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Assessing the Impacts of Coal Mining on Soil Quality in Kogi East, Nigeria

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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ABSTRACT

This study investigates the effects of coal mining on soil physical and chemical properties in Kogi East, Nigeria, focusing on two mined sites (Ika-Ogboyaga and Okaba) and one unmined control site (Abache). Soil samples were collected from 32 plots across mined areas and 16 plots in the unmined site using a 200m x 200m belt transect method. Samples were analyzed for particle size, bulk density, soil pH, organic matter, nitrogen, phosphorus, exchangeable cations, and heavy metal concentrations using standard laboratory methods. Results show minimal differences in soil texture (sandy clay loam) across all sites, with slightly higher bulk density in mined areas (1.89±0.2g/cm^3, 1.87±0.6 g/cm^3), indicating soil compaction from mining activities. Chemical properties, including pH, organic carbon, nitrogen, and cation exchange capacity, showed minor variations, while heavy metal concentrations (Zn, Cu, Fe, Pb) were within safe limits across all sites. Analysis of Variance (ANOVA) (F-value=0.00449; F-crit=3.1907; P-value=0.995511) showed no significant differences in most soil properties between mined and unmined areas, suggesting limited impact of coal mining on soil quality in the region. To improve soil health and sustainability the study recommended

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mitigating soil compaction, implementing vegetation rehabilitation with native species, conducting continuous soil monitoring, raising community awareness, and promoting sustainable mining practices.

Keywords: Coal mining; soil compaction; heavy metals; soil quality.

1. INTRODUCTION

"The mining sector worldwide is greatly important for income generation, employment, economic growth, development and competitive advantage" (Jerome 2003; Oelofse, Hobbs, Rascher and Cobbing, 2008). "Mining, however, poses major threats and hazards that can jeopardize ecosystems of nations. Nigeria has been actively engaged in solid mineral exploitation for decades and is endowed with deposits of more than 34 solid minerals, including coal, tin, columbite, gold, lead, zinc, thorium, lignite, uranium and tantalum in more than 450 locations across the country" (Mining Journal 2006). "Mining brought new potential hazards and risks to the environment" (Lazareva and Pichler 2007; Othman and Al-Masri 2007; Li, Zhang, Shao, Zhou, Xie, Fang and Wang 2014). "In addition, mining waste land is an inevitable by-product which caused a great mass of soils being spoiled away" (Liu et al. 2003; Li et al. 2014). "On the contrary, coal is the most abundant fossil fuel on the earth (Rashid et al. 2014) that comprises about 75% of the total fuel resources" (Elliott 1981; Rashid et al. 2014). "So, coal mine is necessary to meet the energy demand of a country and coal mines are being excavated frequently in the world. But coal mining has severe environmental, ecological, and human-health consequences. If not done properly, coal mining has potential to damage landscape, soils, surface water, groundwater, air during all phases of exploration" (Martha 2001).

"Mining of solid minerals like coal has the potential of causing environmental degradation. Vegetation in form of natural forest and crop land are usually the first casualty in exploration and exploitation of coal. Open cast method of mining is in use in the coal mines in Ankpa and Omala LGA of Kogi State. This strip mining process involves removal of overburden that overlies the coal in order to expose it. The coal is scooped from the ground using very large cranes and trucks. It is an undeniable fact that coal mining and its uses have different effects on the ecosystem" (Thomas 2002).

It must be emphasized that the mining of the coal in the present study areas was never subjected to Environmental Impact Assessment, therefore, the study area lacks basal data on the ecological indices such as soil quality.

A number of studies have reported the high possibility of contamination by heavy metals and hazardous elements due to coal mining and exploitation in ecosystems within mine sites in China Sun et al (2021) Assessed the Effects of vegetation restoration on soil enzyme activity in copper and coal mining areas, Xiao et al (2021) Examined the relationship between coal mining subsidence and crop failure in plains with a high underground water table, in the same vein in Nigeria, Kogi State Ameh, Idakwo and Ojonimi (2021) Assessed the Seasonal Variations of Toxic Metal Pollution in Soil and Sediment Around Okaba Coal Mine Area, Kogi, Nigeria, Oloche et al, 2019 Evaluated the Effect of Coal Mining on the Water Quality of Water Sources in Nigeria, Ekwule, Ugbede and Akpen (2021) Assessed the Effect of Heavy Metal Concentration on the Soil of Odagbo Area, Kogi State Nigeria.

