



Research Article

Effect of Lead Mining on the Physico-Chemical and Microbial Properties of the Soil in Anyiin Community, Logo Local Government Area Benue State, Nigeria

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ABSTRACT

This study evaluated the effects of lead mining on the physicochemical, biological properties and contamination status of soils in Anyiin Community, Benue State, Nigeria. Soil samples were collected at two depths (0–30 cm and 30–60 cm) and distances of 0 m, 200 m, and 400 m from the mining sites. Samples were analyzed for physicochemical, biological properties, heavy metals, hydrocarbons, nutrients, and microbial populations. Sampling depth significantly influenced soil pH, copper (Cu), mercury (Hg), nickel (Ni), and iron (Fe), while most parameters were not significantly affected. Soil pH reduced from 7.042 to 6.867 with depth, whereas Cu, Hg, Ni, and Fe increased significantly. The interaction between sampling distance and depth significantly affected soil properties. Most heavy metals decreased with increasing distance from the mining source. Arsenic declined from 13.10 mg/kg at 0 m to 7.35 mg/kg at 400 m, while manganese decreased from 272.50 to 112.80 mg/kg. Similar reductions occurred for other metals. Total petroleum hydrocarbons decreased from 271 to 162.50 mg/kg, while total organic carbon declined from 2.85% to 1.65%. Nutrients, oil and grease, electrical conductivity, hydrocarbon-utilizing bacteria, and total heterotrophic fungi generally decreased with distance. The findings establish that lead mining significantly influences soil quality, with contamination more noticeable near the mining area and spreading horizontally and vertically through the soil profile. Regular monitoring, mining-waste management, and reclamation of degraded areas are recommended to minimize soil contamination and environmental risks.

Keywords: Heavy metals; Lead mining; Physicochemical properties; Soil contamination; Sampling distance; Sampling depth; Soil properties

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INTRODUCTION

Land degradation remains a main environmental problem in Nigeria and other parts of the world (Jande *et al.*, 2018; Ikyaagba *et al.*, 2020; Liman *et al.* 2021; Tsenkus & Musa, 2026), posing significant

threats to ecosystem stability, agricultural productivity, and human livelihoods (Kiage, 2013;). It entails the degradation of the physical, chemical, and biological characteristics of soil as a result of both natural and man-made processes, including mining,

pollution, deforestation, and erosion (Adeoye, 2016; Artiola *et al.*, 2019; Abenu *et al.*, 2023).

In many regions of the nation, mining, especially artisanal and small-scale mining (ASM), has become a major contributor to environmental deterioration. According to Limin *et al.* (2021), Goji & Bala (2024), and Maniyunda *et al.* (2024), mining operations cause land degradation by the removal of vegetation, alteration of soil structure, and contamination with hazardous materials, particularly heavy metals. These effects frequently lead to increased erosion, decreased soil fertility, and long-term ecological harm (Ismail *et al.*, 2025). Mining-related deforestation increases soil instability and nutrient loss, reducing the land's potential to sustain agricultural production (Kalu *et al.*, 2021; Aromolaran *et al.*, 2021). Furthermore, toxic materials are introduced into soil and water systems by mining-related contamination, causing major threats to the environment and public health (Tella & Danjibo, 2024).

Artisanal and small-scale mining is typically informal and relies on manual labor with minimal regulation or environmental oversight (Macdonald *et al.*, 2014). While it provides livelihoods for many rural communities, its unregulated nature often leads to severe environmental consequences, including soil contamination, water pollution, and landscape degradation (Danso-Boateng *et al.*, 2026). Heavy metals such as lead (Pb), cadmium (Cd), mercury (Hg), and arsenic (As) are commonly released during mining processes (Yin *et al.* 2017; Anene *et al.*, 2024; Abalaka *et al.*, 2025; Garkida *et al.*, 2025). These metals are persistent environmental pollutants and can accumulate in soils, entering the food chain and posing risks such as neurological disorders, kidney damage, respiratory problems, and cancer (Emumejaye *et al.*, 2025).

