

Soil Heavy Metal Enrichment and Contamination across Selected Mining Communities in Ebonyi State, Southeastern Nigeria

Ogbonna Kennedy^{1*}; Dr. Aya Friday¹; Emmanuel Ekechukwu Stephen¹;
Igboke Henry Obinna²

¹Department of Chemistry, Alex Ekwueme Federal University Ndufu-Alike Ikwo, Ebonyi State, Nigeria

²Department of Soil and Environmental Management, Ebonyi State University, Abakaliki, Ebonyi State, Nigeria

Corresponding Author: Ogbonna Kennedy^{1*}

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Abstract: Mining activities can alter soil properties and contribute to the accumulation of potentially toxic metals in surrounding environments. This study assessed the pH and concentrations of lead (Pb), zinc (Zn), copper (Cu), and arsenic (As) in soils from selected mining areas in Ebonyi State, southeastern Nigeria. Soil samples were collected at 0–20 cm depth from three mining locations: Enyigba, Nkaleke Achara-Izzi Unuhu, and Mkpuma Akpatakpa, with Okworike Agbaja Farm serving as the control. Soil pH was determined using a 1:2.5 soil-to-water ratio, while Pb, Zn, Cu, and As were determined by atomic absorption spectrophotometry following acid digestion. Contamination was evaluated using contamination factor (CF), geo-accumulation index (Igeo), and pollution load index (PLI). The mining soils were more acidic than the control, with pH values ranging from 5.08 to 5.60 compared with 6.50 in the control. Concentrations of Pb, Zn, Cu, and As were higher in all mining locations than in the control, although they remained below the guideline values used for comparison. All metals recorded very high CF values (>6), while Igeo values indicated substantial enrichment. PLI values exceeded 1 at all mining locations, indicating overall soil deterioration. The findings demonstrate substantial heavy-metal enrichment in the investigated mining soils and highlight the need for continued monitoring and appropriate management of mining-affected soils.

Keywords: Heavy Metals; Soil Contamination; Mining; Contamination Factor; Ebonyi State.

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I. INTRODUCTION

Heavy metals and metalloids are among the environmental contaminants of concern because of their persistence, potential toxicity and ability to accumulate in soils and other environmental media. Although the term “heavy metals” is widely used in environmental studies, it has no universally accepted scientific definition and is often used to describe metallic elements and metalloids associated with environmental contamination and toxicity (Duffus, 2002). Some elements, such as copper and zinc, are essential micronutrients at appropriate concentrations, whereas excessive accumulation of these and other potentially toxic elements can adversely affect soil quality, plants, animals and humans (Kabata-Pendias & Pendias, 2001). Mining is an important anthropogenic source of metal contamination because excavation, ore processing, mine-waste

accumulation and disposal of tailings can redistribute naturally occurring metals into surrounding soils and water bodies. Metals introduced into soils are not degraded biologically and may persist while undergoing changes in chemical form, mobility and bioavailability. Consequently, contaminated soils can serve as long-term reservoirs and potential sources of metal transfer to crops, water resources and humans (Adimalla & Wang, 2018).

Ebonyi State in southeastern Nigeria contains important lead-zinc mineralization associated with the Abakaliki mining district of the Lower Benue Trough. The Abakaliki Pb-Zn deposits occur mainly as fracture-controlled mineralized veins within the Albian Asu River Group shales, with galena, sphalerite, pyrite and chalcopyrite among the principal ore and associated minerals (Akande & Mücke, 1993). Mining activities have occurred in the district for

several decades, resulting in active and abandoned mining sites and the accumulation of mine wastes in surrounding environments. Previous investigations have documented elevated concentrations of potentially toxic metals in soils and other environmental media within the district. Obiora et al. (2016) reported significant heavy-metal contamination in soils around Pb and Zn mining areas in Enyigba, demonstrating the influence of mining activities on soil metal concentrations. Similarly, Obasi (2020) investigated agricultural soils and stream sediments across major Pb-Zn mining areas of Abakaliki, including Enyigba and Mkpuma Akpatakpa, and reported elevated concentrations of several metals, particularly in areas close to active mining sites. Uchendu et al. (2020) also documented Pb and Zn contamination in soils affected by mining overburden in Enyigba. These findings indicate that mining-related metal contamination may extend beyond mine workings into surrounding agricultural and residential environments.

The potential environmental and human-health implications of this contamination are important because mining-affected communities may depend on surrounding land for agricultural production. Studies around Enyigba have reported metal accumulation in soils and edible crops and identified potential human-health risks associated with exposure to contaminated environmental media (Obasi et al., 2020; Oti & Nwabue, 2013). Ugochukwu et al. (2022) also reported heavy-metal contamination of soil, sediment and water associated with galena mining in Ebonyi State, demonstrating the broader environmental implications of mining activities in the region. Recent research has further shown that artisanal Pb-Zn mining continues to influence environmental quality in southeastern Nigeria, emphasizing the need for continued monitoring of mining-affected areas (Tse et al., 2026). Assessment of soil contamination requires not only determination of individual metal concentrations but also evaluation of the degree of contamination relative to appropriate background or guideline values. Pollution indices such as the contamination factor (CF), geoaccumulation index (Igeo) and pollution load index (PLI) provide complementary approaches for characterizing the contamination status of soils and sediments (Müller, 1969; Håkanson, 1980). These indices have been applied in environmental studies to evaluate the magnitude and spatial distribution of metal contamination (Adimalla & Wang, 2018). Despite previous investigations of mining-related contamination in parts of Ebonyi State, comparative assessment of selected metals in soils across different mining communities using a consistent sampling and analytical approach remains necessary. In particular, comparable data from Mkpuma Akpatakpa, Enyigba and Nkaleke Achara-Izzi Unuhu can provide additional information on the spatial variation and contamination status of soils within the Abakaliki mining corridor.

➤ *Aim and Objectives*

The aim of this study was to assess the concentrations and contamination status of selected heavy metals in soils from mining areas of Ebonyi State, southeastern Nigeria.