However, none of the studies has examined the implications of coal mining on soil quality in the Ika-ogboyaga mine sites in the study area and this constitute the gap of the study. Hence, the need for this study.

2. RESEARCH METHODS

2.1 Description of the Study Area

"Ankpa LGA lies between longitude 7°36'E to 7°39' E and latitude 07°23' N to 07°26' N (Fig. 1). Ankpa has an area of 1,200km^2 and a population of 267,353 according to Nigeria population census of 2006" (Ishaka, 2012).

"Ankpa falls within the Nigeria meteorological zone that is characterized by warm temperature days and moderately cool nights. Two distinct climatic divisions are demarcated as the dry and rainy seasons representing two broad periods of significant but contrasting variations of weather parameters. The area has warm Tropical Savanna Climate with clearly marked wet and dry seasons" (Ali, 2010). "Rainfall is well distributed and is of double maxima" (Iloeje, 1972). "The amount of rainfall ranges between 1,000mm^3 to 1,750mm^3. Temperature is moderately high throughout the year, averaging 25°C. The maximum temperature of the area lies between 29.7°C – 35.6°C while the minimum temperature ranges between 23.3°C and 25.2°C" (Ali, 2010).

"The dominant vegetation communities remain the tropical savanna woodland of secondary types and mixtures of scattered tropical trees and grassland formations. Vegetation distribution in this area follows a pattern that is similar to that of rainfall distribution" (Ukwedeh ,2003).

"The study area is known for its rich source of a variety of medicinal, cultural and edible wild plants, such as; *Abrus precatorius Linn*, *Allophyllus Africanus, Butyrospermum paradoxum* (Gaerrn, f.) Hepper/ vitellaria paradoxum (Gaertn,f), *Dennettia tripetala* and *Cola nitida"* (Aniama et al, 2016).

The prevalent land use and socioeconomic activity of the study area includes farming, mining, trading among others. Although, over time there has been a rapid change in the land-use/land cover characteristics in the study area due to development and change in land use from farmland to residential and commercial among others that are prevalent in the area and may be responsible for the considerable reduction in agrarian land use. In a study by Tokula and Ejaro, 2018, they discovered a considerable change in the land-use/land cover characteristics in Ankpa town.

