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Heavy Metal Contamination Assessment in Soils and Surface Waters around an Abandoned Mine Site in Jiko Village, North-Central Nigeria

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Abstract

Six soil and eight water samples were collected from the abandoned mine site at Jiko village, near Minna Metropolis, Northcentral Nigeria, to determine the concentrations and contamination status of selected heavy metals (Pb, Zn, Cu, Ni, Cr, Fe, Mn, As, and Cd). The study evaluates contamination levels using established geochemical indices and assesses associated environmental implications. Mean concentrations in soils are Pb (77.09 ppm), Zn (68.82 ppm), Cu (44.08 ppm), Ni (78.23 ppm), Cr (183.84 ppm), Fe (41,466.34 ppm), Mn (525.69 ppm), and As (0.071 ppm), with the order of abundance: Fe > Mn > Cr > Ni > Pb > Zn > Cu > As. In water, mean concentrations are Pb (0.78 ppm), Zn (0.55 ppm), Cu (0.25 ppm), Ni (0.53 ppm), Cr and Cd (below detection limit), Fe (19.61 ppm), Mn (3.53 ppm), and As (0.060 ppm), following the order: Fe > Mn > Pb > Zn > Ni > Cu > As. The concentrations of Pb, Zn, Cu, Ni, Cr, and Fe in soils exceed average crustal abundance values, indicating enrichment relative to natural background levels. In water samples, Pb, Ni, Mn, Fe, and As exceed the permissible limits set by the Nigerian Standard for Drinking Water Quality (NSDWQ) and World Health Organization guidelines, indicating deterioration of water quality. Contamination indices reveal varying degrees of metal enrichment. The geo-accumulation index (I_{geo}) indicates that all analysed metals, except As, fall within the extremely contaminated category. The contamination factor (CF) shows considerable contamination for Pb, Cu, Ni, and Cr, moderate contamination for Zn, Fe, and Mn, and low contamination for As. Similarly, the enrichment factor (EF) indicates moderate enrichment for Pb, Cu, Ni, and Cr, while other metals fall within deficiency to minimal enrichment. These results demonstrate that mining activities have modified the geochemical baseline of the study area. Although Pb appears to be predominantly geogenic, its enrichment suggests additional contributions from artisanal mining activities. Field observations further indicate significant ecological degradation, including loss of farmland and vegetation, proliferation of open mining pits, and contamination of surface waters. The elevated concentrations of heavy metals, particularly Pb, Ni, Mn, Fe, and As in water, highlight potential environmental and public health risks. This study provides baseline data on contamination around the abandoned Jiko mine site and demonstrates that abandoned mine environments remain active sources of pollution long after mining activities have ceased. Continuous environmental monitoring and appropriate remediation strategies are therefore required to mitigate long-term ecological and public health impacts.

Keywords

Heavy Metals, Abandoned Mine Site, Soil and Water Contamination, Artisanal and Small-Scale Mining (ASM), North-Central Nigeria

1. Introduction

Artisanal and small-scale mining (ASM) is a globally widespread extractive activity that provides livelihoods for an estimated 40 million people across more than 80 countries (World Bank, 2019). In sub-Saharan Africa, ASM has expanded rapidly due to persistent poverty, unemployment, and rising commodity prices. Gold remains the most exploited mineral within the mining sector because of its high economic value and accessibility (Owusu-Prempeh et al., 2022). Although ASM contributes significantly to rural income generation and national mineral output, its predominantly informal and poorly regulated nature has resulted in severe environmental degradation and public health issues.

Nigeria historically relied on mining as a major contributor to national revenue prior to the discovery of petroleum in the Niger Delta in the 1950s and 1960s (Chete et al., 2014). The subsequent oil boom relegated this important mining sector for decades, leading to weak institutional oversight and abandonment of numerous mine sites across the country. With recent fluctuations in global oil prices and gradual shifts to renewable energy technologies, renewed governmental interest in economic diversification has revived attention toward mineral resource development (Azubuike et al., 2023). However, the long period of neglect facilitated the proliferation of informal ASM activities and left many legacy and abandoned mine sites without environmental remediation and reclamation.

Mining and mineral processing operations, including excavation, crushing, grinding, concentration, and tailings disposal, generate substantial quantities of mine wastes enriched in potentially toxic elements (PTEs) such as Pb, Cd, As, Hg, Cu, Zn, and Ni (Schoenberger, 2016). These elements can be mobilized through surface runoff, leaching, wind erosion, and acid mine drainage, resulting in contamination of soils, sediments, and water bodies. Once released, heavy metals exhibit persistence, non-biodegradability, and bioaccumulation behaviour, posing long-term ecological and human health risks (e.g., Briffa et al., 2020).

Several studies in West Africa have documented elevated heavy metal concentrations in soils and surface waters surrounding ASM sites. For example, Owusu-Prempeh et al. (2022) reported severe ecological risks associated with Hg and Cd contamination in mine spoils within the Atewa Forest landscape, Ghana, using geoaccumulation index (I_{geo}) and potential ecological risk index (PERI). Similarly, Okonkwo et al. (2021) demonstrated significant contamination factors (CF), enrichment factors (EF), and pollution load index (PLI) values in soils around pegmatite mining sites in southwestern Nigeria. Surface water contamination and associated human health risks have also been documented in Nigerian gold mining districts (Odukoya et al., 2017). These studies underscore the critical need for systematic contamination assessment and ecological risk evaluation, particularly in environments where mining operations have ceased without structured closure or decommissioning plans.

Mine closure represents the final phase of the mining life cycle and ideally involves decommissioning, rehabilitation, reclamation, and long-term monitoring (Nehring & Cheng, 2016). In many developing countries, however, abandoned mine sites remain unmanaged, with tailings and waste rock dumps left exposed. These materials frequently contain elevated concentrations of arsenic (As), cadmium (Cd), lead (Pb), copper (Cu), and zinc (Zn), which can migrate into surrounding soils and water systems (Esshaimi et al., 2012). Abandoned sites may present even greater environmental hazards than active operations due to the absence of containment measures and environmental monitoring. Contaminants from tailings can be redistributed through clastic movement, surface runoff, and groundwater flow, leading to progressive contamination of agricultural lands and domestic water sources. Persistent exposure to contaminated media may result in ecological toxicity and increased risk of heavy metal bioaccumulation within food chains and its transfer to man.

The environmental consequences of unregulated ASM in Nigeria have manifested in severe public health crises. The widely reported lead poisoning outbreak in Zamfara State (Nigeria) in 2010 resulted in the deaths of over 400 children under the age of five (Plumlee et al., 2013). A similar outbreak occurred in Niger State (Nigeria) in 2015, further highlighting the vulnerability of mining communities to heavy metal exposure (Gottesfeld et al., 2019). These incidents demonstrate the urgent necessity of proactive contamination assessment, particularly in regions with known mineralization and abandoned mining infrastructure. Northern Nigeria has a fair share of high poverty rates, youth unemployment, and limited formal education opportunities, conditions that encourage continued informal mining activities (e.g., Oramah et al., 2015). While ASM contributes to local livelihoods and may support certain Sustainable Development Goals (SDGs), it simultaneously undermines SDG targets related to clean water, ecosystem protection, and good health and well-being (Abdelaal et al., 2023).