• *The Specific Objectives Were to:*

- ✓ Determine the pH and concentrations of selected heavy metals (Pb, Zn, Cu and As) in soils from mining-impacted and non-mining locations within the selected study communities;
- ✓ Assess the degree of soil contamination using the contamination factor (CF), geoaccumulation index (Igeo) and pollution load index (PLI);
- ✓ Compare the concentrations and contamination status of the selected heavy metals among Mkpuma Akpatakpa, Enyigba and Nkaleke Achara-Izzi Unuhu; and
- ✓ Evaluate the measured metal concentrations in relation to relevant soil quality guideline or permissible values.

II. MATERIALS AND METHODS

➤ *Study Area*

The study was conducted in selected lead-zinc mining areas of Ebonyi State, southeastern Nigeria, within the Abakaliki block of the Lower Benue Trough. The mining locations were Enyigba and Nkaleke Achara-Izzi Unuhu in Abakaliki Local Government Area (LGA), and Mkpuma Akpatakpa in Izzi LGA. Okworike Agbaja Farm, Abakaliki, a non-mining agricultural area, was used as the control site. The selected mining locations represent soils directly affected by long-term Pb-Zn mining activities, while the control site provided a non-mining reference environment. Abakaliki lies within the derived savannah agroecological zone of southeastern Nigeria and has a tropical climate characterized by distinct wet and dry seasons. Rainfall follows a bimodal pattern, occurring mainly from April to July and September to November, with a short dry spell in August. Annual rainfall has been reported to range from approximately 1,500 to 2,000 mm, while mean temperatures generally range from about 27 to 32°C (ODNRI, 1989; Nimet, 2016). Geologically, the Abakaliki area is underlain predominantly by the Asu River Group of the Lower Benue Trough, comprising mainly shales, mudstones, sandstones and associated sedimentary formations. The Pb-Zn mineralization occurs principally within the Abakaliki Shales, with galena and sphalerite occurring alongside associated sulphide minerals including pyrite and chalcopyrite (Akande & Mücke, 1993). The soils of Abakaliki are developed largely from shale-derived materials and belong predominantly to the Ultisol order. They have been classified as Typic Haplult in parts of the Abakaliki area, while Typic Hapludult has also been reported under the Ezzamgbo soil association. The soils are generally characterized by variable sandy-loam to clayey textures and relatively low to medium fertility (Federal Department of Agriculture and Land Resources [FDALR], 1985, 1987; Nimet, 2016).

➤ *Experimental Design and Soil Sampling*

The study adopted a Completely Randomized Design (CRD) involving four locations: three mining locations (Enyigba, Nkaleke Achara-Izzi Unuhu, and Mkpuma Akpatakpa) and one non-mining control location (Okworike Agbaja Farm). The locations served as the experimental groups for assessing variations in soil pH and heavy-metal concentrations. Soil samples were collected from the three

selected mining locations and the non-mining control location. Sampling was carried out at a depth of 0–20 cm using a digger and scoop. At each location, soil was collected from three different points to account for spatial variability. Soil collected from the three points within each location was thoroughly mixed and bulked to form one representative composite sample. Three independent composite samples were prepared for each location and treated as three sampling replicates. Thus, a total of 12 composite soil samples were obtained, comprising three composite samples each from Enyigba, Nkaleke Achara–Izzi Unuhu, Mkpuma Akpatakpa, and the non-mining control location. The samples were placed in clean Ziplock bags, properly labelled and transported to the laboratory for preparation and analysis.

➤ Soil Sample Preparation

The collected soil samples were air-dried at room temperature and homogenized. Representative portions were obtained using the coning and quartering procedure. The samples were subsequently oven-dried at 105°C, pulverized to obtain a fine homogeneous material, and prepared for acid digestion and subsequent determination of the selected heavy metals. The sample preparation procedure was adapted from the United States Environmental Protection Agency (USEPA) method for soil sample preparation and digestion (USEPA, 1986).

➤ Determination of Soil pH

Soil pH was determined potentiometrically in a 1:2.5 soil-to-water suspension. A representative portion of each soil sample was mixed thoroughly with distilled water at a soil-to-water ratio of 1:2.5 and allowed to equilibrate before measurement. The pH of the suspension was measured using a calibrated digital pH meter.

➤ Acid Digestion of Soil Samples

Reagent-grade chemicals were used throughout the analytical procedures. Soil samples were digested using an acid digestion procedure adapted from USEPA Method 3050B. Approximately 1 g of each prepared soil sample was weighed into a digestion vessel, after which 10 mL of 1:1 nitric acid (HNO₃) was added. The vessel was covered with a watch glass and heated for 15 min without boiling. After cooling, an additional 5 mL of HNO₃ was added and the mixture was heated for 30 min. A further 5 mL of HNO₃ was added and heating continued until no brown fumes were observed. The digest was then concentrated by evaporation to less than 5 mL and allowed to cool. Two millilitres of distilled water and 3 mL of 30% hydrogen peroxide (H₂O₂) were added, and the mixture was heated for approximately 2 h until effervescence ceased. The solution was subsequently concentrated to approximately 5 mL. Ten millilitres of hydrochloric acid (HCl) was added and the mixture was heated for 15 min without boiling. After cooling, the digest was filtered through Whatman No. 41 filter paper into a 100-mL volumetric flask. The filtrate was made up to volume with ultrapure water and prepared for analysis. This procedure was adapted from USEPA Method 3050B, which employs nitric acid digestion followed by hydrogen peroxide treatment and hydrochloric acid addition for the determination of metals in soils and sediments.

➤ Determination of Heavy Metals by Atomic Absorption Spectrophotometry

The concentrations of lead (Pb), zinc (Zn), copper (Cu), and arsenic (As) in the digested soil samples were determined using atomic absorption spectrophotometry (AAS). Reagent blanks were included during the analytical procedure to monitor possible contamination arising from reagents and laboratory procedures. Calibration standards were prepared from appropriate stock solutions over a concentration range of 0–10 µg/mL (mg/L). Six calibration standards were used to establish the calibration relationship between absorbance and metal concentration. The reported calibration coefficient was $R^2 = 0.997$. The concentrations of Pb, Zn, Cu and As in the soil digest samples were subsequently determined from the respective calibration relationships.