Nigeria continues to face increasing challenges associated with unregulated mining practices (Olujobi & Irumekhai, (2024)). Poor enforcement of environmental regulations has resulted in widespread land degradation, contamination of water bodies, and accumulation of hazardous substances in soils (Mu'azu *et al.*, 2025). Incidents of lead poisoning linked to mining activities have been reported in several parts of the country, highlighting the urgent need for effective monitoring and management. In response, the National Environmental Standards and Regulations Enforcement Agency (NESREA) established regulatory guidelines, including the National Environmental (Mining and Processing of Coal, Ores and Industrial

Minerals) Regulations, 2009, which require environmental impact assessment for new mining developments, environmental evaluation of existing facilities, and periodic environmental auditing to minimize pollution (NESREA, 2009; Olujobi & Irumekhai, 2024).

Despite these regulatory frameworks, many mining activities, particularly in rural communities, remain poorly controlled. Anyiin community in Logo Local Government Area of Benue State is an example where lead mining has caused soil contamination, deforestation, and landscape disruption. These changes threaten agricultural productivity and local health, highlighting the need to assess soil quality.

Soil physicochemical properties, including pH, electrical conductivity, organic carbon, and cation exchange capacity, indicate soil fertility and contaminant behavior. Heavy-metal concentrations indicate environmental pollution. Assessing these properties alongside enrichment factor (EF), contamination factor (CF), geo-accumulation index (Igeo), and pollution load index (PLI) provides a comprehensive assessment of pollution status.

Previous studies (Isah *et al.*, 2019; Orosun *et al.*, 2023; Umeobi *et al.*, 2024) in other parts of North Central Nigeria have shown that contamination from mining activities often exhibits strong spatial variability, with higher concentrations of pollutants near mining sites and decreasing levels with distance. Vertical distribution patterns may also vary depending on soil characteristics and the mobility of specific contaminants.

However, limited information exists on the combined effects of distance and depth on soil quality in Benue State, particularly Anyiin community where Lead mining is pronounced. Therefore, this study assesses soil physicochemical and biological properties and heavy-metal concentrations at different distances and depths. The findings will support understanding of mining-induced degradation and strengthen environmental management, monitoring, remediation, and policy enforcement.

MATERIALS AND METHODS

The Study Area

Anyiin is a rural community in Mbagber Ward, Logo Local Government Area, Benue State, Nigeria. Its approximate coordinates are 7°49'08"N and 9°14'43"E (figure 1). With a rainy season from April to October and a dry season from November to March, the region has a tropical wet-and-dry climate. The typical temperature range is between 25°C and 35°C. The majority of the vegetation is Southern Guinea

Savanna, which is made up of grasses, shrubs, and sporadic trees. The native vegetation has been altered by agriculture, settlement, and fuelwood

gathering. Lead and zinc are among the mineral resources found in the region, along with major crops like rice, maize, yam, and cassava.