Despite documented contamination in several Nigerian mining districts, there is limited empirical data on the contamination status and ecological risk levels associated with abandoned mine sites in Jiko village, near Minna City, Niger State. Given the historical lead contamination incidents reported within the state (e.g., Gottesfeld et al., 2019), evaluating soil and water quality around abandoned mining infrastructure is both environmentally and socially imperative. A comprehensive assessment integrating heavy metal concentration analysis with ecological risk indices, such as contamination factor (CF), geoaccumulation index (I_{geo}), pollution load index (PLI), and potential ecological risk index (PERI), provides a quantitative basis for evaluating environmental quality and potential toxicological threats. Such assessment also contributes to the growing body of ASM contamination literature in sub-Saharan Africa and supports evidence-based decision-making for environmental management and public health protection.

This study therefore aims to determine the concentrations of selected heavy metals (Pb, Zn, Cu, Ni, Cr, Fe, Mn, As, Cd) in soils and surface water around the abandoned Jiko mine site with a view to: 1) evaluating the degree of contamination using established contamination indices, and 2) discussing the implications of contamination for environmental sustainability and potential human health exposure pathways. By providing baseline data on contamination status in Jiko village, this study contributes to environmental risk assessment efforts in Nigeria and supports policy formulation for sustainable management and remediation of abandoned mine sites.

2. Materials and Methods

2.1. The Study Area

The study area, Jiko village, is located in the north-central region of Nigeria within Munya Local Government Area (LGA) of Niger State. Geographically, it falls within the Minna Sheet 164 and is situated approximately 70 km northwest of Minna, the state capital, and close to the Niger-Kaduna State boundary. Nigeria's Federal Capital Territory (Abuja) lies approximately 200 km to the southeast of the study area. The village is bounded by latitudes 9˚39'25.6"N and 9˚42'26.2"N, and longitudes 6˚48'12.2"E and 6˚49'23.0"E (**Figure 1**). Access to the area is primarily through a minor untarred road and interconnected footpaths linked to the major Minna-Mutum Daya Road corridor.

Jiko village lies within the Guinea Savanna ecological zone of Nigeria, characterized by a tropical wet-dry climate with two distinct seasons (Animashaun et al., 2023). The wet season typically extends from April to October, with peak rainfall occurring in September, while the dry season spans from November to March. The early rains commence in April, marking the onset of hydrological recharge in surface and subsurface systems (Animashaun et al., 2020). The wet season is associated with high relative humidity and moderate temperatures generally below 30˚C, whereas the dry season is characterized by low humidity, elevated evapotranspiration rates, and temperatures that may exceed 35˚C, particularly during the Harmattan period (Animashaun et al., 2023). The area falls within the North-Central Hydrological Area (NCHA) basin, whose topographic configuration significantly influences runoff patterns, groundwater recharge, and sediment transport dynamics. The regional geomorphology includes gently undulating terrain with low-lying plains associated with the River Niger basin (Oguntunde et al., 2011). Such topographic features play a critical role in controlling the redistribution and accumulation of mining-derived contaminants, particularly during intense rainfall events when erosion and surface runoff facilitate the lateral transport of metal-enriched particulates. Land use within the study area is predominantly agricultural, with subsistence farming and fishing as major livelihood activities. Artisanal mining operations, both active and abandoned, are also prevalent. The close interaction between mining sites, agricultural land, and water bodies increases the vulnerability of environmental media to heavy metal contamination and potential exposure pathways.

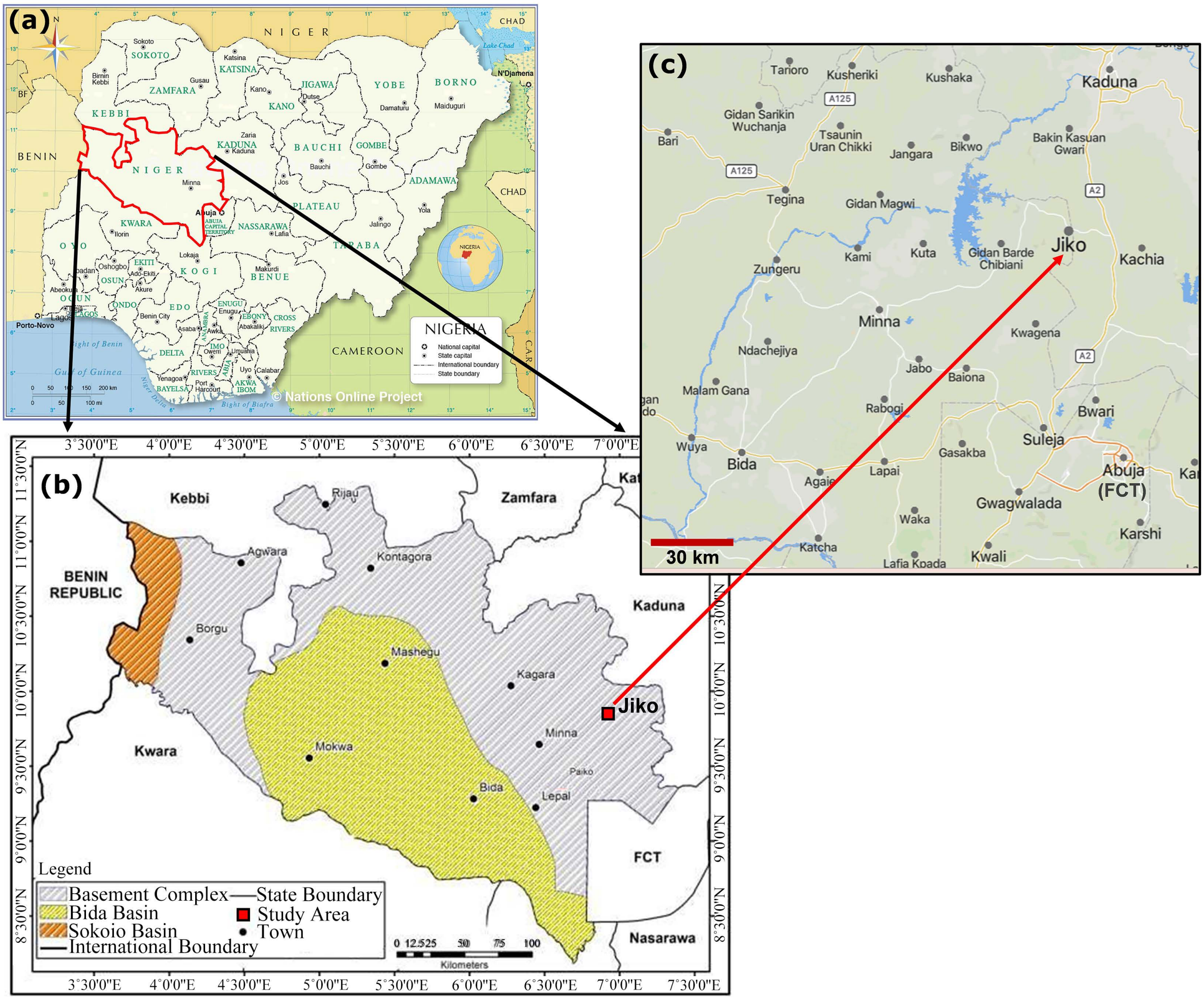

Figure 1. Location map of Jiko Village in Munya LGA, Niger State, Nigeria: (a) Administrative map of Nigeria (adapted from Nations Online Project, https://www.nationsonline.org/oneworld/map/nigeria-administrative-map.htm); (b) Geological map of Niger State showing the study area (modified after Ahmed et al., 2020); and (c) Map showing Jiko Village (adapted from Mapcarta, https://mapcarta.com/33243376).

