OP2 and 4OP2 from open pit mines had lower concentrations. Lead and copper levels increased with mining depth, particularly higher in underground mining compared to open pit mining. The t-test shows no significant difference in lead ($p = 0.175$) or copper ($p = 0.170$) levels between groups. However, Cohen's d effect sizes indicate a moderate effect for both lead ($d = 0.72$) and copper ($d = 0.73$), confirming that Site 4 has higher lead and copper concentrations than Site 3.

Zinc and Chromium contamination

At Site 3, zinc levels ranged from 14.4 to 22.9 mg/kg, averaging 19.28 ± 4.01 mg/kg, and chromium ranged from below detection limit to 16.5 mg/kg, averaging 19.4 ± 7.75 mg/kg, both below Tanzania's 150 mg/kg and WHO's 300 mg/kg limits.

At Site 4, zinc levels ranged from 18.6 to 321.6 mg/kg, averaging 96.15 ± 150.31 mg/kg, with 25% exceeding Tanzania's and WHO's limits. Chromium ranged from below detection to 124.8 mg/kg, averaging 39.28 ± 6.73 mg/kg, with 25% surpassing WHO's limit.

Samples 3OP2 and 4OP2 had lower concentrations, and zinc and chromium levels increased with mining depth. The t-test shows no significant difference in zinc ($p = 0.173$) or chromium ($p = 0.1187$) concentrations. However, Cohen's d effect sizes indicate a moderate effect for zinc ($d = 0.72$) and a very large effect for chromium ($d = 2.74$), suggesting that while zinc differences between sites are moderate, the difference in chromium concentrations is highly substantial

Arsenic and Nickel contamination

At Site 3, arsenic levels ranged from 23.1 to 38.9 mg/kg, averaging 31.65 ± 7.85 mg/kg, exceeding Tanzania's 1 mg/kg and WHO's 20 mg/kg limits. Nickel ranged from below detection to 33.8 mg/kg, averaging 24.25 ± 16.23 mg/kg, all below regulatory limits.

At Site 4, arsenic ranged from 28.7 to 81.3 mg/kg, averaging 45.725 ± 24.35 mg/kg, surpassing both limits. Nickel ranged from 30.6 to 71.3 mg/kg, averaging 42.13 ± 19.53 mg/kg, with 75% below the WHO limit.

The t-test indicates no significant difference in arsenic (p = 0.178) or nickel (p = 0.104) concentrations between groups in Geita. However, Cohen’s d effect sizes indicate a moderate to large effect for arsenic (d = 0.78) and a large effect for nickel (d = 1.00), suggesting that while statistical significance is not observed, there is still a meaningful difference in concentration levels between sites.

Manganese and Iron contamination

At Site 3, manganese levels ranged from 578.3 to 710.9 mg/kg, averaging 648.57 ± 67.31 mg/kg, while Site 4 ranged from 637.9 to 2721.6 mg/kg, averaging 1178.65 ± 1029.19 mg/kg. The t-test shows no significant difference in manganese concentrations (p = 0.172). However, Cohen’s d effect size indicates a moderate effect for manganese (d = 0.73), suggesting a notable difference in concentration levels between sites.

At Site 3, iron levels ranged from 9,823 to 157,581 mg/kg, averaging 82,745 ± 419 mg/kg, while Site 4 ranged from 12,346 to 159,841 mg/kg, averaging 86,203 ± 84,403 mg/kg. The p-value of 0.077 suggests a slight variation in iron concentrations based on mining type and location. However, Cohen’s d effect size for iron (d = 0.06) suggests a very small effect, indicating minimal variation in iron concentrations between the two sites.

3.3 Tailings Characterization in Zamfara State and Geita Region

Table 3 present the summary results of characterization of lead and other heavy metal contamination in tailings for four villages in Zamfara State and Geita.

TABLE 3: Characterization of lead and other heavy metals contamination in tailings

	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg
	Pb	**As**	**Cu**	**Zn**	**Cr**	**Ni**
SITE 1 (1TL)	485119.6	24871.1	8814.2	745.66	182.43	797.75
SITE 2 (2TL)	298023.8	11686.52	4811.86	506.66	160.09	338.67
SITE 3 (3TL)	28.1	46.1	275.3	26.2	19.4	42.1
SITE 4 (4TL)	31.6	5794.1	1245.5	452.9	156.1	82.9

Table 3 shows that lead was the most toxic heavy metal in Zamfara's tailings, with a maximum concentration of 485,119.6 mg/kg, the highest among all analysed metals. Chromium had the lowest concentration at 160.09 mg/kg.

In Geita, copper had the highest concentration at 236.9 mg/kg, while chromium had the lowest. Several heavy metals exceeded WHO-permissible limits, posing potential environmental risks.

3.4 Site 1 and 2 Comparison of lead and other heavy metals contamination in ore and tailings

The average site 1 and 2 of heavy metal in ore and tailings are shown in Table 4 below.