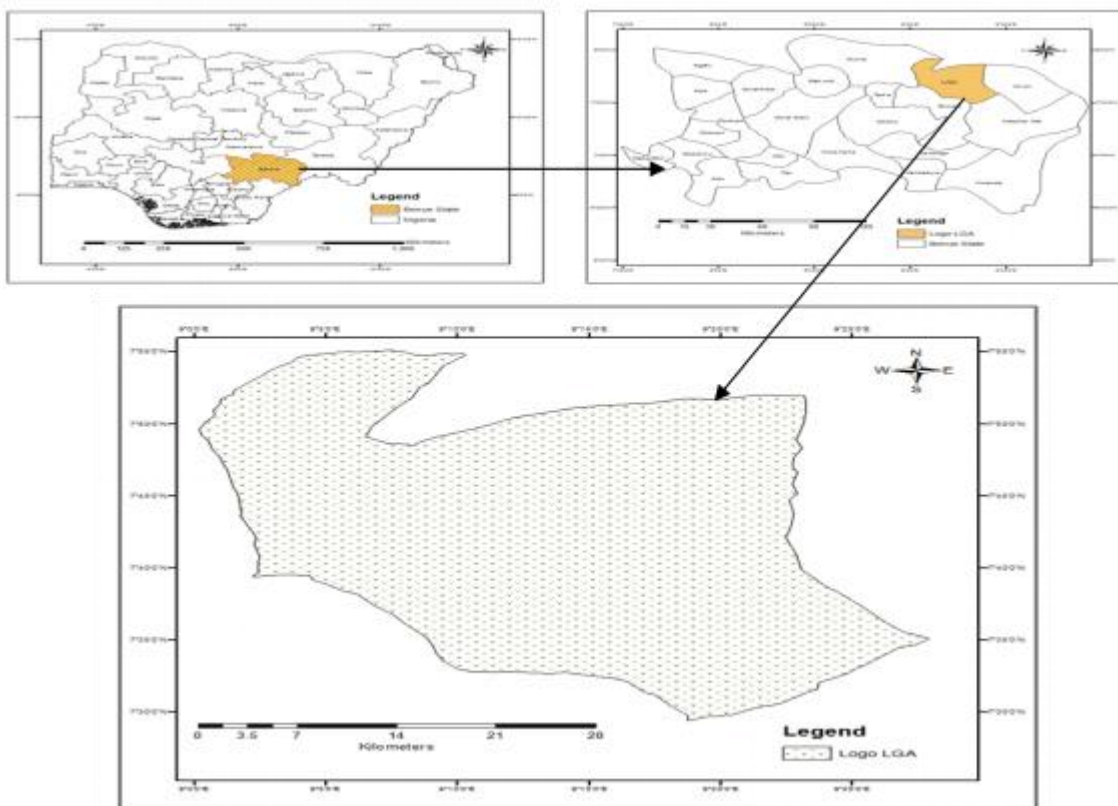


Fig.1: Map of the study Area

Data Collection/ Soil Sampling

Collection and Procedure

Soil samples were collected from selected locations around mining sites at depths of 0–30 cm and 30–60 cm using a soil auger. Sampling points were established on a grid, with five composite samples collected at each point. Additional samples were obtained at 0, 200 and 400 m from mining sites, with distal locations serving as reference/background areas. Samples were placed in labelled, sterilized polythene bags, sealed and transported to the laboratory for analysis following USEPA (1991) procedures.

Preparation

Samples were air-dried for 48 hours, gently ground, homogenized and sieved through a 2-mm (10-mesh) sieve. Subsamples required for physicochemical analyses were obtained before sieving, following USEPA (1991).

Physicochemical Analysis

Soil pH: Soil pH was determined electrometrically in a 1:2.5 soil–water suspension using an Ag/AgCl

electrode. The pH meter was calibrated with standard buffer solutions at pH 4 and pH 7 before measuring the soil samples (Adeyemo & Aliu, 2021).

Particle Size: Sand, silt and clay fractions were determined using the Bouyoucos hydrometer method (1965), following dispersion with sodium hexametaphosphate and sodium carbonate. Textural fractions were calculated from hydrometer readings.

Electrical Conductivity: Electrical conductivity was measured using a Jenway 4510 conductivity meter and expressed in $\mu\text{S}/\text{cm}$.

Organic Carbon: Organic carbon was determined by the Walkley–Black dichromate oxidation method (Bukoye *et al.*, 2023).

Effective Cation Exchange Capacity: ECEC was calculated as the sum of total exchangeable bases and exchangeable acidity (Moore *et al.*, 1998).

Heavy Metal Extraction and Analysis

Laboratory equipment was acid-washed with 3% HNO_3 and rinsed thoroughly with distilled water. One gram of each soil sample was digested using concentrated acids under controlled heating. The

digests were filtered, diluted to appropriate volumes and analyzed for Cr, Pb, Cd and other metals using an Atomic Absorption Spectrophotometer (AAS), following established procedures for the determination of metals in environmental samples (U.S. Environmental Protection Agency [USEPA], 1991; Beaty & Kerber 1993). Mercury was determined separately using a dedicated mercury analysis system. Calibration standards and reagent blanks were included as part of the analytical quality-control procedure.

Heavy Metal Contamination Assessment Method

The metal contamination of the soil samples was evaluated by applying enrichment Factor (EF), Contamination Factor (CF) Geo accumulation Index (GEO) and pollution load Index (PLI) The Enrichment Factor (EF) is a useful indicator reflecting the status and degree of environmental contamination (Feng *et al.*, 2004). The Enrichment Factor (EF) calculations compares each value with a given background level to establish the metal contamination from anthropogenic source (Choi *et al.*, 2012). The EF was calculated using the method proposed by Sinex and Helz, 1981 as follows:

$$EF = (\text{Metal/Fe})_{\text{sample}} / (\text{metal/fe})_{\text{background}}$$

Where (me/fe) sample is the metal to fe ratio in the sample interest.