The study area is underlain predominantly by Precambrian Basement Complex rocks comprising granites, gneisses, and schists (**Figure 1(b)**). These lithological units form part of the Nigerian Basement Complex terrain, which is known to host structurally controlled mineralization, including auriferous quartz veins. Field observations indicate the presence of mineralized veins and weathered bedrock exposures that likely contributed to secondary enrichment processes. Mechanical weathering and fluvial reworking of auriferous veins have resulted in the downstream accumulation of alluvial gold deposits (e.g., Batchelor & Bowden, 1985; Arndt & Ganino, 2011). The geogenic background composition of granitic and schistose rocks may naturally contain trace concentrations of elements such as As, Pb, Cu, Zn, and Cd (e.g., Soltani-Gerdefaramarzi et al., 2021). However, artisanal mining activities, including excavation, ore crushing, washing, and sediment reworking modulated by the ambient environmental conditions such as pH and oxidation-reduction conditions, can enhance the mobilization and concentration of these potentially toxic elements in surrounding soils and surface waters. Numerous open mining pits observed along river channels and floodplains during field investigations confirm the occurrence of alluvial gold mining within the area.

2.2. Soil and Water Sampling, Collection and Analytical Procedures

Field investigations were conducted at Jiko village between 15 April and 10 June 2019 (at the onset of wet season) to characterize the abandoned mine site and its surrounding environments. Reconnaissance activities included geological mapping, identification of lithological units, assessment of mine-related disturbances (e.g., tailings piles, excavation pits, stream channel modifications), and systematic collection of soil and surface water samples for geochemical analysis.

Soil samples were collected using a grid-controlled sampling design to ensure spatial representativeness across the study area. Sampling points were established at regular intervals using a grid spacing of 50 metres, where the terrain allows, covering mined locations. At each grid node, composite soil samples were collected from the topsoil horizon (0 - 25 cm depth) using a stainless-steel hand auger to minimize contamination. *In-situ* characteristics, including colour, texture, moisture condition, and proximity to mining features, were recorded. The geographic coordinates of all sampling locations were determined using a handheld Global Positioning System (GPS) device and are presented in **Table 1**.

Table 1. Details of water and soil samples collected from Jiko and analysed in this work.

Sample Number	Latitude [Northings]	Longitude [Eastings]	Sample Description
WS1	09˚40'12.0"	006˚49'04.0"	Water
WS2	09˚39'33.4"	006˚48'17.4"	Water
WS3	09˚40'10.8"	006˚49'04.0"	Water
WS4	09˚42'26.2"	006˚49'23.0"	Water

Continued

WS5	09˚39'25.6"	006˚48'24.0"	Water
WS6	09˚39'28.8"	006˚48'29.7"	Water
WS7	09˚39'56.0"	006˚49'01.6"	Water
WS8	09˚40'42.3"	006˚48'29.9"	Water
S1	09˚39'56.0"	06˚49'01.6"	Soil
S2	09˚42'26.2"	006˚49'23.0"	Soil
S3	09˚42'26.6"	006˚49'23.0"	Soil
S4	09˚40'12.2"	006˚49'05.8"	Soil
S5	09˚39'55.0"	006˚49'04.5"	Soil
S6	09˚39'56.0"	006˚49'01.6"	Soil

Surface water, including open pit water, samples were collected from streams draining the mining area as well as from water sources (shallow wells) within the village used for domestic purposes. Sampling locations were selected based on hydrological flow direction, proximity to mine pits, and potential human exposure pathways. Water samples were collected in pre-cleaned polyethylene bottles following standard environmental sampling protocols. All samples were transported to the National Geosciences Research Laboratories (NGRL) of the Nigeria Geological Survey Agency (NGSA), Kaduna, Nigeria, for chemical analysis. Heavy metal concentrations were determined using Atomic Absorption Spectrometry (AAS) technique. Detailed sample preparation procedures for soil and water samples are described in the subsequent sections (§Section 2.2.1 for soil, and §Section 2.2.2 for water).

2.2.1. Soil Sample Preparation and AAS Analysis

The analytical procedure adopted for soil geochemical analysis follows established protocols reported in similar environmental geochemistry studies (e.g., Akande et al., 2014). Approximately 1000 g of each soil sample was air-dried at ambient laboratory temperature to constant weight to facilitate disaggregation. Dried samples were gently pulverized using an agate mortar and pestle to avoid metallic contamination. The pulverized material was sieved through a 171 μm (−80 mesh) nylon sieve. Nylon sieves were preferred over metallic sieves to prevent introduction of extraneous trace metals.

The fraction passing through the sieve was subjected to partial acid digestion using aqua regia extraction. For each sample, 5.0 g of the homogenized soil was weighed into a 50 mL acid-washed glass beaker (pre-treated with 20% HNO_3). Ten millilitres (10 mL) of freshly prepared aqua regia (HCl: HNO_3, 3:1 v/v) were added to the sample. Aqua regia digestion (i.e., partial digestion) was selected to extract environmentally available and anthropogenically associated metal fractions while avoiding complete silicate lattice dissolution associated with HF digestion (i.e., complete digestion). The mixture was heated on a sand bath within a fume cupboard at approximately 95˚C for one hour. Care was taken to prevent complete evaporation by periodically adding small volumes of deionized water when necessary.

After digestion, the solution was allowed to cool, diluted with deionized water, and filtered through Whatman No. 42 filter paper into a 25 mL volumetric flask. The filtrate was made up to volume with deionized water to obtain a dilution factor of 50. Aliquots of the resulting solutions were transferred into acid-washed polyethylene bottles for instrumental analysis. Heavy metal concentrations (Cu, Zn, Pb, Ni, Fe, Mn, Cr, and As) were determined using a Thermo Scientific Atomic Absorption Spectrophotometer equipped with element-specific hollow cathode lamps. Calibration curves were prepared using certified standard solutions for each analyte. Analytical conditions, including appropriate wavelength selection, flame type (air-acetylene), and burner height, were optimized according to manufacturer specifications to ensure analytical accuracy. Analytical data quality was ensured through using the NGRL's internal standards.

2.2.2. Water Sample Preparation and AAS Analysis

Water samples were delivered to the NGRL, Kaduna, within 24 hours of collection and preserved in ice-chilled containers during transport to minimise physicochemical alterations (i.e., chemical or biological reactions) prior to geochemical analysis (Ukah et al., 2019). Upon arrival at the laboratory, samples were filtered through 0.45 µm membrane syringe filters to remove suspended particulates. To preserve dissolved metal species and prevent adsorption onto container walls, concentrated nitric acid (HNO_3) was added immediately after sampling in the field to reduce the pH to <2, in accordance with standard preservation protocols. The samples were subsequently filtered at the NGRL after submission for chemical analysis.

Samples were subjected to mild acid digestion at the NGRL by heating to near boiling (approximately 90˚C - 95˚C) for 30 minutes to oxidise organic matter and release bound metal ions. After cooling, the digested solutions were quantitatively transferred into volumetric flasks and diluted to a known volume with deionised water to ensure that concentrations fell within the instrument's linear calibration range. The AAS instrument was calibrated using multi-element standard solutions prepared from certified reference materials, and blank solutions alongside calibration standards were analysed intermittently to verify instrument stability and analytical precision. The prepared samples were then aspirated into the spectrometer, and metal concentrations (Cu, Zn, Pb, Ni, Fe, Mn, Cr, As, and Cd) were determined based on absorbance measurements at element-specific wavelengths. Analytical data quality was ensured through the inclusion of procedural blanks. The method detection limit for all analysed elements was 0.0001 ppm, and concentrations below this limit were reported as "not detected" (ND). Non-detect values were excluded from statistical analyses (e.g., mean calculations) to minimise bias in the dataset.