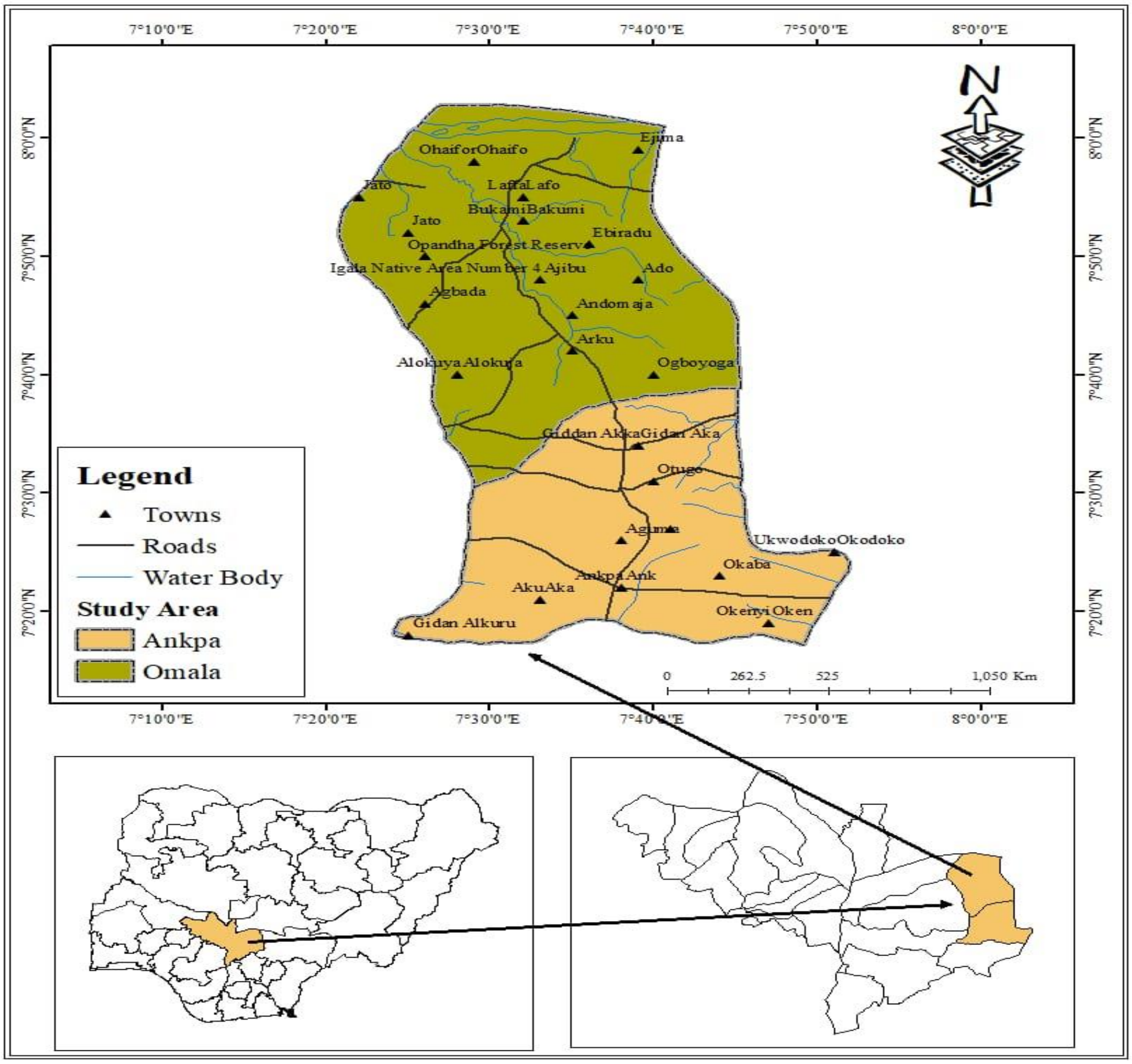

Fig. 1. Map of the study area

2.2 Sample Collection and Preparation

"The soils for the study were obtained from the Ika-Ogboyaga and Okaba mine sites with a control in Abache. A 200m× 200m belt transect was constructed across each of the mined and unmined study sites. Each belt transect was divided into 16 plots with each plot measuring 50m× 50 m. In all, 4 belt transects (200m× 200 m) were constructed in the mined areas and 2 belt transects (200m× 200 m) in the unmined study site for the soil sampling. At each sampling location, 8 out of the 16 constructed plots (50m× 50 m) were randomly selected for sampling. Soil samples were taken from the midpoint of each randomly selected plot. The soils were collected with hand auger to the depth of 0–30 cm at each sampling point. Soil replicates (three replicates for each sample) were taken to help monitor the precision of the overall procedure and field variability" (NIST, 1995). "A total of 32 soil samples were collected from the mine sites and 16 samples from the unmined site. The soils were sealed in plastic bags and returned promptly to the laboratory and air-dried. The soils were then rolled gently with a roller, and clods were broken to facilitate drying. Soil debris and larger coarse fragments were hand-picked. Mortar and pistil were used to grind the soils to break down the soil aggregates and reduce soil particle size so as to pass through a 2mm sieve. The soils were then screened through a 2mm sieve using robber stopper to obtain representative subsamples" (Klesta and Bartz, 1996). The sieved soil samples were put into plastic pots and sent for analysis in the laboratories of the Federal University of Technology Minna.

2.3 Laboratory Analyses

"The particle size analysis was determined using hydrometer method in 5% sodium hexametaphosphate as the dispersing agent" (Bouyoucos, 1951).

Total porosity, bulk density and soil moisture content were determined using methods outlined by Odu et al. (1986). The pH of the soil was determined electrometrically using a pH meter in 1:1 soil – 1M KCl and 1:1 soil-water suspensions (Mclean, 1982). Organic matter was determined using Walkley -Black wet oxidation method (Nelson and Sommers, 1982). Total nitrogen of the soil was determined using the macro Kjeldahl method (Bremner and Mulvaney, 1982). Available phosphorus in the soil was determined using Bray P1 method (Olsen and Sommers, 1982).