➤ Assessment of Soil Heavy-Metal Contamination

The degree of heavy-metal contamination was assessed using the contamination factor (CF), geoaccumulation index (I_{geo}), and pollution load index (PLI).

• Contamination Factor

The contamination factor was calculated as the ratio of the concentration of an individual metal in the investigated soil to its concentration in the control soil. Contamination Factor was calculated according to the method proposed by Hakanson (1969):

$$CF = C_i / B_i$$

Where:

- CF = contamination factor for metal;
- (C_i) = concentration of metal i in the soil sample; and
- (B_i) = concentration of metal i in the reference/control soil.

The contamination factor was interpreted as follows: CF < 1 indicates low contamination; CF = 1–3 indicates moderate contamination; CF = 3–6 indicates considerable contamination; and CF > 6 indicates very high contamination.

• Geoaccumulation Index

The geoaccumulation index (I_{geo}) was calculated according to the method proposed by Müller (1969):

$$I_{geo} = \log_2 (C_i / 1.5B_i)$$

Where:

- I_{geo} = geoaccumulation index;
- C_i = measured concentration of metal i in the soil;
- B_i = concentration of metal i in the reference/control soil; and
- 1.5 = correction factor used to account for natural variations in background concentrations.

• Pollution Load Index

The pollution load index was calculated from the contamination factors of the four investigated metals:

$$PLI = (CF_{Pb} \times CF_{Zn} \times CF_{Cu} \times CF_{As})^{1/4}$$

Where:

CF_{Pb} , CF_{Zn} , CF_{Cu} and CF_{As} represent the contamination factors for Pb, Zn, Cu and As, respectively. A PLI value of 1 represents the reference or baseline level, whereas values greater than 1 indicate deterioration relative to the reference condition.

➤ Statistical Analysis

Data obtained from the three composite soil samples collected from each location were subjected to descriptive analysis. The concentrations of Pb, Zn, Cu and As and soil pH were calculated and expressed as mean values for each location. The mean values were used for comparison among the three mining locations and the non-mining control. Contamination factor (CF), geoaccumulation index (Igeo), and pollution load index (PLI) were calculated using the

mean concentration values and the control soil as the reference background. The resulting contamination indices were used to assess the degree of heavy-metal enrichment and overall soil pollution at the investigated mining locations.

III. RESULTS

➤ Soil pH and Heavy Metal Concentrations

Table 1 presents the soil pH and concentrations of Pb, Zn, Cu and As in soils from the three mining sites and the control site. The soil pH ranged from 5.08 to 6.50. The highest pH value was recorded at the control site (6.50), while the lowest value occurred at the Nkaleke Achara–Izzi Unuhu mining site (5.08). The pH values at Enyigba (5.60) and Mkpuma Akpatakpa (5.40) were also lower than that of the control soil. Overall, the mining-site soils were more acidic than the control soil, with Nkaleke Achara–Izzi Unuhu showing the greatest difference.

Table 1 Soil pH and Heavy Metal Concentrations in the Study Sites

Site	pH	Pb (mg/kg)	Zn (mg/kg)	Cu (mg/kg)	As (mg/kg)
Enyigba mining site	5.60	7.385	0.160	9.175	5.560
Nkaleke Achara–Izzi Unuhu mining site	5.08	5.835	0.500	7.260	4.047
Mkpuma Akpatakpa mining site	5.40	7.225	0.300	2.020	1.860
Control site	6.50	0.040	0.009	0.119	0.125
FAO/WHO guideline value	—	100	300	100	20

Table 2 Contamination Factor (CF) of Heavy Metals

Site	Pb	Zn	Cu	As
Enyigba	184.63	17.78	77.10	44.48
Nkaleke Achara–Izzi Unuhu	145.88	55.56	61.01	32.38
Mkpuma Akpatakpa	180.63	33.33	16.97	14.88

Table 3 Geoaccumulation Index (Igeo) of Heavy Metals in the Mining Sites

Site	Pb Igeo	Zn Igeo	Cu Igeo	As Igeo
Enyigba	6.94	3.57	5.68	4.89
Nkaleke Achara–Izzi Unuhu	6.60	5.21	5.34	4.43
Mkpuma Akpatakpa	6.90	4.47	3.49	3.31

Table 4 Pollution Load Index (PLI)

Site	PLI
Enyigba	52.33
Nkaleke Achara–Izzi Unuhu	65.31
Mkpuma Akpatakpa	41.52

For Pb, the highest concentration was recorded at the Enyigba mining site (7.385 mg/kg), followed closely by Mkpuma Akpatakpa (7.225 mg/kg), while Nkaleke Achara–Izzi Unuhu recorded 5.835 mg/kg. The control site had a much lower Pb concentration of 0.040 mg/kg. Thus, Pb concentrations were substantially higher at all three mining sites than at the control site, with Enyigba showing the highest concentration.

The concentration of Zn followed a different pattern. Nkaleke Achara–Izzi Unuhu recorded the highest Zn concentration (0.500 mg/kg), followed by Mkpuma Akpatakpa (0.300 mg/kg) and Enyigba (0.160 mg/kg). The control site recorded the lowest Zn concentration (0.009

mg/kg). Although Zn was the lowest among the four investigated metals at the mining sites, its concentration at each mining location was higher than that of the control site.

Copper concentration was highest at Enyigba (9.175 mg/kg), followed by Nkaleke Achara–Izzi Unuhu (7.260 mg/kg), while Mkpuma Akpatakpa recorded a lower concentration of 2.020 mg/kg. The control soil recorded only 0.119 mg/kg. The results therefore show a marked increase in Cu concentrations at the mining sites compared with the control site, with Enyigba having the highest observed Cu concentration.

Similarly, As concentration was highest at Enyigba (5.560 mg/kg), followed by Nkaleke Achara–Izzi Unuhu (4.047 mg/kg) and Mkpuma Akpatakpa (1.860 mg/kg). The control site recorded the lowest concentration (0.125 mg/kg). The considerably higher As concentrations at the mining sites indicate greater accumulation of As in the soils from the mining areas relative to the non-mining control.