3. Results of Geochemical Analyses of Soils and Surface Waters

3.1. Results of Geochemical Analysis of Soils

The results of the geochemical analysis of the soil samples are presented in Table 2. The concentrations of lead (Pb) range from 35.55 to 112.96 ppm, with a mean value of 77.09 ppm. Zinc (Zn), copper (Cu), nickel (Ni), and chromium (Cr) exhibit concentration ranges of 14.87 - 119.70 ppm, 5.42 - 105.39 ppm, 38.61 - 111.57 ppm, and 9.24 - 262.21 ppm, respectively. The corresponding mean concentrations are 68.82 ppm (Zn), 44.08 ppm (Cu), 78.23 ppm (Ni), and 183.84 ppm (Cr). Iron (Fe) is the most abundant element in the analyzed soil samples, with concentrations ranging from 8556.16 to 70442.65 ppm, equivalent to approximately 0.86 - 7.04 wt.%, and a mean concentration of 41466.34 ppm (~4.15 wt%). Manganese (Mn) concentrations vary between 165.73 and 896.20 ppm, with a mean value of 525.69 ppm, whereas arsenic (As) exhibits relatively low concentrations ranging from 0.034 to 0.218 ppm, with a mean value of 0.071 ppm.

Table 2. Summary of chemical analyses of the analysed soil samples at the abandoned Jiko mine sites. All concentrations are reported in ppm.

S/N	Pb	Zn	Cu	Ni	Cr	Fe	Mn	As
1	112.96	14.87	5.42	64.39	168.54	8556.16	333.53	0.0390
2	88.45	72.93	28.87	82.14	9.24	47208.59	165.73	0.0480
3	35.55	44.73	16.14	38.61	196.98	62119.98	277.36	0.0340
4	92.51	119.7	105.39	96.16	255.71	70442.65	896.20	0.2180
5	72.13	76.42	77.64	111.57	262.21	46127.69	710.50	0.0380
6	60.95	84.27	31.01	76.52	210.33	14342.94	770.79	0.0507
Mean	77.09	68.82	44.08	78.23	183.84	41466.34	525.69	0.0710
Range	35.55 - 112.96	14.87 - 119.70	5.42 - 105.39	38.61 - 111.57	9.24 - 262.21	8556.16 - 70442.65	165.73 - 896.20	0.0340 - 0.2180
Std dev	27.07	35.76	38.89	25.35	92.63	25058.57	303.21	0.0722
CV (%)	35.11	51.95	88.23	32.40	50.39	60.43	57.68	101.22

CV = (Std dev/Mean) * 100, a coefficient of variation (CV) which is a measure of variability. Cd was not analysed for soil samples due to analytical constraints and not reported here.

The variability in metal concentrations across the sampling locations suggests spatial heterogeneity in geochemical distribution, which may be attributed to lithological variations as well as localized anthropogenic inputs associated with artisanal mining activities. To further evaluate the degree of spatial variability, the coefficient of variation (CV), defined as the ratio of the standard deviation to the mean concentration, was individually calculated for the analyzed elements. The

CV provides an indication of the dispersion of elemental concentrations and potential enrichment processes within the study area. Arsenic (As) exhibits the highest coefficient of variation (101.22%), indicating strong spatial variability and possible localized enrichment. Copper (Cu) also shows high variability with a CV of 88.23%, whereas nickel (Ni) displays the lowest variability with a CV of 32.40% (**Table 2**). In general, higher CV values may reflect heterogeneous contamination sources or geochemical mobilization processes within the soils.

Metal Contamination Assessment

To evaluate the degree of metal contamination in the soils of the study area, three widely applied geochemical indices were employed: Contamination Factor (CF), Enrichment Factor (EF), and Geo-accumulation Index (I_{geo}). These indices are commonly used in environmental geochemistry to assess the magnitude of anthropogenic metal enrichment relative to natural background concentrations (e.g., Okonkwo et al., 2021; Owusu-Prempeh et al., 2022).

1) Contamination Factor (CF)

The contamination factor (CF) is widely used to evaluate the degree of metal contamination in soils by comparing measured metal concentrations with their corresponding geochemical background values. This index provides an indication of the extent to which anthropogenic activities may have contributed to metal accumulation in the environment.

The contamination factor is calculated using the following equation (Cabrera et al., 1999):

$$\mathrm{CF} = \frac{C_{m(\text{sample})}}{C_{m(\text{background})}} \tag{1}$$

where:

$C_{m(\text{sample})}$ represents the concentration of a given metal in the soil sample, and

$C_{m(\text{background})}$ represents the background concentration of the corresponding metal.

Based on CF values, soils can be classified into different contamination categories ranging from low contamination to very high contamination, as summarized in **Table 3**. The calculated CF values for the analyzed elements in the study area and their corresponding interpretations are presented in **Table 4**.

Table 3. Classification and interpretation of contamination factor values in soils (Cabrera et al., 1999).

Contamination Factor (CF)	Contamination Level
CF < 1	Low contamination
1 ≤ CF < 3	Moderate contamination
3 ≤ CF < 6	Considerate contamination
CF ≥ 6	Very high contamination

Table 4. Summary of chemical analyses of the analysed soil samples at Jiko Village with their enrichment factors.

S/N	Element	Mean concentration in ppm (C_n)	+ACA in ppm (Wedepohl, 1995) = (B_n)	Contamination Factor (CF)	Interpretation (Cabrera et al., 1999)
1	**Pb**	77.09	17	4.53	**Considerate contamination**
2	**Zn**	68.82	52	1.32	Moderate contamination
3	**Cu**	44.08	14.3	3.08	**Considerate contamination**
4	**Ni**	78.23	18.6	4.21	**Considerate contamination**
5	**Cr**	183.84	35	5.25	**Considerate contamination**
6	**Fe**	41466.34	30890	1.34	Moderate contamination
7	**Mn**	525.69	527	1.00	Moderate contamination
8	**As**	0.071	2	0.04	Low contamination

$^+$ACA = Average crustal abundance; element concentrations (in ppm) in the Upper Continental Crust (UC)-Wedepohl (1995).

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

The geo-accumulation index (I_{geo}) is another widely applied index used to assess the degree of metal enrichment in soils relative to pre-industrial or natural background levels. This index was originally proposed by Müller (1969) for evaluating sediment contamination but has since been widely applied in soil contamination studies (e.g., Okonkwo et al., 2021; Owusu-Prempeh et al., 2022).

The geo-accumulation index is calculated using the following expression:

$$I_{geo} = \log_2\left(\frac{C_n}{1.5 \times B_n}\right) \tag{2}$$

where:

C_n represents the measured concentration of the element in the soil sample, and

B_n represents the geochemical background concentration of the element.

The constant factor 1.5 is incorporated to account for possible natural variations in background metal concentrations due to lithogenic influences.

According to Müller (1969), the I_{geo} scale classifies soils into seven contamination categories, ranging from unpolluted ($I_{geo} \le 0$) to extremely polluted ($I_{geo} > 5$). The classification scheme used in this study is summarized in **Table 5**. The computed I_{geo} values for the analyzed soil samples, along with their contamination classifications, are presented in **Table 6**.

Table 5. Classification of index of geo-accumulation (I_{geo}) values in soils (Müller, 1969).

I_{geo} Value	Class	Soil quality
$I_{geo} < 0$	0	Unpolluted
$0 < I_{geo} < 1$	1	Unpolluted to moderately polluted
$1 < I_{geo} < 2$	2	Moderately polluted
$2 < I_{geo} < 3$	3	Moderately to strongly polluted
$3 < I_{geo} < 4$	4	Strongly polluted
$4 < I_{geo} < 5$	5	Strongly to extremely polluted
$I_{geo} > 5$	6	Extremely polluted

Table 6. Classification and interpretation of index of geo-accumulation (I_{geo}) values in the studied soils at Jiko Village.