TABLE 4 : Comparison Mean concentration of heavy metals in ore and tailing from sites 1 and 2

	Mean (mg/kg)						
Source	**Pb**	**As**	**Cu**	**Zn**	**Cr**	**Ni**	**Mn**
Ore from Site 1 & 2	15019.1	7444.2	2890.9	232	125.2	154.2	686.2
Tailings from Site 1 & 2	391571.7	18278.8	6813	626.2	171.3	568.2	1535.5

Table 4 shows that the mean concentration of lead in ore was 15,019.08 mg/kg, the highest among all heavy metals, while chromium had the lowest mean concentration at 125.2 mg/kg. The order of concentrations was Pb > As > Cu > Zn > Ni > Cr, with Pb, Cu, As, Cr, and Ni exceeding permissible levels.

In the tailings, the mean concentration of lead was 391,571.7 mg/kg, also the highest, while chromium had the lowest at 171.3 mg/kg. The order remained the same: Pb > As > Cu > Zn > Ni > Cr, with all values surpassing the WHO-prescribed permissible limits.

3.5 Site 3 and 4 Comparison of lead and other heavy metals contamination in ore and tailings

The average of heavy metal in ore and tailings are shown in Table 5 below

TABLE 5: Comparison Mean concentration of heavy metals in ore and tailing from sites 1 and 2

	Mean (mg/kg)						
Source	**Pb**	**As**	**Cu**	**Zn**	**Cr**	**Ni**	**Mn**
Ore from Site 3 & 4	17.31	38.69	299.03	57.71	25.31	33.19	913.61
Tailings from Site 3 & 4	29.85	228.75	760.4	239.55	54.7	62.5	2,795.7

Table 5 reveals that the mean concentration of copper in ore was 299.03 mg/kg, the highest among the heavy metals, while lead had the lowest at 17.31 mg/kg. The order of concentrations was Cu > Zn > As > Ni > Cr > Pb, with copper and arsenic surpassing the permissible limits set by Tanzania and the WHO.

In the tailings, the mean concentration of copper was 760.4 mg/kg, the highest, while lead remained the lowest at 29.85 mg/kg. The ranking mirrored that of the ore: Cu > Zn > As > Ni > Cr > Pb, with copper and arsenic exceeding the WHO's permissible limits.

3.5 Correlation relationship between lead and other heavy metals

The correlation relationship descriptions between lead and other heavy metals for site 1,2,3 and 4 are shown in Figure 1,2,3,4 and 5 below.