(Me/Fe) background is the natural background value of metal to fe ratio

The ion was chosen as the element of normalization because of natural sources (1.5%) vastly dominates its input. Enrichment factor categories are listed in the Table 2.

Contamination Factor

The level of contamination factor by metal is expressed in terms of a containment factor (CF) calculated as –

$$CF = C_n \text{ Sample} / c_n \text{ Background}$$

Where, n is the number of metals

Data analysis Technique

Data on the physico-chemical and microbiological characteristics of the Soil from the laboratory analysis were analysed using descriptive statistics and inferential statistics (one-way analyses of variance). The one-way analysis of variance (ANOVA) was also used to test for significance differences among the variables. The ANOVA test assumes that, the data were normally distributed and the variances were homogeneous. Preliminary analyses were carried out to ensure that the data collected from the experiment meet the requirements for carrying out ANOVA test as violation of any of the assumptions of the ANOVA could lead to wrong inference. The software used to analysis the data for statistical analysis is STATA 17.

Table 1: EF categories (Mmolawa *et al.*, 2011)

S/N	EF	EF CATEGORIES
1	$EF < 2$	Deficiency to minimal enrichment
2	$2 \leq EF < 5$	Moderate enrichment
3	$3 \leq EF < 20$	Significant enrichment
4	$20 \leq EF < 40$	Very high enrichment
5	$EF \geq 40$	Extremely high enrichment

Table 2: contamination Factor (CF) level of contamination

S/N	CF	CONTAMINATION LEVEL
1	$CF < 1$	Low contamination
2	$1 \leq CF \leq 3$	Moderate contamination
3	$3 \leq CF < 6$	Considerable contamination
4	$CF > 6$	Very high contamination

Table 3: National Environmental Standards and Regulations Enforcement Agency [NESREA] Limit

Parameter	NESREA Limits
pH	7.0-8.5
As, mg/kg	0.05
Mn, mg/kg	50
Cd, mg/kg	2.0
Cr, mg/kg	10
Co, mg/kg	6.0
Cu, mg/kg	0.05
Hg, mg/kg	0.1
Pb, mg/kg	5.0
Ni, mg/kg	2.0
Zn, mg/kg	5.0
Fe, mg/kg	500
TPH, mg/kg	1.0
TOC, %	20
No ₃ ⁻ , mg/kg	100
PO ₄ ³⁻ , mg/kg	5.0
SO ₄ ²⁻ , mg/kg	200
Cl ⁻ , mg/kg	1000
Oil and grease mg/kg	0.1
Conductivity uS/cm	70
HUB X102(Cfu/g)	0.5
THF X104 (Cfu/g)	5.0

RESULTS

Effect of Sampling Distance on Soil Properties

The result of the study on sampling depth presented in Table 4 revealed that sampling depth considerably influenced some the soil properties tested, while most parameters did not differ significantly between the 0–30 cm and 30–60 cm depths. The soil pH decreased significantly from 7.042 at 0–30 cm to 6.867 at 30–60 cm ($p = 0.01$), though both depths stayed within the neutral to slightly alkaline range. Among the heavy metals, Cu, Hg, Ni, and Fe indicated significant differences between sampling depths. Copper increased significantly from 23.22 to 23.85 mg/kg ($p = 0.028$), mercury also increased from 0.1317 to 0.1517 mg/kg ($p = 0.003$).

Equally, nickel increased significantly from 50.28 to 51.72 mg/kg ($p = 0.016$), furthermore, iron increased from 177.0 to 185.8 mg/kg ($p = 0.002$) with increasing depth.

Nevertheless, As, Mn, Cd, Cr, Co, Zn, and TPH presented no significant differences between the two sampling depths ($p > 0.05$). Likewise, soil organic carbon (TOC), nitrate (NO₃), phosphate (PO₄), sulphate (SO₄), chloride (Cl), oil and grease, electrical conductivity, hydrocarbon-utilizing bacteria (HUB), and total heterotrophic fungi (THF) were not significantly affected by sampling depth.