Considering the four metals together, Enyigba recorded the highest concentrations of Pb, Cu and As, whereas Nkaleke Achara–Izzi Unuhu recorded the highest concentration of Zn. Mkpuma Akpatakpa showed intermediate concentrations for Pb and Zn but comparatively lower concentrations of Cu and As. In contrast, the control site consistently recorded the lowest concentration of all four metals. The general pattern therefore indicates that the soils from the mining locations contained substantially higher concentrations of the investigated metals than the control soil. Comparison with the guideline values presented in Table 1 shows that the measured concentrations of Pb, Zn, Cu and As at all the investigated locations were below the corresponding FAO/WHO guideline values used for comparison. However, the clear differences between the mining sites and the control site indicate substantial enrichment of the investigated metals in the mining-site soils relative to the control soil.

Table 2 presents the contamination factors (CF) of Pb, Zn, Cu and As in the soils from the three mining sites. All the investigated metals recorded CF values greater than 6 at every mining site, indicating very high contamination relative to the control soil.

At Enyigba, Pb recorded the highest CF value (184.63), followed by Cu (77.10), As (44.48) and Zn (17.78). This shows that Pb had the greatest degree of enrichment at the site, while Zn had the lowest CF among the four metals. At Nkaleke Achara–Izzi Unuhu, Pb also recorded the highest CF (145.88), followed by Cu (61.01), Zn (55.56) and As (32.38). At Mkpuma Akpatakpa, Pb had the highest CF (180.63), followed by Zn (33.33), Cu (16.97) and As (14.88).

Across the three mining sites, Pb consistently recorded the highest CF values, ranging from 145.88 at Nkaleke Achara–Izzi Unuhu to 184.63 at Enyigba. This indicates that Pb showed the greatest enrichment relative to the control soil across the study area. The highest CF for Pb, Cu and As occurred at Enyigba, whereas the highest CF for Zn occurred at Nkaleke Achara–Izzi Unuhu. The CF values also show that the degree of enrichment varied among the metals and locations. Enyigba exhibited particularly high CF values for Pb, Cu and As, while Nkaleke Achara–Izzi Unuhu showed comparatively high enrichment of Zn. Mkpuma Akpatakpa recorded a high Pb CF but lower CF values for Cu and As than the other two mining sites. Overall, the CF results demonstrate substantial enrichment of all four investigated metals in the mining-site soils relative to the control soil. The consistently very high CF values indicate that the difference between the mining soils and the control soil was pronounced for Pb, Zn, Cu and As, with Pb showing the strongest enrichment across the three mining locations.

Table 3 presents the geoaccumulation index (Igeo) values of Pb, Zn, Cu and As in soils from the three mining sites. All the metals recorded positive Igeo values at each location, indicating enrichment relative to the control soil.

The Igeo values ranged from 3.31 to 6.94 across the study sites. Pb recorded the highest values, ranging from 6.60 to 6.94, while the lowest values were recorded for As at Mkpuma Akpatakpa (3.31) and Cu at the same site (3.49). The relatively high Igeo values across the metals indicate substantial accumulation in the mining-site soils. Enyigba recorded Igeo values of 6.94, 3.57, 5.68 and 4.89 for Pb, Zn, Cu and As, respectively. At Nkaleke Achara–Izzi Unuhu, the corresponding values were 6.60, 5.21, 5.34 and 4.43, while Mkpuma Akpatakpa recorded 6.90, 4.47, 3.49 and 3.31, respectively.

Overall, the Igeo results indicate that Pb had the most pronounced accumulation across the mining sites, while all four investigated metals showed substantial enrichment relative to the control soil. The results therefore support the evidence of metal accumulation indicated by the contamination factor in Table 2.

Table 4 presents the Pollution Load Index (PLI) for the three mining sites. The PLI values ranged from 41.52 to 65.31, with the highest value recorded at Nkaleke Achara–Izzi Unuhu (65.31), followed by Enyigba (52.33), while Mkpuma Akpatakpa recorded the lowest value (41.52).

All three sites recorded PLI values substantially greater than 1, indicating an overall pollution load relative to the control soil. The high PLI values demonstrate that the combined concentrations of Pb, Zn, Cu and As contributed to considerable deterioration in soil quality at the mining locations. The highest PLI at Nkaleke Achara–Izzi Unuhu reflects the combined influence of the four investigated metals at that site, while the lower value at Mkpuma Akpatakpa indicates a comparatively lower overall pollution load among the three mining locations. Overall, the PLI results confirm that the mining-site soils were substantially enriched in the investigated heavy metals relative to the control soil.

IV. DISCUSSIONS

➤ Soil pH

The lower pH observed in the mining site soils relative to the control indicates that the sampled mining environments were more acidic than the non-mining reference soil. This difference is important in interpreting the heavy-metal results because soil pH influences the chemical behaviour of metals and can affect their retention, dissolution and mobility. The acidic conditions observed at the mining locations therefore provide an important part of the environmental context in which the elevated metal concentrations and high contamination indices occurred.

The present finding is consistent with observations from other mining environments in southeastern Nigeria. Nnabo (2015) reported acidic to neutral soil conditions in the

Enyigba mining district, while Okafor et al. (2024) similarly reported generally low pH in soils collected along the Enyigba mining site. Similarly, substantial variation in soil pH has been reported within mining environments. Osuocha et al. (2015) found that soils affected by quarry-mining effluent in Ishiagu had acidic pH values ranging from 3.98 to 5.93, whereas the control soil was slightly alkaline (pH 7.37), demonstrating clear differences between mining-affected and reference soils. These findings collectively support the observation that mine-affected soils can exhibit appreciable acidity, although the magnitude of acidity varies among locations and mining features. Further support comes from the study of Umeobi et al. (2024), which compared mine-affected and non-mine-affected soils at Ameka and Nkalagu in southeastern Nigeria. Although that study focused primarily on potentially toxic elements and soil profiles rather than pH alone, its finding that mine-affected soils differed from their corresponding non-mine environments demonstrates that mining-related disturbances can produce spatial differences in soil chemical conditions. The authors also emphasized that site characteristics alone were insufficient to explain the distribution of potentially toxic elements, highlighting the importance of soil properties in interpreting contamination patterns. A plausible explanation for the lower pH of the mining soils is the weathering and oxidation of sulphide-bearing materials associated with mining activities. Such processes can generate acidity and subsequently alter the chemical environment controlling metal behaviour. Evidence from Ishiagu also shows that mine tailings can have particularly acidic conditions, supporting the possibility that mining-derived materials contribute to localized acidification. However, the present results do not establish that mining activity was the sole cause of the lower pH, since soil parent material, mineral composition, land use and other site-specific properties may also influence soil reaction.