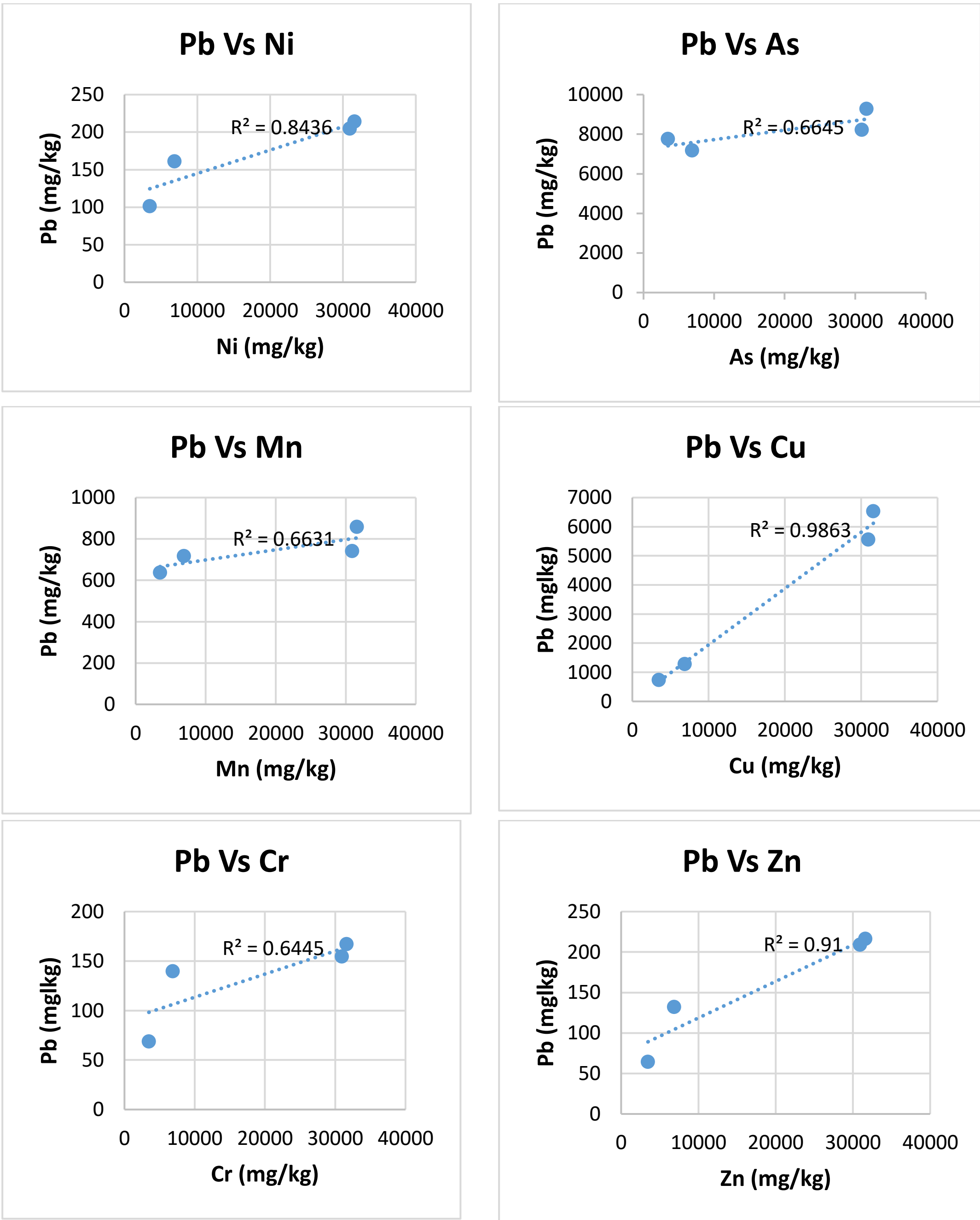


Figure 1: At Site 1, the correlation results suggest that lead has a strong association with copper (R^2 =0.9863), zinc (R^2 = 0.9100), and nickel (R^2 =0.8436), indicating co-occurrence in mineralized zones. In contrast, moderate correlations are observed with arsenic (R^2 =0.6645), chromium (R^2 =0.6445), and manganese (R^2 =0.6631), suggesting that while these elements are present in ore deposits, they may not be as directly linked to lead mineralization