The effect of sampling depth on soil properties

The results on effects of sampling depth on the physicochemical properties, heavy metal concentrations, hydrocarbon contents, nutrient levels, and microbial populations of the soil were presented in table 5. The result revealed that sampling depth significantly affected some soil properties, however, some of the parameters were not significantly influenced by depth.

Soil pH differed significantly between the two depths ($p = 0.01$), decreasing from 7.042 at 0–30 cm to 6.867 at 30–60 cm. Conversely, both soil layers were generally within the neutral range.

Among the heavy metals, Arsenic (As), Manganese (Mn), Cadmium (Cd), Chromium (Cr), Cobalt (Co), and Zinc (Zn) were not significantly different between the two sampling depths ($p > 0.05$). On the other hand Copper (Cu), Mercury (Hg), Nickel (Ni), and Iron (Fe), were significantly affected by sampling depth. Copper increased from 23.22 mg/kg at 0–30 cm to 23.85 mg/kg at 30–60 cm ($p = 0.028$), similarly, Mercury increased from 0.1317 mg/kg to 0.1517 mg/kg ($p = 0.003$). Nickel also shows significant increase from 50.28 mg/kg in the surface layer to 51.72 mg/kg in the deeper layer ($p = 0.016$). Furthermore, there was significant increase in Iron concentration from 177.0 mg/kg at 0–30 cm to 185.8 mg/kg at 30–60 cm ($p = 0.002$).

Table 5 also revealed that, Total petroleum hydrocarbons (TPH) showed no significant difference between the two depths, with concentrations of 210.3 and 213.0 mg/kg at 0–30 cm and 30–60 cm, respectively. Also, Total Organic Carbon (TOC), Nitrate (NO₃), Phosphate (PO₄), Sulphate (SO₄), Chloride (Cl), oil and grease, and electrical conductivity were not significantly affected by sampling depth ($p > 0.05$).

The microbial parameters, including hydrocarbon-utilizing bacteria (HUB) and total heterotrophic fungi (THF), also indicated no significant differences between the two soil depths. HUB values were 2.617 and 2.608 Cf/g, while THF values were 3.875 and 3.908 Cf/g at 0–30 cm and 30–60 cm, respectively.

Combine Effect of Sampling Distance and Depth on Soil Properties

The results in table 6 revealed that the interaction between sampling distance and depth had significant effects on all the measured soil properties. Soil pH varied significantly across the sampling locations and depths, ranging from 6.575 at 0 m and 0–30 cm depth to 7.425 at 400 m and 0–30 cm depth. Largely, the concentrations of most heavy metals decreased with increasing distance from the contamination source. For instance, arsenic decreased from 13.10 mg/kg at 0 m to 7.35 mg/kg at 400 m, while manganese declined from 272.50 to 112.80 mg/kg.

Similar decreasing trends were observed for cadmium, chromium, cobalt, copper, nickel, zinc, and

iron. Mercury also varied significantly, with the highest concentration (0.175 mg/kg) recorded at 0 m and 0–30 cm depth and the lowest (0.095 mg/kg) at 400 m and the same depth. These findings suggest that the areas closer to the contamination source were more affected by heavy metal accumulation.

Total petroleum hydrocarbons (TPH) and total organic carbon (TOC) were also significantly affected by the interaction between sampling distance and depth. TPH was highest at 0 m, recording 271 mg/kg at 0–30 cm depth, and generally decreased with increasing distance, reaching 162.50 mg/kg at 400 m. Similarly, TOC declined from 2.85% at 0 m to 1.65% at 400 m. Soil nutrients, including nitrate, phosphate, sulphate, and chloride, also showed significant differences and generally decreased with increasing distance from the source.

Oil and grease and electrical conductivity followed similar patterns, with higher values recorded at locations closer to the source and lower values at greater distances. Oil and grease declined from 85.70 at 0 m to 48.85 at 400 m, while conductivity decreased from 60.83 to 31.70 $\mu\text{S}/\text{cm}$. The microbial populations were also significantly influenced by the interaction of distance and depth. Hydrocarbon-utilizing bacteria (HUB) and total heterotrophic fungi (THF) were generally higher at locations closer to the contamination source and decreased with increasing distance.