Element	I_{geo}	Interpretation (Müller, 1969)
Pb	9.77	Extremely polluted
Zn	11.22	Extremely polluted
Cu	8.72	Extremely polluted
Ni	9.92	Extremely polluted
Cr	12.07	Extremely polluted
Fe	29.67	Extremely polluted
Mn	17.49	Extremely polluted
As	−3.40	Unpolluted

3) Enrichment Factor (EF)

The enrichment factor (EF) is a widely used geochemical index for assessing the degree of anthropogenic influence on metal concentrations in environmental media by normalizing measured concentrations against a conservative reference element. It provides a means of distinguishing between metals derived from natural lithogenic sources and those introduced through anthropogenic activities (Feng et al., 2004; Soltani-Gerdefaramarzi et al., 2021).

The EF was calculated using the following expression (Sinex & Helz, 1981):

$$\text{EF} = \frac{(\text{Me}/\text{Fe})_{\text{sample}}}{(\text{Me}/\text{Fe})_{\text{background}}} \tag{3}$$

where $(\text{Me}/\text{Fe})_{\text{sample}}$ represents the ratio of the concentration of the target metal (Me) to iron (Fe) in the soil sample, and $(\text{Me}/\text{Fe})_{\text{background}}$ represents the corresponding ratio in the geochemical background. The background values adopted in this study are based on average crustal abundances reported by Wedepohl (1995), as presented in **Table 4**.

Iron (Fe) was selected as the reference element for normalization because of its predominantly lithogenic origin, relatively high natural abundance, and generally low susceptibility to anthropogenic enrichment under typical environmental conditions (Tippie, 1984; Reimann et al., 2005). In addition, Fe is commonly used in environmental geochemistry as a conservative element due to its strong association with crustal materials and its role as a major component of soil-forming minerals. Other conservative elements such as Al, Sc, Ti, and Li are also frequently used as normalizing elements because they are considered relatively immobile and largely unaffected by anthropogenic inputs (Lu et al., 2010). However, these elements were not analysed in the present study, and Fe therefore provides a suitable alternative for normalization.

The EF values are commonly interpreted using classification schemes that reflect the degree of enrichment relative to natural background levels. According to Mmolawa et al. (2011), EF values can be categorized into classes ranging from minimal enrichment (EF < 2) to extremely high enrichment (EF > 40), with intermediate categories indicating moderate to significant anthropogenic influence. The classification scheme adopted in this study is presented in **Table 7**. The calculated EF values for the analysed soil samples are presented in **Table 8** and are used to evaluate the extent of anthropogenic contribution to metal concentrations in the study area. Heavy metals such as Pb (EF = 3.38), Cr (EF = 3.91), Cu (EF = 2.30), and Ni (EF = 3.13) fall within the enrichment factor range of 2 ≤ EF < 5, indicating moderate enrichment and implying a measurable anthropogenic contribution to their accumulation in the soils.

Table 7. Classification and interpretation of contamination factor values in soils (Mmolawa et al., 2011).

Enrichment Factor (EF)	Enrichment factor (EF) Categories
EF < 2	Deficiency to minimal enrichment
2 ≤ EF < 5	Moderate enrichment
5 ≤ EF < 20	Significant enrichment
20 ≤ EF < 40	Very high enrichment
EF ≥ 40	Extremely high enrichment

Table 8. Classification and interpretation of enrichment factor (EF) values in the studied soils at Jiko Village.

Element	Enrichment Factor (EF)	Interpretation
Pb	3.38	**Moderate enrichment**
Zn	0.99	Deficiency to minimal enrichment
Cu	2.30	**Moderate enrichment**
Ni	3.13	**Moderate enrichment**
Cr	3.91	**Moderate enrichment**
Fe*	1.00	Deficiency to minimal enrichment
Mn	0.74	Deficiency to minimal enrichment
As	0.03	Deficiency to minimal enrichment

Iron (Fe*) being the selected reference element for normalization (see the texts for details).

3.2. Results of Geochemical Analysis of Water Samples

The results of the geochemical analysis of the water samples are presented in **Table 9**. Lead (Pb) concentrations range from 0.147 to 1.6257 ppm, with a mean concentration of 0.78 ppm. Cadmium (Cd) and chromium (Cr) were not detected in any of the analysed water samples, as their concentrations were below the analytical detection limit of 0.0001 ppm. Zinc (Zn), copper (Cu), nickel (Ni), and manganese (Mn) exhibit concentration ranges of 0.0246 - 0.9085 ppm, 0.014 - 0.560 ppm, 0.2933 - 0.7930 ppm, and 1.4306 - 6.5215 ppm, respectively. The corresponding mean concentrations are 0.55 ppm (Zn), 0.25 ppm (Cu), 0.53 ppm (Ni), and 3.53 ppm (Mn). Iron (Fe), similar to the pattern observed in the soil samples, is the most abundant metal in the analysed water samples. Its concentrations vary widely from 1.3138 to 56.4244 ppm, with a mean value of 19.61 ppm. Arsenic (As) concentrations range from 0.004 to 0.309 ppm, with a mean concentration of 0.060 ppm. The relatively low concentrations of As in the water samples are consistent with the generally low levels observed in the analysed soil samples.

Table 9. Results of the chemical analysis for the analyzed water samples (concentration of all elements is in mg/l) and basic statistics.

Sample ID	Pb	Zn	Cu	Ni	Mn	Cr	Fe	As
PSTW2	0.1470	0.6630	0.3500	0.2933	1.4306	ND	ND	0.0080
MMB	0.9802	0.7232	0.0140	0.6357	ND	ND	ND	0.0040
STWL1	0.5384	0.9085	0.4062	0.5683	2.6379	ND	8.9737	0.0060
GDK2	0.9270	0.0246	0.0858	0.7930	ND	ND	22.4120	0.0600
JSTW1	0.6238	0.5743	ND	0.2983	ND	ND	8.9115	0.0370
JVS	0.2045	0.7843	0.0544	0.3739	ND	ND	1.3138	0.0040
WLS1	1.1653	0.1236	0.2484	0.5483	6.5215	ND	56.4244	0.3090
PSTW1	1.6257	0.6197	0.5600	0.7336	ND	ND	ND	0.0540
Mean	0.7765	0.5527	0.2455	0.5306	3.5300	-	19.6071	0.0603
Min	0.1470	0.0246	0.0140	0.2933	1.4306	-	1.3138	0.0040
Max	1.6257	0.9085	0.5600	0.7930	6.5215	-	56.4244	0.3090

ND = Not detected. Concentrations of Cr & Cd are below the detection limit (<0.0001 ppm); Cd is not shown here.

To evaluate the potential implications of these concentrations for water quality, the mean concentrations of the analysed heavy metals were compared with established drinking water standards, including the Nigerian Standard for Drinking Water Quality (NSDWQ, 2015) and the World Health Organization Guidelines for Drinking-water Quality (WHO, 2011). As shown in **Table 10** and **Figure 2**, the concentrations of Pb, Ni, Mn, Fe, and As exceed the permissible limits recommended by both national and international regulatory guidelines.

Table 10. Comparison of the mean concentrations (all in mg/l) of heavy metals in analyzed water samples with Nigerian Standard for Drinking Water Quality (2007) and World Health Organization Guidelines for Drinking-Water Quality (2011), both in mg/l.