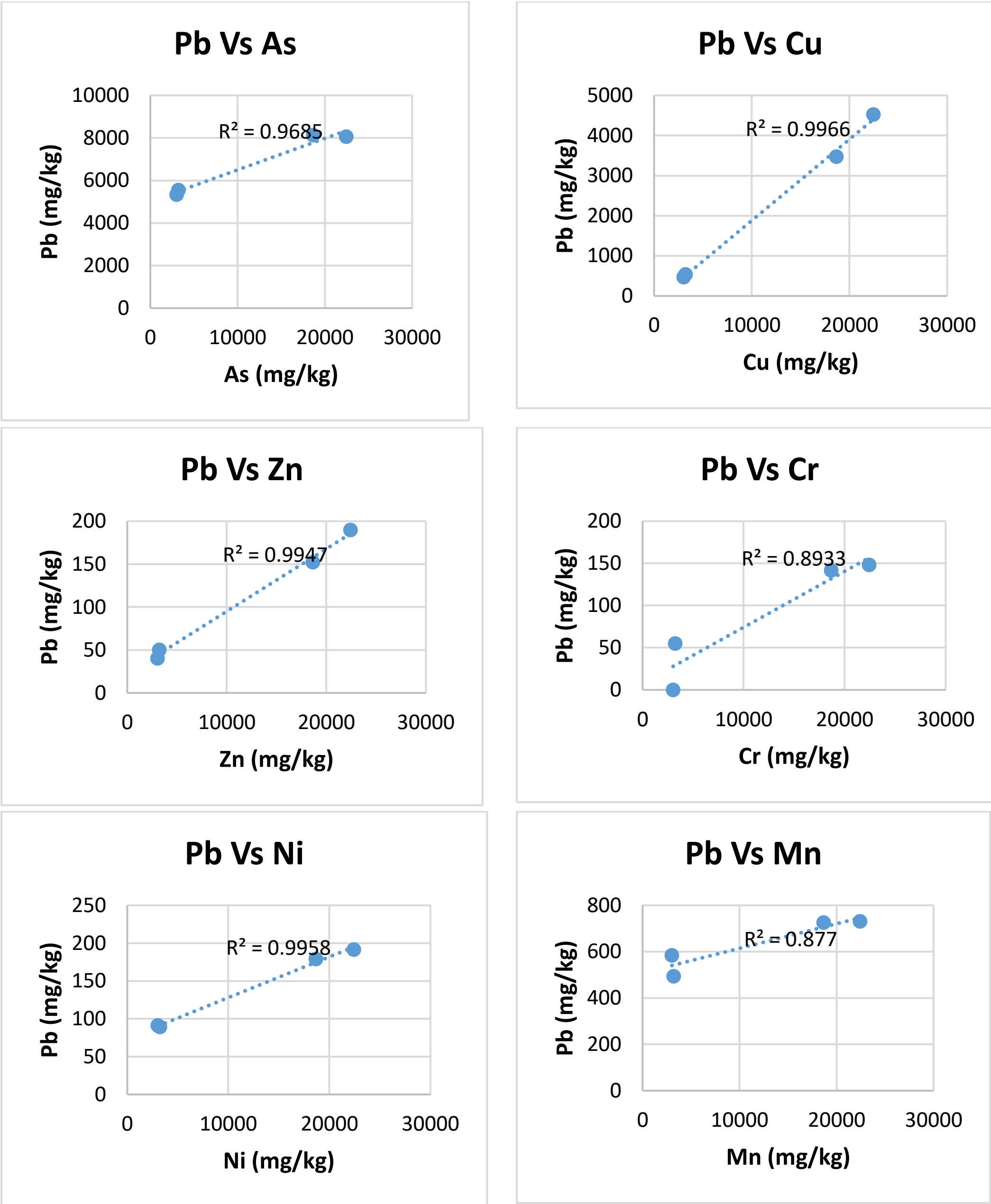


Figure 2: At Site 2, the correlation results for ores indicate that lead has an extremely high association with copper (R^2 = 0.9966), zinc (R^2 = 0.9947), nickel (R^2 = 0.9958), and arsenic (R^2 = 0.9685), suggesting that these metals frequently occur together in ore deposits. Lead also shows a strong correlation with chromium (R^2 = 0.8933) and manganese (R^2 = 0.877), although these associations are slightly lower compared to the other elements.