The present finding is not, however, identical to all previous observations. Nweke et al. (2008) reported a mean pH of approximately 7.0 for agricultural soils at Enyigba, which is considerably higher than the values observed in the present mining soils. Similarly, studies of mining environments have reported substantial within-site variation in pH rather than a uniformly acidic condition. Ogbonna et al. (2013), for example, recorded pH values extending from strongly acidic to near-neutral conditions across different depths and mining features in Ishiagu.

The differences among these studies can reasonably be attributed to differences in sampling environment, land use, sampling depth, proximity to mine-derived materials and spatial variability. Agricultural soils may have different chemical conditions from soils sampled directly within mining locations, while tailings and other mine wastes can produce more localized changes in pH than surrounding soils. The study by Umeobi et al. (2024) also demonstrates that mine-affected and non-mine-affected soils can show different contamination patterns within relatively close areas, reinforcing the importance of site-specific conditions when interpreting soil properties.

The pH results also help explain, although they do not by themselves prove, the differences observed between the mining soils and the control in the present study. The mining locations had lower pH together with substantially greater concentrations of Pb, Zn, Cu and As, followed by high background-normalized CF and Igeo values. This combination suggests that the mining soils had both a distinct chemical environment and greater metal enrichment relative to the control. Nevertheless, the relationship should be interpreted cautiously because the observed enrichment is likely to reflect the combined influence of mining-derived materials, parent material and other soil properties rather than pH alone. Overall, the present results are supported by studies from both the immediate study region and other mining environments in southeastern Nigeria that have reported acidic or variable soil pH in mine-affected soils. The contrasting reports of near-neutral conditions further show that soil acidity is not uniform across mining landscapes. The lower pH recorded in the present mining soils is therefore best interpreted as a site-specific characteristic of the sampled locations, with potential implications for the behaviour of the heavy metals investigated.

➤ Lead (Pb)

Lead was the most prominent contaminant in the present study when the concentrations were considered relative to the non-mining reference soil. The mining-site soils contained markedly higher Pb concentrations than the control, and this difference was reflected in the very high contamination factor (CF) and geoaccumulation index (Igeo) values. Thus, although the measured Pb concentrations were below the guideline value used for comparison, the background-normalized indices indicate substantial Pb enrichment in the sampled mining soils. This distinction is important because a soil may have a concentration below a generalized guideline while still showing considerable enrichment relative to its local background condition.

The present finding agrees with Obiora et al. (2016), who assessed soils from three mining locations in Enyigba, southeastern Nigeria. Their study reported substantial enrichment of several metals associated with the mining activities and identified Pb as one of the major contaminants. The authors used contamination indices to demonstrate that the degree of enrichment could be considerable even where interpretation was based on comparison with background concentrations. The agreement with the present study is therefore mainly in the observation that Pb enrichment becomes much more evident when mining-site concentrations are evaluated relative to a reference or background condition rather than by concentration alone. Study by Nwogha et al. (2018) also supports the present observation. Their investigation of soils from the Ameka mining area in Abakaliki, Ebonyi State, showed that mining activities were associated with increased concentrations of heavy metals, including Pb, compared with less affected soils. The authors attributed the observed metal accumulation to artisanal mineral mining and associated disturbance of the soil environment. The agreement is particularly relevant because Ameka, like the present study locations, is within southeastern Nigeria and is characterized by mining-related

disturbance. Evidence from outside Nigeria provides further support for the present Pb result. Wu et al. (2018) investigated agricultural soils around a Pb/Zn mining and smelting area in southwestern China and reported a mean Pb concentration of 512 mg/kg. Pb had the highest mean Igeo among the metals investigated, indicating substantial accumulation relative to the regional soil background. The study therefore agrees with the present result in showing that Pb can become one of the dominant contaminants in soils affected by mining activities.

However, the absolute Pb concentrations reported in these did not agree to those obtained in the present investigation. For example, Chukwu and Oji (2018) reported a mean Pb concentration of 109.55 mg/kg in agricultural soils around the abandoned Mkpuma Ekwoku lead-zinc mine in southeastern Nigeria. Their study also found Pb contamination factors greater than 1, but the overall pollution load index was generally low. Although this study still supports the occurrence of Pb enrichment around mining environments, its mean Pb concentration was substantially higher than the values obtained in the present study. This difference may be related to the different sampling environments: Chukwu and Oji (2018) sampled agricultural soils around an abandoned mine and settlements, whereas the present study used composite samples collected directly from selected mining locations. Differences in mine history, waste distribution, soil properties, sampling positions and spatial heterogeneity can therefore produce different Pb concentrations. A much stronger contrast is provided by Elom (2018), who investigated soils around four mining sites in Ebonyi State and reported exceptionally high mean Pb concentrations ranging from 3,198 to 7,881 mg/kg. These concentrations were far higher than those obtained in the present study and exceeded the soil guideline values considered by the author. The difference is substantial and suggests that Pb accumulation can vary by several orders of magnitude among mining environments within the same state. A likely explanation is the intensity and specific nature of mining activities, the degree of exposure to Pb-rich ore and mine wastes, and the locations at which samples were collected. The present study used three composite samples per location, each formed from three sampling points, which may also have reduced the influence of localized contamination hotspots compared with sampling individual highly contaminated points.