Table 4: Effect of Sampling Distance on Soil Properties

sampling spacing	pH	As (mg/kg)	Mn (mg/kg)	Cd (mg/kg)	Cr (mg/kg)	Co (mg/kg)	Cu (mg/kg)	Hg (mg/kg)	Ni (mg/kg)	Zn (mg/kg)	Fe (mg/kg)	TPH (mg/kg)	TOC(%)	NO3 (mg/kg)	po4 (mg/kg)	SO4 (mg/kg)	Cl (mg/kg)	oil and grease	Conductivity (uS/cm)	HUB(Cf u/g)	THF(Cf u/g)
0	6.763	12.19	248.8	0.155	21.38	12.69	26.85	0.165	58.34	132.5	211.1	253	2.65	39.74	15.76	26.52	26.52	80.25	56.49	3.625	5.4
200	6.925	9.75	178.8	0.0938	15.76	9.66	23.47	0.145	50.8	111.5	181.2	207.8	2.2	32.49	12.5	21.54	21.54	63.37	45.54	2.538	3.8
400	7.175	8.05	129.5	0.0613	11.32	7.03	20.27	0.115	43.86	94.8	151.8	174.2	1.75	27.01	9.93	16.48	16.48	51.37	34.83	1.675	2.475
f.pro	<.001	<.001	<.001	<.001	<.001	<.001	<.001	<.001	<.001	<.001	<.001	<.001	<.001	<.001	<.001	<.001	<.001	<.001	<.001	<.001	<.001
lsd ≤ 0.05	0.1556	0.609	18.62	0.0119	1.726	0.976	0.678	0.015	1.382	6.14	6.28	8.65	0.152	1.843	0.91	1.304	1.304	4.472	3.728	0.2648	0.3956

Source: Field 202**Table 5: Effects of sampling depth on Soil Properties**

Samplin g depth	pH	As (mg/kg)	Mn (mg/kg)	Cd (mg/kg)	Cr (mg/kg)	Co (mg/kg)	Cu (mg/kg)	Hg (mg/kg)	Ni (mg/kg)	Zn (mg/kg)	Fe (mg/kg)	TPH (mg/kg)	TOC (%)	NO ₃ (mg/kg)	PO ₄ (mg/kg)	SO ₄ (mg/kg)	Cl (mg/kg)	oil and grease	Conduc tivity (uS/cm)	HUB (Cfu/ g)	THF (Cfu/ g)
0-30	7.042	9.91	183.4	0.1037	15.9	9.61	23.22	0.1317	50.28	111.7	177	210.3	2.217	32.97	12.7	21.58	21.58	64.71	45.55	2.617	3.875
30-60	6.867	10.08	187.9	0.1029	16.41	9.98	23.85	0.1517	51.72	114.2	185.8	213	2.183	33.19	12.76	21.44	21.44	65.29	45.68	2.608	3.908
f.pro	0.01	0.465	0.538	0.857	0.454	0.34	0.028	0.003	0.016	0.305	0.002	0.434	0.572	0.754	0.869	0.781	0.782	0.738	0.927	0.936	0.829
lsd ≤ 0.05	0.127	Ns	Ns	Ns	Ns	ns	0.554	0.01231	1.128	Ns	5.13	ns	Ns	Ns	ns	ns	Ns	ns	Ns	Ns	ns

Source: Fieldwork 2026**Table 6: Combined Effect of Sampling Distance and Depth on Soil Properties**