Element	Measured Element Conc. (ppm)	Permissible Concentration (NSDWQ, 2007)	Permissible Guideline (WHO, 2011)	Remarks
Pb	0.776	0.010	0.010	**Above permissible limit**
Zn	0.553	3.000	4.000	Below permissible limit
Cu	0.246	1.000	2.000	Below permissible limit
Ni	0.531	0.020	0.070	**Above permissible limit**
Mn	3.530	0.200	0.100	**Above permissible limit**
Fe	19.607	0.300	0.300	**Above permissible limit**
As	0.060	0.010	0.010	**Above permissible limit**

Measured Element Conc. refers to the mean metal concentration reported in this study. Concentrations of Cr and Cd are below the detection limit (<0.0001 ppm), and both are not shown here.

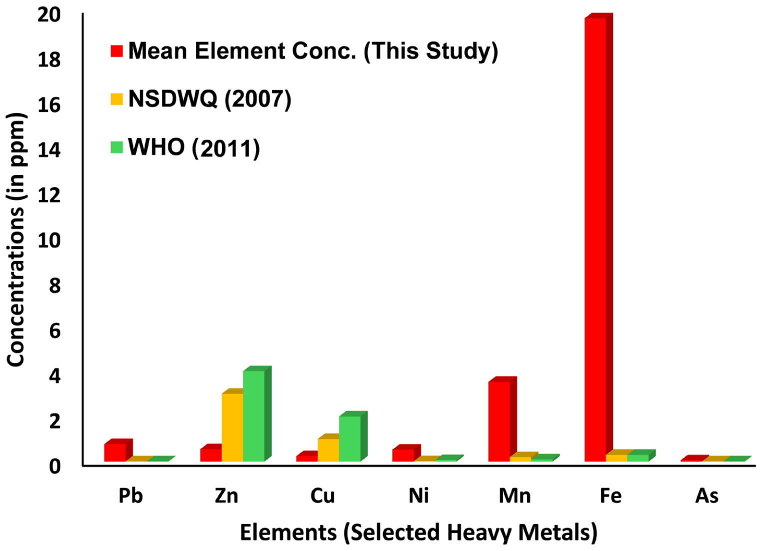

Figure 2. Pictorial 3D comparison of the mean concentrations of heavy metals in analyzed water samples with national (NSDWQ, 2007) and global (WHO, 2011) standards. Concentrations of Cr and Cd are below the detection limit (<0.0001 ppm), and they are not shown.

To further illustrate the spatial variability of metal concentrations in the study area, concentration distribution maps were generated for the analysed heavy metals. These maps provide a visual representation of the spatial distribution and relative enrichment of metals within the water samples. Figure 3 presents an example of a geochemical map showing the spatial distribution of Pb concentrations across the sampled water locations.

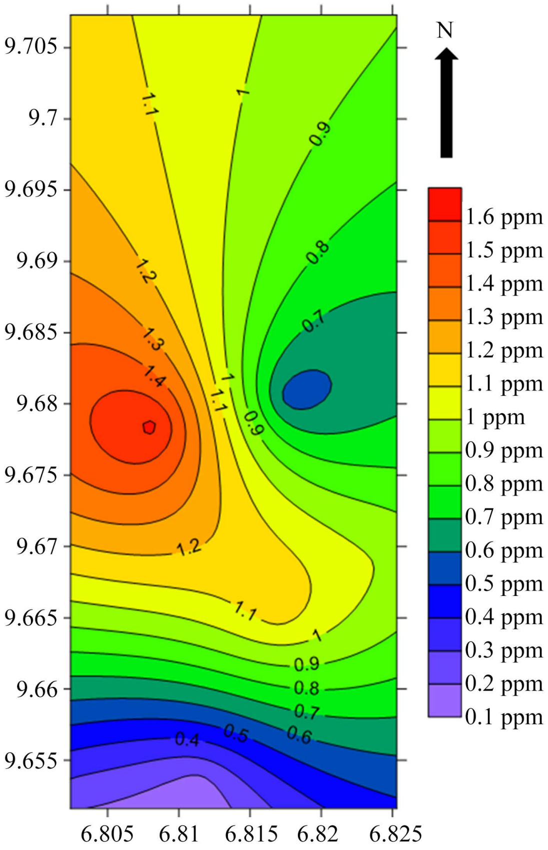

Figure 3. Concentration map showing spatial distribution of lead concentration in water samples from Jiko Village, a localised geochemical anomaly of the element to the western side of the area.

4. Discussion of Results

4.1. Heavy Metal Distribution and Sources in Soils

The concentrations of heavy metals in soils surrounding the abandoned Jiko mine site indicate varying degrees of geochemical enrichment that may reflect both lithogenic contributions from the underlying basement complex rocks and anthropogenic inputs associated with historical mining activities. Iron (Fe), which occurs at concentrations ranging between approximately 0.86 and 7.04 wt% (mean ≈ 4.15 wt%), represents the dominant element in the analysed soils. Such elevated Fe levels are typical of soils derived from weathered granitic and schistose basement rocks containing Fe-bearing minerals such as biotite, magnetite, and amphiboles (Reimann et al., 2005; Alloway, 2013). Consequently, the abundance of Fe in the study area is most likely controlled by the natural lithological composition of the host rocks.

In contrast, the elevated concentrations of Pb, Zn, Cu, Ni, and Cr observed in the soils may be linked to the disturbance and redistribution of mineralised materials during artisanal mining activities. Lead concentrations reaching up to 112.96 ppm and Zn concentrations up to 119.70 ppm are consistent with enrichment patterns typically observed in mining environments where sulphide mineralization and ore-processing residues contribute to localized metal accumulation (Li et al., 2022). Similar enrichment patterns have been reported in soils around pegmatite mining sites in southwestern Nigeria and in artisanal mining landscapes in West Africa, where excavation, crushing, and reworking of ore materials resulted in increased concentrations of trace metals in surface soils (Okonkwo et al., 2021; Owusu-Prempeh et al., 2022).

The relatively high coefficients of variation observed for several metals further indicate spatial heterogeneity in soil contamination. High CV values, particularly for arsenic (As) and copper (Cu), suggest that metal distribution is influenced by localized contamination sources such as mine pits, spoil heaps, and tailings deposits rather than uniform geogenic processes. Spatially heterogeneous contamination patterns are characteristic of abandoned mine environments where metals are redistributed through runoff, sediment transport, and mechanical disturbance of mine wastes (Macklin et al., 2003; Li et al., 2022). The contamination factor (CF), enrichment factor (EF), and geo-accumulation index (I_{geo}) values computed for the soil samples provide further insight into the degree of anthropogenic influence on the geochemical composition of the soils. These indices are widely applied in environmental geochemistry for assessing metal enrichment relative to background concentrations and identifying potential anthropogenic inputs (Müller, 1969; Okonkwo et al., 2021). Elevated CF and I_{geo} values for several metals (e.g., Pb, Zn, Cu, Ni, Cr, and Fe) suggest that mining-related activities have modified the natural geochemical baseline of the area. However, it is important to note that the interpretation of contamination indices in this study may be influenced by the use of average crustal abundance as background values (e.g., Wedepohl, 1995). In crystalline basement terrains, natural lithological variability can result in elevated geogenic concentrations of certain elements, which may lead to an overestimation of contamination levels when compared to global averages. As such, the contamination classifications derived in this study should be considered indicative rather than absolute, and are supported by complementary mineralogical and geochemical evidence presented in a follow-up study by Rasheed et al. (2026, in press).