International evidence also demonstrates that Pb concentrations can vary greatly even within mining environments. Qi et al. (2016) investigated soils from a Zn-Pb mining district in southern China and reported substantial spatial variation in soil heavy-metal concentrations. Their study emphasized the importance of spatial distribution when evaluating contamination around mining areas. This supports the interpretation that differences between the present Pb concentrations and those reported elsewhere should not automatically be regarded as contradictory; rather, they may reflect differences in geological setting, mining history, source intensity, distance from contamination sources and spatial distribution of mine-derived materials.

The very high CF values obtained for Pb in the present study further demonstrate the importance of the reference soil in interpreting the results. CF is calculated using the concentration of a metal relative to its background value; consequently, the very low Pb concentration in the control soil produces a large contrast with the mining-site concentrations. The Igeo values similarly indicate pronounced Pb accumulation relative to the selected background. Therefore, the present findings should be interpreted as evidence of strong Pb enrichment relative to the local reference condition, rather than as evidence that the absolute Pb concentrations are among the highest reported from mining environments. The agreement among the local and international studies indicates that Pb enrichment is a recurring feature of mining-affected soils. At the same time, the contrasting concentrations reported by Chukwu and Oji (2018) and particularly Elom (2018) demonstrate that the magnitude of Pb accumulation is highly site-specific. Differences in mining intensity, ore composition, mine-waste management, sampling position, soil characteristics and sampling design can all influence measured concentrations. Consequently, the combination of concentration data with CF and Igeo provides a more informative assessment of Pb contamination in the present study than reliance on the guideline comparison alone.

Overall, the present study agrees with evidence from Nigerian and international mining environments that mining activities can produce substantial Pb enrichment in soils. The lower absolute Pb concentrations observed in the present study compared with some previous investigations do not negate the contamination indicated by the CF and Igeo values. Rather, they demonstrate the strong spatial and site-specific variability of Pb contamination around mining environments.

➤ Zinc (Zn)

Zinc concentrations in the present study were higher in all the mining-site soils than in the non-mining control, indicating enrichment associated with the sampled mining environments. Although the absolute concentrations were relatively low compared with the guideline value used for comparison, the contamination factor and geoaccumulation index showed considerable enrichment when the results were evaluated against the reference soil. This indicates that the interpretation of Zn contamination in the present study depends strongly on the background condition and not solely on comparison with a generalized permissible concentration.

The present finding agrees with the study of Nwogha et al. (2018) in the Ameka mining area of Abakaliki, southeastern Nigeria. The authors reported that Zn concentrations in soils from the mining area were significantly higher than those of the unmined control soil. Their study further demonstrated that the influence of mining on Zn was detectable across sampling distances from the mining sites. The agreement with the present study is therefore based on the consistent observation that mining-affected soils contained more Zn than the corresponding non-mining reference soil. The similarity is particularly relevant because both studies compared mining-affected soils with an unmined soil within southeastern Nigeria. Further support is

provided by Umeobi et al. (2024), who investigated mine-affected and non-mine-affected soils at Ameka and Nkalagu in southeastern Nigeria. They reported that Zn concentrations in the upper soil horizons of mine-affected sites were higher than those in corresponding non-mine-affected soils and related this pattern to anthropogenic mining activities. Their geoaccumulation assessment also showed moderate to extreme contamination involving Zn at the Ameka mine-affected site. This agrees with the present observation that Zn was enriched in the mining soils relative to the control and that the enrichment became more evident when evaluated using a background-normalized index.

However, the absolute Zn concentrations in the present study are considerably lower than those reported by these studies. For example, the Zn concentrations reported by Wu et al. (2018) were several orders of magnitude higher than those measured in the present study. This difference can be explained partly by differences in the intensity and type of mining activity. The Chinese study investigated an area affected by both mining and smelting, providing an additional atmospheric and industrial source of Zn, whereas the present investigation focused on selected mining locations. Smelting and the handling of concentrated ores can introduce larger quantities of metal-bearing particles into surrounding soils, resulting in substantially higher total Zn concentrations.

A contrasting pattern can also be observed in the recent Nigerian study by Badamasi et al. (2022) at the Riruwai mining area in northwestern Nigeria. The authors reported Zn concentrations above the guideline threshold in active and abandoned mining areas and found strong overall soil pollution based on the pollution load index. In contrast to the relatively low absolute Zn concentrations recorded in the present study, their results demonstrate much greater accumulation of Zn in some Nigerian mining environments. This difference may reflect variation in the geological source of the ore, the intensity and duration of mining, the distribution of mine wastes, and the extent to which the sampled soils were directly exposed to mineralized materials. It also demonstrates that Zn concentrations cannot be assumed to be uniform across mining environments, even within the same country.

The difference between the absolute Zn concentrations and the contamination indices in the present study is particularly important. The CF values were calculated using the concentration in the control soil as the reference, and the very low Zn concentration of the control resulted in relatively large CF values at the mining sites. The Igeo values similarly indicate that the Zn concentrations represented substantial accumulation relative to the selected background. Therefore, the present findings do not imply that the study sites contained exceptionally high absolute quantities of Zn when compared with heavily contaminated mining environments elsewhere. Rather, they demonstrate that Zn was considerably enriched relative to the local non-mining reference condition. The variation among the three mining locations further indicates that Zn enrichment was not uniform across the study area. Nkaleke Achara-Izzi Unuhu recorded the highest Zn concentration and consequently the highest Zn CF and Igeo

values, whereas Enyigba recorded the lowest Zn concentration among the mining locations. Such spatial variation may arise from differences in the distribution of mineralized materials, mining intensity, waste deposition and local soil characteristics. The findings of Umeobi et al. (2024), which demonstrated differences in PTE distributions between mine-affected and non-mine-affected soils and between mining locations, similarly illustrate the importance of site-specific conditions in interpreting metal accumulation.