samplin g spacing	Samplin g depth	pH	As	Mn	Cd	Cr	Co	Cu	Hg	Ni	Zn	Fe	TPH	TOC	NO ₃	PO ₄	SO ₄	Cl	oil and grease	conduct ivity	HUB	THF
0	0-30	6.575	13.1	272.5	0.175	22.9	13.68	28.4	0.175	61.95	139.5	221.9	271	2.85	42.17	17.05	28.72	28.72	85.7	60.83	4.075	6.025
	31-60	6.95	11.27	225	0.135	19.85	11.7	25.3	0.155	54.73	125.5	200.4	235	2.45	37.3	14.48	24.32	24.32	74.8	52.15	3.175	4.775
200	0-30	7.125	9.27	165	0.085	14.72	9.03	22.55	0.125	48.6	106.5	170.5	197.5	2.15	31.25	11.85	20.8	20.8	59.57	44.13	2.3	3.45
	31-60	6.725	10.22	192.5	0.1025	16.8	10.3	24.4	0.165	53	116.5	191.9	218	2.25	33.72	13.15	22.27	22.27	67.17	46.95	2.775	4.15
400	0-30	7.425	7.35	112.8	0.0512	10.07	6.13	18.7	0.095	40.3	89	138.5	162.5	1.65	25.47	9.2	15.22	15.22	48.85	31.7	1.475	2.15
	31-60	6.925	8.75	146.2	0.0712	12.57	7.93	21.85	0.135	47.42	100.5	165	186	1.85	28.55	10.65	17.73	17.73	53.9	37.95	1.875	2.8
f.pro		<.001	<.001	<.001	<.001	0.006	0.002	<.001	<.001	<.001	<.001	<.001	<.001	0.002	<.001	<.001	<.001	<.001	<.001	<.001	<.001	<.001
lsd ≤ 0.05		0.22	0.861	26.33	0.01683	2.441	1.38	0.959	0.02131	1.954	8.69	8.88	12.24	0.213	2.606	1.287	1.844	1.844	6.324	5.272	0.3745	0.5594

Source: Fieldwork 2026

DISCUSSION

Results (Table 4) reveal that sampling distance significantly affected all soil parameters ($p < 0.05$), demonstrating strong spatial difference in soil physicochemical and biological properties around the mining area. Similar patterns have been reported in mining-impacted soils, where contaminant concentrations vary with proximity to mining and smelting sources (Li *et al.*, 2020; Yao *et al.*, 2021; Zhang *et al.*, 2022). Soil pH increased from 6.763 at 0 m to 7.175 at 400 m, showing a shift from slightly acidic to near-neutral situations with increasing distance. Mining activities can change soil pH and other edaphic conditions, influencing metal movement and microbial processes (Chen *et al.*, 2021; Wang *et al.*, 2021).

All heavy metals (As, Mn, Cd, Cr, Co, Cu, Hg, Ni, Zn and Fe) steadily decreased with increasing distance, revealing a strong spatial contamination gradient. Similar distance-related declines have been reported around mining and smelting sites, reflecting reduced anthropogenic inputs and processes such as dispersion and adsorption (Li *et al.*, 2020; Yao *et al.*, 2021; Liu *et al.*, 2022). Nutrient concentrations also varied with distance, consistent with mining-related changes in vegetation, soil structure and biogeochemical processes (Wang *et al.*, 2021). Mining disturbance can additionally alter soil microbial communities and their functions, with soil pH influencing microbial distribution (Xiao *et al.*, 2021). Table 5 shows that sampling depth significantly influenced only selected soil properties, while most physicochemical, heavy metal, hydrocarbon, nutrient, and microbiological parameters did not differ significantly between the 0–30 cm and 30–60 cm depths. Soil pH decreased from 7.042 to 6.867, indicating a slight increase in acidity with depth, potentially due to differences in mineral composition, water movement, organic matter dispersion, and downward chemical transport. This agrees with Eludoyin *et al.* (2017), who reported that artisanal gold mining alters soil physicochemical properties and pollutant distribution.

Copper, nickel, iron, and mercury increased significantly with depth, signifying downward movement and deposition through leaching and translocation, predominantly where mining disturbance improves contaminant movement. Similar concerns were reported by Emumejaye *et al.* (2025) and Garkida *et al.* (2025), while Maniyunda *et al.* (2024) noted that mining can alter soil properties and ecosystem suitability. In contrast, As, Mn, Cd, Cr,

Co, and Zn revealed no significant depth differences, indicating fairly uniform distribution within the 0–60 cm profile. TPH, TOC, nutrients, oil and grease, EC, HUB, and THF were also unaffected by depth, probably reflecting vertical mixing or contaminant movement across the soil profile.

These findings support evidence that mining modifies soil and environmental conditions (Liman *et al.*, 2021; Mhangara *et al.*, 2020).

Table 6 showed that the interaction between sampling distance and soil depth significantly affected all measured soil properties. Soil pH increased from 6.575 at 0 m to 7.425 at 400 m in the 0–30 cm layer, indicating greater acidity near the mining source. This agrees with Okafor *et al.* (2024), who reported significant variations in soil physicochemical properties around the Enyigba mining site in Ebonyi State, Nigeria, due to mining activities.