"Exchangeable cations (Ca^{2+}, Mg^{2+}, K^+ and Na^+) were determined using 1M NH_4OAc (Ammonium acetate) buffered at pH 7.0 as extractant" (Thomas, 1982). "The K^+ and Na^+ concentrations in soil extracts were read on Gallenkamp flame photometer while Ca^{2+} and Mg^{2+} concentrations in soil extracts were read using Perkin-Elmer Model 403 atomic absorption spectrophotometer (AAS). The exchangeable acidity (H^++Al^{3+}) in the soil was extracted with 1M KCl" (Thomas, 1982). "Solution of the extract was titrated with 0.05M NaOH to a permanent pink endpoint using phenolphthalein as indicator. The amount of base (NaOH) used is equivalent to the total amount of exchangeable acidity (H^++Al^{3+}) in the aliquot taken" (Odu et al., 1986).

To determine the concentration of heavy metals in the samples, one gram of pulverized and oven-dried soil (dried at 50°C) was weighed into a 100 mL conical flask and moistened with distilled water. Ten milliliters (10 mL) of aqua regia (HNO_3:HCl in a 3:1 ratio) was added, and the mixture was boiled with steady heat until almost dry. The residue was allowed to cool and then leached with 5 mL of 6M H_2SO_4. An additional 5 mL of distilled water was added, and the mixture was boiled for 10 minutes. After cooling, the solution was filtered, and the filtrate was diluted to 100 mL for metal analysis. The concentrations of Cu, Pb, Fe, and Zn were determined using a Buck Scientific 211 Atomic Absorption Spectrophotometer (AAS VGP).

2.4 Statistical Analyses

The statistical software R (R Core Team 2014) was used to perform all the statistical analyses of soil physical and chemical properties. Analysis of variance (ANOVA) was used to test for a difference in soil properties between the mined and unmined sites.

The quality of soil with respect to heavy metal concentrations was determined using the Nemerow Index (*Ps*). The Nemerow Pollution Index classifies the quality of soil into five domains; "Safety" (*Ps* = less than 0.7), "Precaution" (*Ps* = 0.7–0.99), "Slightly Polluted" (*Ps* = 1.0–1.99), "Moderately Polluted" (*Ps* = 2.0–2.99), and "Seriously or Heavily Polluted" (*Ps* = greater than 3.0) (Liang, Chen, Song, Han, & Liand, 2011; Qingjie, Jun, Yunchuan, Qingfei, & Liqiang, 2008).

$$Ps = \sqrt{(P^2ave + P^2max)/2}$$

$$P_I = \frac{Ci}{Cref}$$

where *Ps*= Index; P^2ave = Average of *Pi* of all the metals considered; P^2max = Maximum of *Pi* of all the metals considered; *Pi* = the single pollution index of heavy metal; *Ci* = Mean concentrations of heavy metal (*i*) from at least five sampling sites; *Cref* = Evaluation criteria value.

3. RESULTS AND DISCUSSION

3.1 Soil Physical Properties

Result of the physical properties presented in Table 1 revealed that sand fraction in Ika-Ogboyaga mine site, Okaba mine site and Abache (control) include; 60 ± 0.7, 61 ± 1.4 and 60 ± 1.2% respectively. The sand content across all sites is quite consistent, with only minor variations. This indicates a similarity in the sand fraction of the soils from both mined and control sites, suggesting that mining activities may not have a significant impact on sand content. In the same vein the silt content in Ika-Ogboyaga mine site, Okaba mine site and Abache (control) include; 19 ± 0.5, 17 ± 1.4 and 15 ± 1.7% respectively. The silt content is slightly higher at the mined sites, particularly at Ika-Ogboyaga. The control site, Abache, shows a lower silt content. The slightly elevated silt content in the mine sites may indicate some changes in soil structure due to mining activities, such as the deposition of finer materials. Also, the clay content in Ika-Ogboyaga mine site, Okaba mine site and Abache (control) include; 21 ± 0.8%, 22 ± 2.1% and 25 ± 0.9% respectively. The clay content is higher in the control site (Abache) compared to the mine sites. This suggests that mining activities could lead to a reduction in clay content, possibly due to soil disturbance and erosion associated with mining processes. Clay particles are easily dislodged and can be carried away by runoff, which could explain the slightly lower values in the mined areas. Studies have shown that clay have large surface area by virtue of its small size. It is the most active mineral that aids in the aggregation of primary soil particles and ensure stability of such aggregate (Idoga, 1985). Therefore, the relatively high clay content of the studied soils showed that the soils have good water and nutrient retention potentials, if properly managed.