Overall, the present results agree with Nigerian and international evidence that mining activities can increase Zn concentrations in soils relative to non-mining reference conditions. The substantially higher concentrations reported in some other mining environments represent a contrasting magnitude rather than necessarily a contradiction, and can reasonably be associated with differences in mining and processing intensity, geological setting, mine-waste characteristics and sampling conditions. The combination of the measured Zn concentrations with CF and Igeo therefore indicates that Zn was enriched in the sampled mining soils relative to the local reference soil, even though its absolute concentrations remained well below the guideline value used for comparison.

➤ *Copper (Cu)*

Copper concentrations in the present study were higher in all three mining-site soils than in the non-mining control, indicating enrichment of Cu in the mining environments. The difference was particularly evident at Enyigba and Nkaleke Achara-Izzi Unuhu, while Mkpuma Akpatakpa recorded a comparatively lower Cu concentration. The corresponding CF and Igeo values further indicate that the observed Cu concentrations represented substantial enrichment relative to the reference soil, despite the measured concentrations remaining below the guideline value used for comparison.

The present finding agrees with Ezech and Chukwu (2011), who investigated heavy-metal contamination of agricultural soils in the Ishiagu mining district of southeastern Nigeria. They reported Cu concentrations ranging from 4 to 36.5 mg/kg and identified localized Cu enrichment in soils associated with mining areas. The authors attributed the distribution of the metals to mineralized veins and mine dumps, demonstrating that mining-derived materials can contribute to the accumulation of Cu in surrounding soils. This agrees with the present study because Cu concentrations were consistently greater in the mining locations than in the non-mining reference soil. Further support comes from Orji et al. (2021), who investigated trace metals in soils from farmlands around Enyigba mining sites. Although their mean soil Cu concentration was below the agricultural-soil threshold values considered in their study, Cu was detected in the mining-affected soils, and Cu was among the metals subsequently accumulated by crops grown on those soils. This finding agrees with the present observation that Cu can occur in mining-affected soils even when its absolute concentration does not exceed a general soil guideline. The difference between the absolute Cu concentrations reported by Orji et al. (2021) and those obtained in the present study may partly reflect the different sampling environments, since

their samples were collected from agricultural farmlands surrounding mining sites, whereas the present samples were collected directly from selected mining locations. International evidence also supports the occurrence of Cu enrichment in mining environments. Zheng et al. (2022) investigated Cu contamination in soils from the Huaibei coal-mining area of China and found a mean soil Cu concentration of 75 mg/kg compared with a local background value of approximately 22.13 mg/kg. Isotopic analysis showed that mining and combustion contributed substantially to the Cu present in the contaminated topsoils, with mining-derived inputs accounting for an average of 72% of total soil Cu. This agrees with the present finding that mining environments can contain greater Cu concentrations than their corresponding reference soils and demonstrates that mining-derived materials can make an important contribution to soil Cu enrichment. However, the Cu concentrations obtained in the present study were substantially lower than those reported by Zheng et al. (2022). This difference is understandable because the Chinese study involved a coal-mining and combustion environment in which Cu was introduced not only through mining but also through combustion-related materials. In addition, the geological composition of the mined material, the nature of mine wastes, the duration and intensity of mining and the surrounding land-use conditions differ between the two study areas. These differences demonstrate that the presence of mining activity does not produce a uniform Cu concentration across all mining environments.

A contrasting observation was reported by Daku et al. (2025) in mine spoils from Jos and its environs, where the mean Cu concentration was 19.16 mg/kg. Despite considerable contamination factors for several potentially harmful elements, the overall PLI was 0.439, indicating no overall pollution according to the PLI criterion used in that study. Cu was nevertheless classified as considerably contaminated by the CF assessment. This contrasts with the present study in two respects: the absolute Cu concentrations were higher in the Jos mine spoils than in the present soils, while the integrated PLI interpretation differed. The difference is likely related to the nature of the sampled material and the background conditions used in calculating the contamination indices. Mine spoils represent freshly disturbed or waste-derived materials and may have a different geochemical composition from established surface soils. In addition, the overall PLI depends on the combined behaviour of all metals investigated rather than on Cu alone.

The spatial differences in Cu among the present mining locations also deserve attention. Enyigba recorded the highest Cu concentration and the highest Cu CF and Igeo values, whereas Mkpuma Akpatakpa recorded the lowest. Such variation is consistent with the heterogeneous distribution of metal-bearing minerals and mine-derived materials within mining environments. Evidence from the Dexing copper mine in China similarly showed that Cu was the dominant contaminant in many soil samples and that its spatial distribution was strongly associated with mining activities and the distribution of mine-derived materials. The contrast between the absolute Cu concentrations and the contamination indices is particularly important in the present

study. The relatively low measured concentrations might suggest limited Cu contamination if interpreted only against the guideline value. However, the high CF and positive Igeo values demonstrate that Cu was considerably enriched relative to the control soil. Therefore, the results indicate background-relative Cu enrichment rather than exceptionally high absolute Cu concentrations. This distinction also helps explain why the present results can agree with studies reporting Cu accumulation while still having considerably lower concentrations than some highly contaminated mining environments.

Overall, the present Cu results agree with evidence from southeastern Nigeria and international mining environments that mining activities can increase Cu concentrations in soils relative to non-mining or background conditions. The contrasting concentrations reported elsewhere demonstrate that the magnitude of Cu enrichment depends on the geological source, type and intensity of mining, mine-waste characteristics, surrounding land use and sampling environment. The present CF and Igeo results therefore provide important evidence that Cu was enriched at the sampled mining locations, even though its measured concentrations remained below the guideline value used for comparison.

➤ Arsenic (As)

The As concentrations recorded in the present study were higher at all three mining locations than at the non-mining control, indicating enrichment of As in the mining-site soils. The difference was most pronounced at Enyigba, followed by Nkaleke Achara-Izzi Unuhu and Mkpuma Akpatakpa. Although the measured As concentrations remained below the guideline value used for comparison, the CF and Igeo values indicate considerable enrichment relative to the reference soil. Thus, as with the other metals, the interpretation of As contamination depends not only on its absolute concentration but also on its departure from the local background condition.