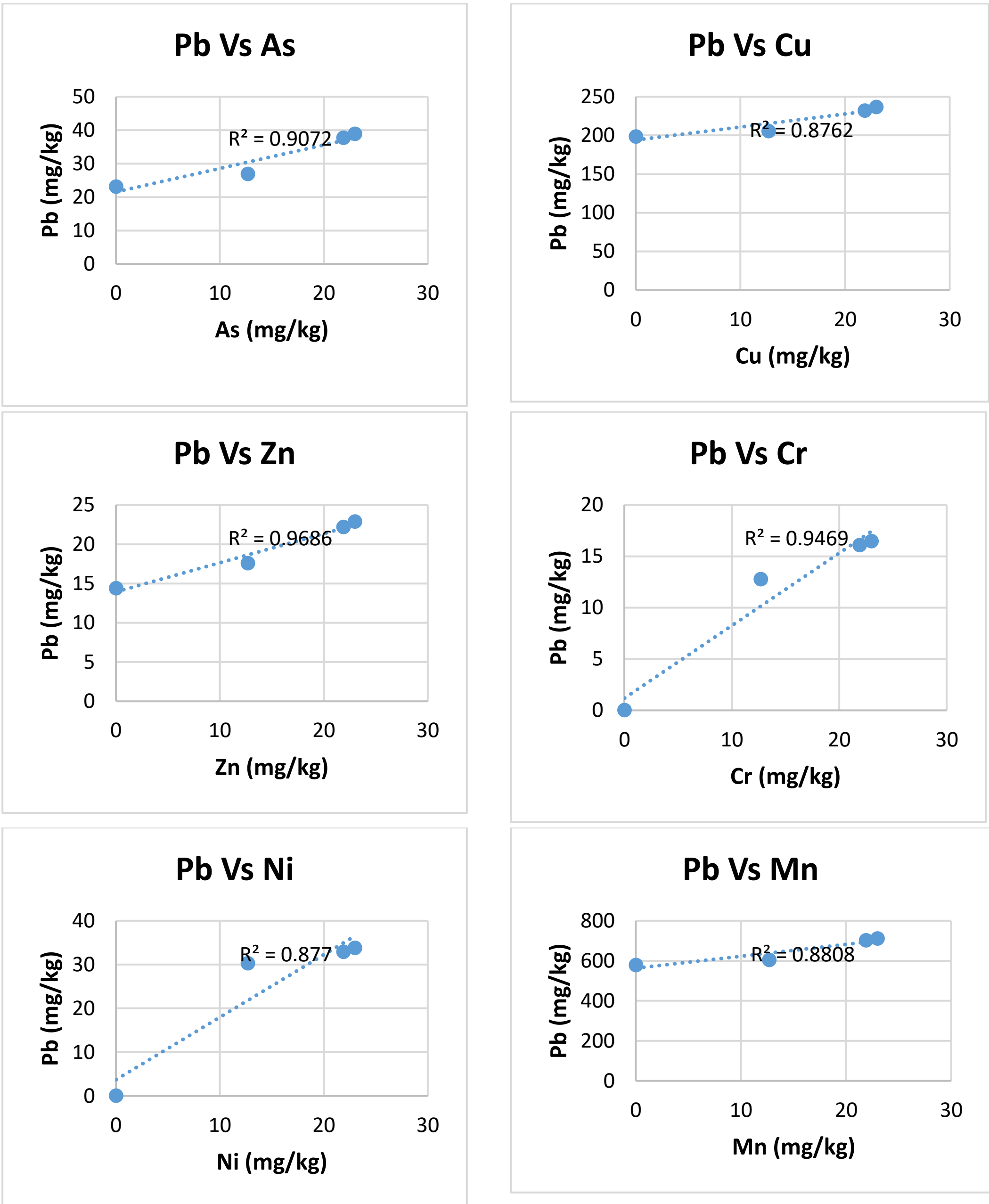


Figure 3: At Site 3, The correlation results for ores indicate that lead has a strong association with zinc (R^2 = 0.9686), chromium (R^2 = 0.9469), and arsenic (R^2 = 0.9072) suggesting a notable presence together in mineralized deposits. Lead also shows high correlation with copper (R^2 = 0.8762), nickel (R^2 = 0.877), and manganese (R^2 = 0.8808) implying a significant but slightly lower relationship with these metals.

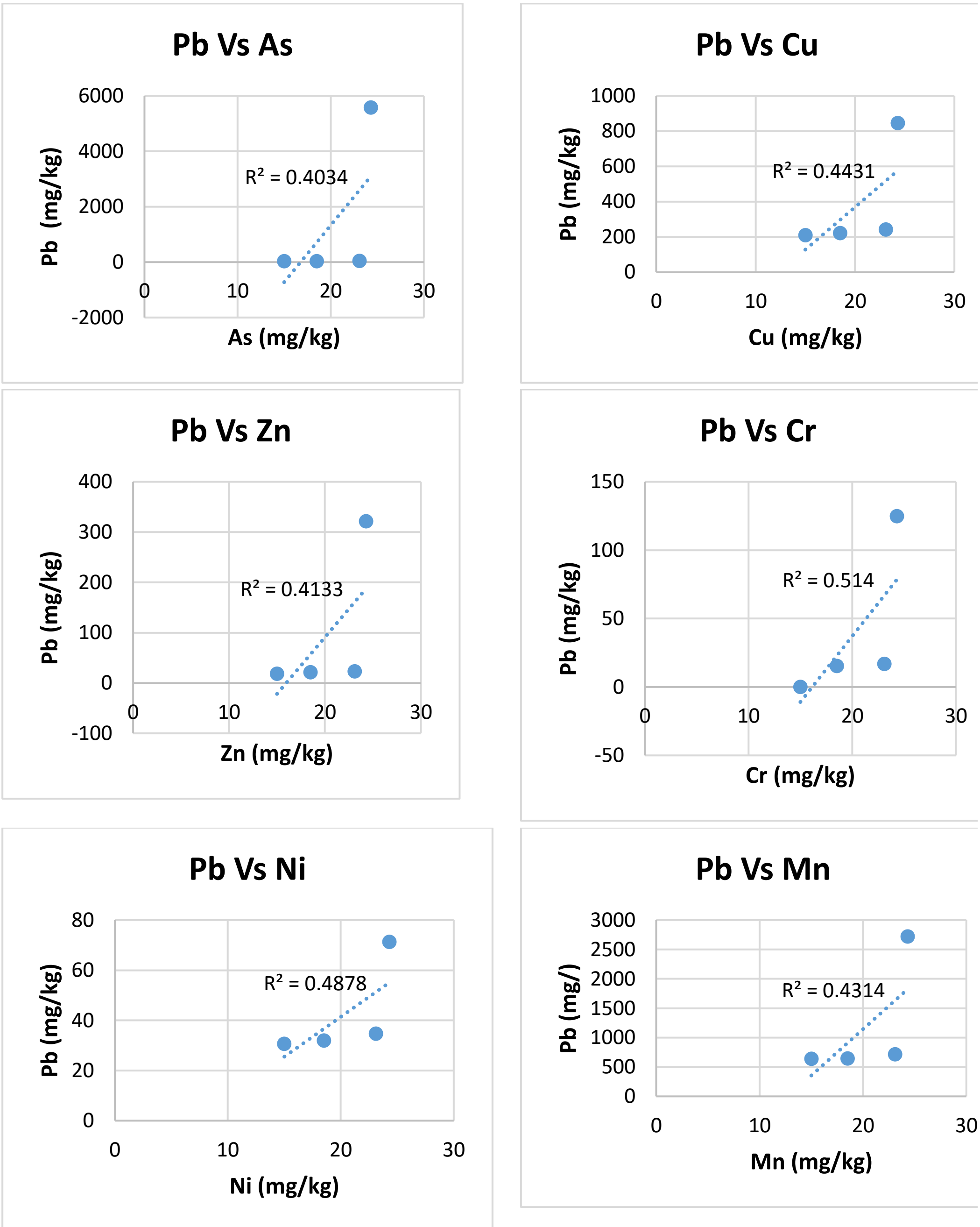
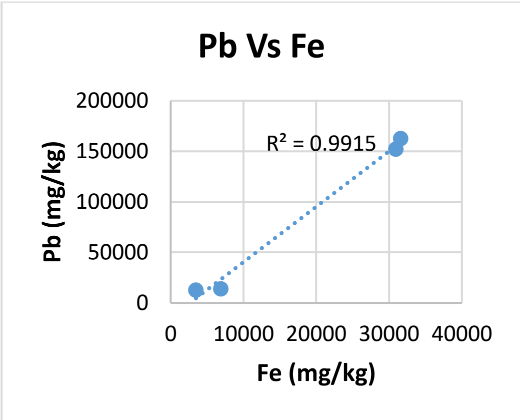
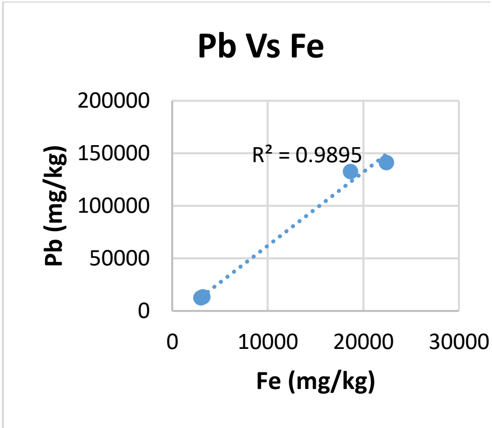