Also, bulk density values in Ika-Ogboyaga mine site, Okaba mine site and Abache (control) include; 1.89 ± 0.2 g/cm³, 1.87 ± 0.6 g/cm³ and 1.78 ± 0.4 g/cm³ respectively. This result shows that bulk density is slightly higher in the mine sites compared to the control site. Higher bulk density in the mined areas could indicate soil compaction resulting from heavy machinery use during mining activities. Compaction reduces soil porosity and can negatively affect root growth, water infiltration, and overall soil health. The lower bulk density in the control site suggests less compaction, allowing for better soil structure and aeration. Heavy traffic on the top soil within the vicinity of the mining may have contributed to the high bulk density within the mining area (Aina, 1989).

Also, all three sites are classified as Sandy Clay Loam (SCL). This consistency in textural class implies that, despite the small differences in particle size distribution and bulk density, the overall soil texture remains relatively similar across both mined and unmined sites. This is normal for this type of humid tropical soils that are mostly sandy in nature (Lal, 1985).

3.2 Soil Chemical Properties

Result of the chemical properties presented in Table 2 revealed that the pH (H_2O) values of the soils across the sites are slightly acidic to neutral, with minor variations. The soil pH of control (6.8) is between the values of the mine sites. (Ika-Ogboyaga: 6.9, Okaba: 6.7). The results suggest that mining activities have had minimal impact on the soil pH, as both mine and control sites show values within a close range. Similarly, in ($CaCL_2$) the trend is consistent with the pH in H_2O, showing a slight increase in acidity in $CaCl_2$, which is expected as this method often gives lower pH values due to ionic strength differences. Again, the control site exhibits a pH similar to the mine sites, indicating minimal disturbance due to mining. African soils are generally slightly acidic (Akinnifesi et al., 2005) if uncontaminated.

The organic carbon content is slightly higher in the mine sites (Ika-Ogboyaga: 0.29%, Okaba: 0.30%) compared to the control site (0.26%). This could indicate organic matter accumulation or reduced organic matter degradation at the mine sites. The removal of vegetation (Salami et al., 2002) and top soil (Agboola, 1982) had been found to have adverse effect on humid tropics' soil organic matter.

The total nitrogen content is higher in the mine sites (Ika-Ogboyaga: 0.41%, Okaba: 0.39%) than in the control site (0.32%). This could reflect changes in nutrient cycling or nitrogen inputs related to mining activities. The higher nitrogen levels in the mine sites may point to organic matter accumulation or reduced leaching due to mining-induced soil compaction.

Similarly, available phosphorus is lower in the mine sites compared to the control site (Abache: 28.18 mg kg^{-1}). Phosphorus reduction in the mine sites could result from mining processes disturbing the soil structure, leading to reduced availability of phosphorus. The study sites were slightly acidic as reported earlier (Wild, 1995); or capture by Ca to form calcium triphosphate, one of the unavailable forms of phosphorus.

Also, the values of the Exchangeable cations (Na^+, K^+, Mg^{2+}, Ca^{2+}) in Ika-Ogboyaga mine site, Okaba mine site and Abache (control) include; 1.69 ± 0.5, 1.71 ± 0.3, 1.77 ± 0.6; 1.62 ± 0.8, 1.68 ± 0.6, 1.65 ± 0.4; 3.92 ± 0.5, 3.90 ± 0.2, and 3.74 ± 0.5, 4.91 ± 0.2, 4.79 ± 0.3, 4.84 ± 0.6 respectively. Exchangeable cations are essential nutrients for plant growth, and their values are fairly consistent across the mine and control sites.

In the same vein, Exchangeable acidity (EA) is similar across the mine sites and control site, with values ranging between 0.80 and 0.82. This suggests that the mining activities have not significantly impacted the soil's acidity, indicating stability in soil reaction to environmental changes.