The majority of heavy metals gradually decreased as the distance from the mining source increased. For instance, Mn plunged from 272.50 to 112.80 mg/kg between 0 and 400 m, whereas As dropped from 13.10 to 7.35 mg/kg. Cd, Cr, Co, Cu, Ni, Zn, and Fe all showed comparable distance-related declines, suggesting a significant geographical contamination gradient linked to mining activity. This pattern is consistent with the findings of Umeobi *et al.* (2024), who found higher potentially hazardous components in soils damaged by Pb-Zn mining in southeast Nigeria. In a similar vein, Ukpe *et al.* (2022) showed that while evaluating the soil quality surrounding lead-zinc mining regions in Ikwo, Ebonyi State, both sample distance and soil depth were crucial factors.

Similar spatial tendencies were observed in other soil characteristics. Oil and grease decreased from 85.70 to 48.85, TPH from 271 to 162.50 mg/kg, and TOC from 2.85% to 1.65%. Nitrate, phosphate, sulfate, chloride, and electrical conductivity similarly reduced with distance. According to findings of some studies from mining sites in Nigeria (Liman *et al.*, 2021; Mhangara *et al.*, 2020) revealed that mining had an impact on both chemical and biological soil quality. Okafor *et al.* (2024) reported comparable alterations in organic carbon, nutrients and other physicochemical properties of mining-affected soils in Ebonyi State.

The substantial distance–depth interaction shows that pollutants were moving vertically and dispersing horizontally. pH, organic carbon, clay content, and cation exchange capacity can all have an impact on the distribution of metals (Umeobi *et al.*, 2024). According to Wang *et al.* (2025), weathering and leaching caused Pb to migrate downward in soils

impacted by Pb-Zn mining. The similar distribution of TPH and oil and grease suggests that hydrocarbon substrates are available, which could explain the greater HUB concentrations found close to the lead-zinc mining site. However, rather than just TPH, the observed pattern might potentially represent the combined impact of organic matter and other soil characteristics. Microbial communities react significantly to gradients of metal pollution, according to evidence from Pb-Zn mining sites, and microbial biomass and activity can be positively influenced by organic matter and nutrition availability (Liu *et al.*, 2007; Zubek *et al.*, 2020).

CONCLUSION

The study established that lead mining activities affected the physicochemical, chemical, and biological properties of soils in Anyiin Community, Benue State. The study witnessed significant variations in selected soil properties with sampling depth and distance from the mining source. Sampling depth significantly influenced soil pH, Cu, Hg, Ni, and Fe. Soil pH decreased from 7.042 in the 0–30 cm layer to 6.867 in the 30–60 cm layer, while Cu, Hg, Ni, and Fe generally increased with depth, indicating vertical distribution of some contaminants.

Although most of other heavy metals, hydrocarbons, nutrients, and microbial parameters revealed no significant differences between depths, the significant interaction between sampling distance and depth for all evaluated soil properties establishes that contamination patterns varied both horizontally and vertically.

The spatial distribution of contaminants further supports the occurrence of a mining-related contamination gradient. Most heavy metals decreased with increasing distance from the mining source. Arsenic declined from 13.10 mg/kg at 0 m to 7.35 mg/kg at 400 m, while Mn decreased from 272.50 to 112.80 mg/kg. Similar decreases occurred for Cd, Cr, Co, Cu, Hg, Ni, Zn, and Fe. TPH decreased from 271 to 162.50 mg/kg, while TOC declined from 2.85% to 1.65% with increasing distance. These patterns show that contamination was largely more pronounced near the mining source. The corresponding spatial changes in nutrients, oil and grease, electrical conductivity, hydrocarbon-utilizing bacteria, and total heterotrophic fungi further reveal variations in soil conditions around the mining area. The significant depth effects, distance-related concentration gradients, and distance–depth interactions justify the conclusion that mining activities contributed to soil contamination and

degradation. Regular monitoring at different depths and distances is therefore recommended, alongside proper mine-waste management and regulation. Highly contaminated areas should be prioritized for remediation and reclamation through appropriate methods such as phytoremediation, soil stabilization, organic amendment, and revegetation.

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