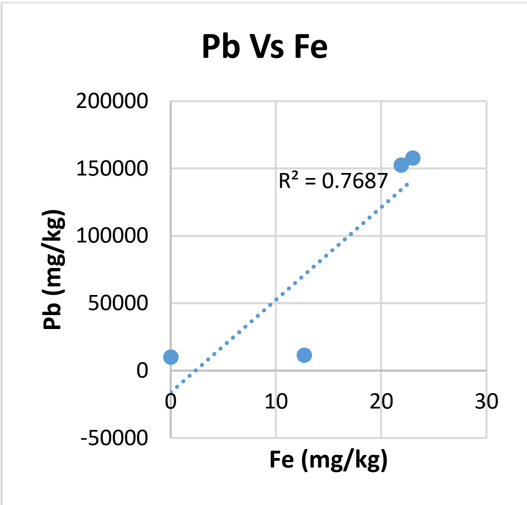
Figure 4: At Site 4, the correlation results for ores reveal that lead has a low relationship with other metals including arsenic (R^2 = 0.4034), copper (R^2 = 0.4431), zinc (R^2 = 0.4133), chromium (R^2 = 0.514), nickel (R^2 = 0.4878), and manganese (R^2 = 0.4314)



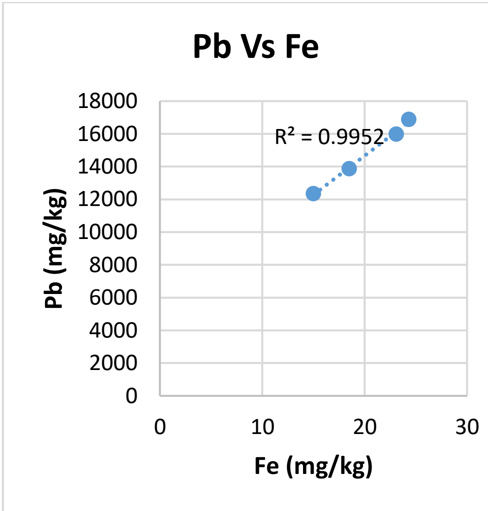
Site 1



Site 2



Site 3



Site 4

Figure 5: At Site 1, the correlation results indicate a strong association between lead and iron (R^2 = 0.9915), suggesting their co-occurrence in mineralized zones. At Site 2, the correlation is extremely high (R^2 = 0.9895), further implying that these metals frequently occur together in ore deposits. At Site 3, the correlation between lead and iron is moderate (R^2 = 0.7687), indicating a relatively weaker association. At Site 4, the correlation is very strong (R^2 = 0.9952), suggesting a close relationship between lead and iron in mineral deposits.,

This study has revealed that both ores and tailings in Zamfara State exhibited significantly higher levels of heavy metal concentrations compared to those found in the Geita region. In Zamfara, concentrations at Site 2 were lower than at Site 1, with the order of metal levels being 1TL > 2TL > 1UGI > 1UG2 > 2UG2 > 2UGI > 1OP2 > 1OP1 > 2OP2 > 2OP1. In the Geita region, metal concentrations at Site 3 were lower than at Site 4, following the order: 4TL > 3TL > 4UGI > 4UG2 > 3UGI > 3UG2 > 4OP1 > 4OP2 > 3OP1 > 3OP2. In both regions, metal concentrations in the ore were significantly lower than in the tailings, with open-pit mining showing lower concentrations than underground mining due to differences in mining depth and location.