The enrichment factor (EF) results indicate that Pb (EF = 3.38), Cr (EF = 3.91), Cu (EF = 2.30), and Ni (EF = 3.13) exhibit moderate enrichment, whereas the remaining analysed heavy metals fall within the category of low enrichment (i.e., deficiency to minimal enrichment). According to Zhang and Liu (2002) and Mmolawa et al. (2011), EF values within the range of $0.5 < EF < 1.5$ suggest that metal concentrations are predominantly controlled by natural weathering processes. In contrast, EF values greater than 1.5 indicate that a significant proportion of the metals may be derived from non-crustal sources, reflecting anthropogenic inputs such as mining activities, point and non-point pollution, or biological processes. The coefficient of variation (CV) provides complementary information on the spatial variability and potential sources of the analysed metals. High CV values are generally associated with heterogeneous distribution patterns and are often indicative of anthropogenic inputs, whereas lower CV values typically reflect more uniform, lithogenically controlled distributions (Han et al., 2005; Okonkwo et al., 2021). In this study, arsenic (As), despite exhibiting the lowest EF value (0.03), shows a very high CV (101.22%), followed by Cu (88.23%), indicating strong spatial variability and suggesting localized anthropogenic influences. In contrast, Pb (CV = 35.11%) and Cr (CV = 50.39%), which exhibit moderate enrichment based on EF, display comparatively lower variability.

The interpretation of CV values in conjunction with EF provides important insights into contamination sources. Previous studies have suggested that CV values exceeding 90% may indicate dominance of anthropogenic contributions (Oyebamiji et al., 2018). Accordingly, the high CV values for As and Cu suggest that their distribution may be influenced by localized mining-related activities, despite the low EF value observed for As. This apparent discrepancy highlights the importance of integrating multiple indices in environmental geochemical assessments. For Pb, the relatively low CV value suggests a more uniform spatial distribution that may be partly controlled by natural geochemical processes. However, its moderate enrichment (EF), together with its contamination factor (CF) and geo-accumulation index (I_{geo}) classifications, indicates that anthropogenic contributions, most likely related to mining activities, also play a significant role in its accumulation. Similarly, Cr exhibits moderate enrichment but moderate variability, suggesting a mixed lithogenic-anthropogenic origin.

Overall, the combined interpretation of EF, CV, CF, and I_{geo} indicates that while As is generally low in concentration and shows minimal enrichment, its high spatial variability points to localized anthropogenic inputs, possibly associated with mining and ore-processing activities. In contrast, Pb emerges as a key contaminant of concern, exhibiting moderate enrichment and elevated contamination indices, thereby reflecting a significant influence of mining-related processes. Comparable contamination patterns have been reported in abandoned mining environments worldwide. For instance, soils surrounding the Imcheon Au-Ag mine in Korea show elevated concentrations of Cd, Cu, Pb, and Zn associated with mine tailings and waste materials, which are subsequently dispersed into surrounding soils and water systems through runoff and sediment transport processes. These findings reinforce the interpretation that legacy mining activities can continue to influence soil geochemistry and environmental quality long after mining operations have ceased.

4.2. Heavy Metal Contamination of Surface Waters

The geochemical composition of the analysed water samples indicates that several metals occur at concentrations exceeding internationally accepted drinking-water standards. In particular, Pb, Ni, Mn, Fe, and As concentrations in several samples exceed the permissible limits recommended by the Nigerian Standard for Drinking Water Quality (NSDWQ, 2015) and the World Health Organization guidelines (WHO, 2017).

The elevated Pb concentrations recorded in the water samples are of particular concern due to the high toxicity of this metal even at relatively low concentrations. Lead contamination in mining environments commonly results from the weathering of Pb-bearing minerals, dissolution of mine wastes, and leaching of tailings materials exposed to atmospheric conditions (Macklin et al., 2003; Li et al., 2022). The elevated Pb concentrations observed at Jiko village may therefore be attributed to the interaction between mine waste materials and surface water systems during rainfall and runoff events. Localised geochemical anomaly of Pb for water samples at Jiko is as shown in **Figure 3**. Nickel and manganese concentrations exceeding permissible limits also indicate potential geochemical mobilisation of metals from mineralized rocks and mine wastes. Specifically, manganese is often associated with redox-sensitive geochemical processes and may be released into surface waters through dissolution of Mn oxides under reducing conditions or through weathering of Mn-bearing minerals (Reimann et al., 2005). The latter interpretation is also supported by the enrichment factor value for Mn in the analyzed water samples which is less than 1.5 (0.74), indicating that its contribution could be primarily from weathering process (Zhang & Liu, 2002; Mmolawa et al., 2011).

The elevated iron concentrations in the analysed water samples further support the interpretation that weathering and oxidation of iron-bearing minerals in mine wastes and host rocks contribute to metal mobilisation in the study area. Iron is known to influence the mobility of other trace metals because Fe oxides and hydroxides act as important scavengers for heavy metals in aquatic systems (Alloway, 2013). Similar contamination patterns have been reported in gold mining districts in southwestern Nigeria, where elevated concentrations of Pb, Fe, and Mn were detected in surface waters near mining activities (Odukoya et al., 2017). Studies in other mining regions around the world have also demonstrated that drainage from abandoned mine tailings can significantly increase metal concentrations in nearby streams and rivers (Jung, 2001; Macklin et al., 2003).

The spatial distribution maps generated for the water samples (e.g., see **Figure 4** for As and Fe geochemical distributions) reveal localized areas of higher metal concentrations, particularly near mining pits and downstream drainage channels. The geochemical anomalies are generally located towards the southern part of Jiko for both iron and arsenic (**Figure 4**), but to the western side of the study area for Pb (**Figure 3**). This spatial pattern indicates that surface runoff and sediment transport likely play important roles in redistributing metals from the abandoned mine site into surrounding water systems.

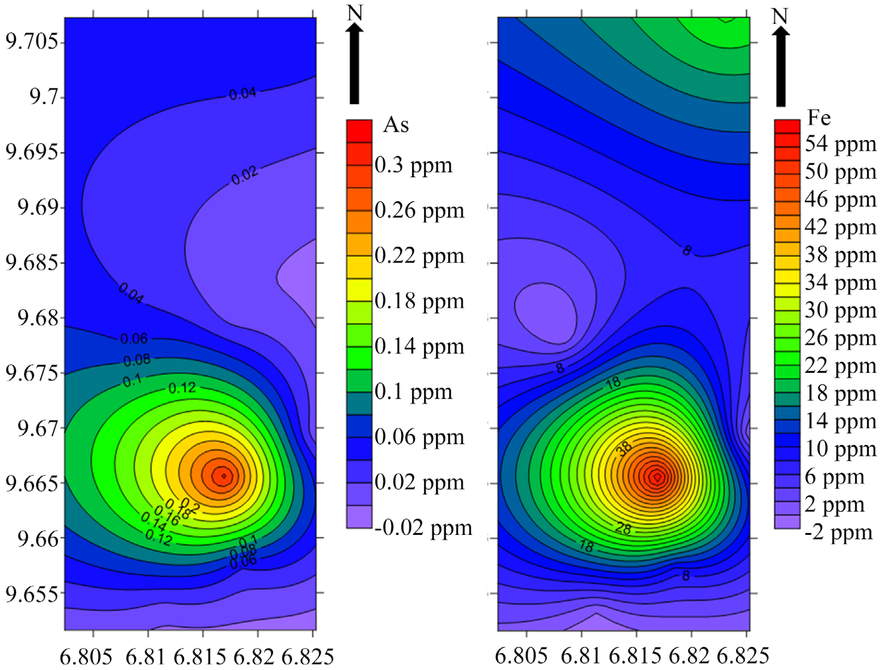

Figure 4. Concentration maps of arsenic (As) and iron (Fe) in water samples from Jiko village showing localised geochemical anomalies of the respective elements. The anomaly to the southern part follows the direction of stream/river flow.