The present finding agrees with Umeobi et al. (2024), who investigated potentially toxic elements in mine-affected and non-mine-affected soils at Ameka and Nkalagu in southeastern Nigeria. Their study included As among the elements investigated and demonstrated differences in the distribution and accumulation of potentially toxic elements between mining and non-mining environments. The authors emphasized that the distribution of these elements was influenced by soil properties and site characteristics. This agrees with the present result because the mining soils contained more As than the reference soil, while the magnitude of enrichment varied among the selected mining locations. Another study also provides supporting evidence. Aja et al. (2025) investigated soils from five mining locations in Ebonyi State and reported As concentrations ranging from 145.90 to 600 mg/kg, with the highest values occurring at some of the more contaminated mining sites. These concentrations were substantially higher than those obtained in the present study, but the study nevertheless agrees with the present observation that mining environments can contain elevated As relative to non-mining conditions. The much

greater concentrations reported by Aja et al. (2025) indicate that As accumulation can become considerably more severe where the mineral composition of the mined materials and the intensity of mining favour As release.

And also Chen et al. (2023) investigated As behaviour in soils surrounding a gold-mining area in China and reported substantial As enrichment, with Igeo values ranging from 1.44 to 6.70. The study linked the accumulation of As to the weathering and movement of mine wastes and identified Fe-bearing phases as important components controlling As retention in the soil. This agrees with the present study because the positive Igeo values obtained for As indicate enrichment relative to background, while the mining environment provides a plausible source of the observed As accumulation. The international evidence also demonstrates that As contamination can occur even where its environmental behaviour is strongly controlled by soil mineralogy and interactions with Fe-containing materials.

However, the magnitude of As contamination in the present study differs substantially from that reported by Aja et al. (2025) and Chen et al. (2023). Aja et al. (2025) recorded concentrations up to 600 mg/kg in selected Ebonyi mining sites, while Chen et al. (2023) reported As concentrations exceeding 1,900 mg/kg in some soils close to a gold-mine waste source. These concentrations are considerably higher than those measured in the present study. The differences may be related to the type of ore being exploited, the geological background, the degree of exposure to As-bearing minerals, the quantity and composition of mine wastes, and the intensity and duration of mining. Gold-mining wastes, in particular, can contain substantial quantities of As-bearing sulphide minerals, whereas the As content of soils associated with different mineral deposits may be considerably lower.

A contrasting Nigerian observation was reported by Okeke and Ifemeje (2021). Their investigation covered several mining locations in Ebonyi State, including Enyigba, Ikwo, Ameri-Ameka, Izza, Mkpume Akwatakwa and Mpume Akwaokuku. Although their study generally reported higher heavy-metal concentrations in mining soils than controls, they found that As did not differ significantly between some mining-site soils and soils collected 500 m from the mining locations at Enyigba and Izza. This differs from the clear separation between the mining soils and the control observed in the present study. The difference may be associated with the reference locations, spatial arrangement of sampling points and the greater distance-based design used by Okeke and Ifemeje (2021). Their comparison was between mining-site soils and soils 500 m away, whereas the present study compared three composite samples collected within the selected mining environments with a separate non-mining agricultural reference site. Consequently, the two studies were assessing different spatial relationships and should not be expected to produce identical patterns.

The spatial variation in As among the present mining locations further supports the importance of local site conditions. Enyigba recorded the highest As concentration and the highest corresponding CF and Igeo values, whereas

Mkpuma Akpatakpa recorded the lowest. Such variation can result from differences in the distribution of mineralized materials, mine wastes and drainage pathways, as well as differences in soil properties that influence As retention. International evidence indicates that As may be strongly associated with Fe-bearing soil phases, while changes in soil chemical conditions can affect its retention and mobility. Therefore, the differences among the present sites should not be interpreted simply as differences in the presence or absence of As; rather, they reflect differences in the degree to which As has accumulated relative to the local reference condition.

The relationship between the measured As concentrations and the contamination indices is particularly important. The absolute concentrations were relatively low compared with some heavily contaminated mining environments, yet the CF and Igeo values were substantially elevated because the control soil contained only a small As concentration. Consequently, the present results indicate strong background-relative enrichment of As, rather than exceptionally high absolute As contamination when compared with every mining environment reported in the literature. This distinction explains why the present findings can agree with studies reporting As enrichment while still showing much lower concentrations than highly contaminated mine-waste environments. The present As results agree with evidence from Nigerian and international mining environments that mining activities can increase As accumulation in soil. At the same time, the substantially higher concentrations reported in some mining environments and the absence of significant differences reported in some spatial comparisons demonstrate that As contamination is highly site-specific. Differences in ore mineralogy, mining intensity, waste characteristics, soil properties and sampling design provide reasonable explanations for these contrasting observations. The present CF and Igeo results therefore indicate that As represents an important component of the metal enrichment observed at the selected mining locations, even though its measured concentrations remained below the guideline value used for comparison.

V. CONCLUSION

The study demonstrated that soils from the selected mining locations in Ebonyi State were more acidic and substantially enriched with Pb, Zn, Cu and As relative to the non-mining control soil. Although the measured metal concentrations were below the guideline values used for comparison, the very high CF values, positive Igeo values and PLI values greater than 1 indicate considerable background-relative contamination and overall deterioration of soil quality. Pb showed the strongest enrichment across the mining locations, while the degree of contamination varied spatially, with Nkaleke Achara-Izzi Unuhu recording the highest overall PLI. The findings indicate that mining activities have contributed to substantial heavy-metal enrichment of the investigated soils and warrant continued environmental monitoring.

RECOMMENDATIONS

- Regular monitoring: Soil around the selected mining locations should be periodically monitored for Pb, Zn, Cu and As to track changes in contamination.
- Mine waste management: Mine wastes and tailings should be properly contained and managed to reduce further dispersion of metal-bearing materials into surrounding soils.
- Agricultural precaution: Agricultural activities on or immediately around highly contaminated mining soils should be carefully managed to minimize potential transfer of metals to crops.
- Further investigation: Future studies should include metal speciation, bioavailability and potential human-health risk assessment to provide a more comprehensive evaluation of the environmental implications of the observed contamination.

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