Lead was the predominant heavy metal in Zamfara, ranking higher than others with the order: Pb > As > Cu > Zn > Ni > Cr. Conversely, in the Geita region, copper was the most predominant heavy metal, with the order: Cu > Zn > As > Ni > Cr > Pb.

This study extends Tirima et al. (2016) and Bartrem et al. (2014), which focused on health effects and lead remediation in Zamfara. While those studies focused on environmental health response and acute lead poisoning in children, our study expands the scope by providing a comparative geochemical analysis of heavy metal contamination in both ores and tailings across two countries Nigeria and Tanzania. By including multiple metals, evaluating depth-specific sampling, and incorporating statistical correlations, this study offers new insights into the spatial variability of contamination, the role of mining practices, and the environmental persistence of tailings. Unlike previous studies, which were often site-specific and health-focused, our findings contribute a broader environmental characterization and provide a basis for regional risk assessment and policy development in ASM-affected areas.

Previous research in Southwestern Nigeria indicated similar trends, with lead and zinc concentrations higher than other metals (Abiya et al., 2019). A separate study on gold and iron mine tailings also found lead levels ranked highest, consistent with Zamfara findings, where the order was Pb > Hg > Cd > Cr > Cu > Zn > Co > As for gold mining tailings, and Pb > Cd > Cr > Co > Cu > Zn > Hg > As for iron mining (Huang et al., 2012). In Tanzania's Singida region, a different order was observed, Mn > Zn > Cr > Cu > Pb > As > Cd, although some concentrations were within the acceptable limits set by the Tanzania Ministry of State (Vice President's Office; Union Affairs and

Environment), the levels of arsenic and chromium raised concerns (Mvile et al., 2023).

The high concentrations of heavy metals in tailings may result from the concentration methods used by miners to extract gold, leading to denser tailings with elevated metal levels. A study in Zamfara identified lead as the most abundant metal, with concentrations of 148.59 mg/kg in Kwali village, while nickel was the least at 1.25 mg/kg in Kadauri village (Barde et al., 2024). The general order of metals was Pb > Fe > Au > Al > Zn, with others following in an unspecified manner.

Research by Mgendi et al. (2020) at the Geita Gold Mine found that the highest total metal concentration in soil was 212.4 mg/kg for chromium, followed by 71.0 mg/kg for zinc, 66.2 mg/kg for copper, 61.2 mg/kg for lead, and 50.2 mg/kg for nickel. All heavy metal concentrations, except zinc, exceeded safe limits, indicating potential soil pollution and risks to local food quality.

Comparatively, our study indicated that heavy metal concentrations in Zamfara villages (Abare, Darata, and Bagega) were higher than those in neighbouring Osun State, where concentrations were Zn (0.70 mg/kg), As (0.09 mg/kg), Cd (0.13 mg/kg), Pb (0.216 mg/kg), Ni (0.08 mg/kg), Cr (0.148 mg/kg), and Cu (0.629 mg/kg) (Abiya et al., 2019). Additionally, another study in Zamfara (Barde et al., 2014) reported lower concentrations than our findings. In contrast, Geita region concentrations were higher than Abiya et al. (2019) but lower than Barde et al. (2014), likely due to variations in ore concentrations across mining sites.

Our research indicates that heavy metals increase with mining depth and may be influenced by geological and geochemical factors, such as mineralization, hydrothermal processes, and weathering. A study by Xing et al. (2022) shows that deeper mining soils contained higher metal concentrations due to enhanced mineralization.

ASM activities in Zamfara State and Geita regions have substantial environmental impacts, particularly in relation to breaches of protection and environmental management. Usman et al. (2023) noted that soil contamination with metals like lead and zinc significantly affects water and aquatic ecosystems. Heavy metals can infiltrate groundwater, polluting water sources. Moreover, rainfall can transport heavy metals from soil into aquatic environments, disrupting ecosystems and food chains, affecting both plants and animals (Li et al., 2022). The comparison of mean heavy metal concentrations between Zamfara and Geita was assessed using a t-test, with statistical significance determined at a 95% confidence level. The p-values obtained were 0.276 for ore samples and 0.131 for tailing samples, indicating no statistically significant difference between the two regions, as both values exceed the conventional significance threshold of 0.05.

The correlation results from the four sites reveal varying geochemical associations between lead and other metals, likely influenced by differences in mineralization processes, ore genesis, and local geology. Site 2 shows the strongest correlations, particularly between lead and copper, zinc, nickel, and arsenic, indicating a polymetallic sulfide deposit, with minerals like galena, chalcopyrite, sphalerite, and pentlandite formed in hydrothermal environments. Site 1 also displays strong correlations, especially between lead and iron, and copper, suggesting the presence of iron sulfides and copper-bearing minerals. Moderate correlations with arsenic and chromium point to variations in mineral paragenesis or secondary alteration. Site 3 exhibits similar patterns but with lower correlation values, indicating possible post-depositional alterations. Site 4 has the weakest correlations, particularly with arsenic, copper, zinc, and nickel, suggesting these metals occur in separate phases or are less abundant. These differences reflect how local geology shapes mineral formation and resource availability.