4.3. Environmental Implications

The presence of elevated heavy metal concentrations in both soils and surface waters within the study area has important environmental implications. Heavy metals are persistent environmental contaminants that do not degrade naturally and may accumulate in soils, sediments, and biological tissues over long periods (Alloway, 2013; Tóth et al., 2016). Consequently, contamination originating from abandoned mine sites may continue to pose environmental risks long after mining activities have ceased.

In agricultural environments such as Jiko village, contaminated soils may lead to the uptake of heavy metals by crops, thereby introducing metals into the human food chain. Lead, copper, and zinc are known to accumulate in plant tissues when present in elevated concentrations in soils, potentially posing risks to both human and animal health (Li et al., 2022). Although plant samples were not analysed in the present study, the elevated concentrations of several metals in the soils suggest that further investigation of plant uptake and food-chain transfer is warranted. Surface water contamination is also of particular concern because local communities may rely on nearby streams and wells for domestic water supply. Chronic exposure to Pb-contaminated water can result in severe neurological, developmental, and cardiovascular health effects, particularly in children (WHO, 2017). Elevated manganese concentrations in drinking water have also been linked to neurological disorders and impaired cognitive development following long-term exposure.

The contamination patterns observed in the present study therefore highlight the environmental legacy of abandoned artisanal mining activities. Field observations also revealed significant physical and environmental impacts associated with mining activities, including loss of arable land and vegetation cover, contamination of surface water along the Gadako River due to gold panning, proliferation of open pits and excavated spaces across the landscape, and widespread disturbance of the natural ecological setting (**Figure 5**). Such disturbances alter natural drainage pathways, increase sediment load in streams, and facilitate the release of fine-grained metal-bearing particulates into adjacent soils and water bodies. Without appropriate remediation measures or environmental monitoring, such sites may continue to release heavy metals into surrounding soils and water bodies through weathering, erosion, and hydrological transport processes. Similar long-term contamination effects have been documented in artisanal mining areas across Africa, Asia, and South America (e.g., Macklin et al., 2003; Li et al., 2022).


(a) (b) (c) (d)

Figure 5. Representative field photographs illustrating physical and ecological degradation associated with artisanal gold mining in the study area: (a) loss of arable land and vegetation cover in Jiko; (b) surface water contamination along the Gadako River due to gold panning; (c) proliferation of open mining pits and excavated landscapes; and (d) abandoned mining pit showing disruption of the local ecological system.

4.4. Limitations of the Study and Future Research Directions

Although the present study provides valuable insights into the contamination status of soils and surface waters around the abandoned Jiko mine site, several limitations should be acknowledged. First, the number of soil and water samples analysed was relatively limited due to logistical constraints and funding limitations. A larger and more spatially extensive sampling programme would allow for better characterization of contamination gradients and identification of potential contamination hotspots. Second, the study focused primarily on soils and surface waters. Other environmental media such as stream sediments, vegetation, crops, livestock products, and groundwater were not investigated. These environmental compartments are important for understanding contaminant transfer pathways and assessing the full extent of ecological and human health risks. Future studies should also prioritise the establishment of site-specific geochemical baseline values through systematic sampling of unimpacted control sites across representative lithological units. This will enable more accurate quantification of anthropogenic contributions and improve the reliability of contamination and ecological risk assessments in the area.

Moreover, advanced analytical techniques such as isotopic tracing or sequential extraction methods were not applied in this study. Techniques such as lead isotope analysis could provide valuable information regarding the sources of contamination and help distinguish between natural geogenic contributions and mining-related anthropogenic inputs. Future studies should therefore aim to expand the scope of environmental sampling in the Jiko mining area by incorporating multiple environmental media, seasonal monitoring programmes, and advanced geochemical techniques such as isotopic analysis and mineralogical characterization. Such integrated approaches would provide a more comprehensive understanding of contamination pathways and environmental risks associated with abandoned mining sites in the region.

5. Conclusion

This study investigated the concentrations and distribution of selected heavy metals in soils and surface waters surrounding the abandoned Jiko mine site in north-central Nigeria, with the aim of evaluating contamination levels, and discussing potential environmental and human health implications. The results demonstrate that mining activities have influenced the geochemical composition of both soils and surface waters within the study area.

The analysed soil samples show a sequence of mean concentrations in the order: Fe > Mn > Cr > Ni > Pb > Zn > Cu > As. Elevated concentrations of several metals, including Pb, Zn, Cu, Ni, and Cr, were recorded, while Fe and Mn occur in relatively high concentrations largely due to lithogenic contributions from the underlying basement complex rocks. The application of contamination indices, including contamination factor (CF), enrichment factor (EF), and geo-accumulation index (I_{geo}), indicates varying degrees of metal enrichment and contamination. The

I_{geo} results reveal that all analysed metals, except As, fall within the extremely contaminated category. The CF results show that Pb, Cu, Ni and Cr exhibit considerable contamination, Zn, Fe, and Mn show moderate contamination, while As has a low contamination status. In the same vein, the EF results indicate that only Pb, Cu, Ni and Cr show moderate enrichment, whereas the remaining metals fall within the deficiency to minimal enrichment category. The combined interpretation of these indices suggests that historical mining activities have modified the natural geochemical baseline of the area. Although the primary source of Pb appears to be geogenic, the EF, CF, and I_{geo} results indicate that secondary contributions from anthropogenic activities associated with artisanal mining cannot be ruled out.

The analysed water samples show a sequence of mean concentrations in the order: Fe > Mn > Pb > Zn > Ni > Cu > As > (Cd and Cr below detection limits). The results indicate that concentrations of Pb, Ni, Mn, Fe, and As exceed the permissible limits established by both the Nigerian Standard for Drinking Water Quality (NSDWQ) and the World Health Organization drinking-water guidelines. This confirms that the abandoned mine site remains a potential source of heavy metal contamination to local water resources. Spatial distribution patterns indicate that runoff, sediment transport, and weathering of mine wastes play important roles in the redistribution of metals within the surrounding environment. The findings of this study therefore address the objectives of contamination assessment by demonstrating that both soils and surface waters in the study area have been impacted by mining-related activities. The presence of elevated metal concentrations and exceedance of water quality standards highlights potential ecological risks and indicates possible exposure pathways to local populations through soil-water interactions and domestic water use.

Despite the insights provided, this study is limited by the relatively small number of samples analysed and the focus on only two environmental media (soils and surface waters). The absence of data on sediments, vegetation, crops, and groundwater limits a comprehensive evaluation of contaminant transfer pathways and bioaccumulation processes. In addition, advanced geochemical techniques such as isotopic analysis and metal speciation were not applied, which constrains detailed source identification and assessment of metal mobility and bioavailability. Future research should therefore include expanded sampling campaigns with greater spatial coverage and seasonal variation, analysis of additional environmental media, and the application of advanced analytical techniques such as isotopic tracing and sequential extraction procedures. Such approaches would provide a more comprehensive understanding of contamination processes and ecological risks in the study area.

Overall, this study provides baseline data on heavy metal contamination around the abandoned Jiko mine site and contributes to the growing body of knowledge on artisanal and small-scale mining impacts in Nigeria. The results emphasize that abandoned mine sites can remain significant sources of environmental contamination long after mining activities have ceased. Continuous environmental monitoring and appropriate remediation strategies are therefore required to mitigate potential long-term ecological and public health impacts associated with such sites.

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Conflicts of Interest

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

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