Lead exposure poses significant health risks, especially in mining communities. A study of Jusko et al., (2008) indicates that lead can severely damage various bodily systems, particularly in children, leading to developmental issues, impaired cognitive function, and potentially fatal consequences at elevated blood lead levels. Overall, the findings underscore the urgent need for soil characterization and potential environmental remediation as well as public health measures in affected mining communities.

The study compares artisanal mining regulations in Nigeria and Tanzania, emphasizing differences in legal frameworks, enforcement, and governance. Tanzania’s 2010 Mining Act supports formalization and technical assistance, while Nigeria’s 2007 Act centralizes authority, hindering enforcement (Jacob, 2016; MMSD, 2016). Tanzania’s decentralized governance fosters compliance, unlike Nigeria’s institutional fragmentation (Odukoya, 2019; Ogwueleka, 2020). Lower licensing fees in Tanzania ease formalization, while higher costs in Nigeria create barriers (Jacob, 2016; Odukoya, 2019). Tanzania promotes community participation in land management, in contrast to Nigeria's centralized model that often causes conflict (URT, 1999; MMSD, 2016). Monitoring and gender inclusion are stronger in Tanzania through village committees (Kinyondo & Mkwizu, 2018; Tanzania Mining Policy, 2022).

The elevated concentrations of lead and arsenic, especially in tailings from Zamfara, demonstrate an urgent need for policy reforms focused on hazardous waste control in artisanal mining zones. These results can guide national environmental authorities to enforce stricter regulations on tailings management, including the creation of formalized disposal zones and mandated site monitoring. At the community level, public health departments should use these data to justify blood lead testing campaigns and environmental health outreach in high-risk areas. The cross-regional comparison between Zamfara and Geita also underscores the need for a harmonized policy framework across countries, integrating geochemical monitoring with sustainable mining education programs.

This study confirms lead as the main contaminant in Zamfara, with tailing concentrations reaching up to 485,119.6 mg/kg significantly higher than previous findings. For instance, Bartrem et al. (2014) reported soil lead levels up to 185,000 mg/kg, while Tirima et al. (2016) focused on residential exposure and health outcomes. The elevated lead levels observed in tailings suggest they have become a more persistent contamination source, likely due to intensified ore processing. According to USEPA soil screening levels, concentrations above 400 mg/kg require remediation. The levels recorded in Zamfara exceed this threshold by over 1,200 times, highlighting an urgent need for containment, community-wide blood lead testing, and environmental monitoring. Tailings-specific strategies including designated disposal zones, safer processing practices, and public health education are essential to mitigate exposure risks and prevent future crises.

4. LIMITATIONS

A key limitation of this study is the small sample size, with data collected only from operational mines in a limited number of villages. This focus on active mining sites may not fully capture contamination levels across different mining stages or less active areas. Additionally, potential contamination during sample collection and handling could have influenced results, despite precautions taken during transport and storage.

Future research should address these limitations by expanding the sample size and including a broader range of mining stages and locations, including inactive sites, to improve statistical power and provide a more comprehensive understanding of contamination levels.

5. CONCLUSIONS

In conclusion, this study highlights significant heavy metal contamination in both ores and tailings from small-scale mining in Zamfara State and the Geita Region, with lead being the predominant contaminant in Zamfara State and copper in the Geita Region. Heavy metal concentrations were notably higher in tailings than in ores. These elevated metal levels, exacerbated by mining depth and extraction methods, pose serious environmental and health risks, particularly from lead exposure. The findings emphasize the urgent need for effective environmental management to protect local communities and ecosystems from long-term contamination and health impacts. To mitigate these risks, targeted health interventions are essential. Authorities should implement community-wide blood lead screenings, increase access to healthcare for early detection, and conduct awareness campaigns focused on vulnerable populations such as children and pregnant women.

On the environmental management front, stricter controls on mining waste, regular soil monitoring, and designated containment zones for tailings should be enforced. Improved processing techniques and site remediation programs will also help minimize contamination.

From a policy and governance perspective, collaboration between governments, public health agencies, and mining stakeholders is critical. Regulatory frameworks must promote sustainable ASM practices, lower the barriers to formalization, and include training programs that educate miners about occupational and environmental hazards.

Overall, these efforts will help reduce the environmental footprint of small-scale mining and safeguard public health. This study provides essential evidence to support regionally tailored interventions and policies that can lead to safer, more sustainable mining practices in Sub-Saharan Africa.

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Declaration of Competing Interest

The authors confirm that they have no known financial or personal conflicts of interest that could have influenced the work presented in this paper.

Data availability statement

All data has been provided

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