Also, the CEC values in Ika-Ogboyaga mine site, Okaba mine site and Abache (control) include; 12.95 ± 0.9, 12.08 ± 1.1 and 12.80 ± 0.8. respectively. CEC is a measure of soil fertility, indicating the soil's ability to hold and exchange cations. The control site (12.80) has a slightly higher CEC than Okaba (12.08) but is similar to Ika-Ogboyaga (12.95). These results indicate that the soils across the sites have moderate fertility levels, with minimal impact from mining activities.

3.3 Heavy Metal Concentration of the Samples

Table 3 shows that the concentration of Zinc in Ika-Ogboyaga mine site, Okaba mine site and Abache (control) include; 3.99 ± 0.8, 4.02 ± 0.6 and 4.00 ± 0.4ppm respectively.

Table 1. Physical properties of the soils from the mined and unmined sites

Property		Ika-Ogboyaga Mine Site	Okaba Mine site	Abache (Control)
Particle size (%)	Sand	60±0.7	61±1.4	60±1.2
	Silt	19±0.5	17±1.4	15±1.7
	Clay	21±0.8	22±2.1	25±0.9
Bulk density (g/cm^3)		1.89±0.2	1.87±0.6	1.78±0.4
Textural class		SCL	SCL	SCL

Table 2. Chemical properties of the soils from the mined and unmined sites

Property		Ika-Ogboyaga Mine Site	Okaba Mine site	Abache (Control)
pH	In H_2O	6.9±0.8	6.7±1.4	6.8±1.2
	In 1:2.5 $CaCL_2$	6.7±0.6	6.4±0.4	6.6±0.7
Organic carbon (%)		0.29±1.8	0.3±1.3	0.26±1.1
Total Nitrogen (%)		0.41±0.6	0.39±0.9	0.32±0.7
Available Phosphorous (mgkg^{-1})		26.13±1.3	25.12±1.5	28.18±1.3
Exchangeable Cations	Na^+	1.69±0.5	1.71±0.3	1.77±0.6
	K^+	1.62±0.8	1.68±0.6	1.65±0.4
	Mg^{2+}	3.92±0.5	3.90±0.2	3.74±0.5
	Ca^{2+}	4.91±0.2	4.79±0.3	4.84±0.6
Exchangeable Acidity (EA)		0.81±1.2	0.82±1.4	0.80±1.2
CEC		12.95±0.9	12.08±1.1	12.80±0.8

Table 3. Result of heavy metals concentration in samples from the mined and unmined sites

Element	Ika-Ogboyaga Mine Site	Okaba Mine site	Abache (Control)
Zinc (ppm)	3.99±0.8	4.02±0.6	4.00±0.4
Copper (ppm)	0.48±1.3	0.47±0.9	0.43±1.1
Iron (ppm)	5.95±0.6	6.01±0.4	5.94±0.7
Lead (ppm)	0.01±0.03	0.01±0.03	0.01±0.03

Zinc is an essential micronutrient for plants, but elevated levels can be toxic. The results show that Zinc concentrations are quite similar across the mine and control sites. Ika-Ogboyaga (3.99 ppm) and Okaba (4.02 ppm) have marginally lower and higher values, respectively, compared to the control site (4.00 ppm). These minor differences indicate that mining activities have not significantly influenced Zinc concentrations in the soil. All values fall within acceptable range for agricultural soils (50ppm). Similarly, the concentrations of Copper in Ika-Ogboyaga mine site, Okaba mine site and Abache (control) include; 0.48 ± 1.3, 0.47 ± 0.9 and 0.43 ± 1.1ppm.

Copper is another essential trace element for plants, but like Zinc, it can be toxic at high concentrations. Copper levels are higher at the mine sites (Ika-Ogboyaga: 0.48 ppm, Okaba: 0.47 ppm) compared to the control site (0.43 ppm). In the same vein, the concentration of Iron in Ika-Ogboyaga mine site, Okaba mine site and Abache (control) include; 5.95 ± 0.6, 6.01 ± 0.4 and 5.94 ± 0.7ppm respectively. Iron is a common element in soils and is essential for plant growth. The Iron concentrations in the mine sites (Ika-Ogboyaga: 5.95 ppm, Okaba: 6.01 ppm) and the control site (5.94 ppm) are very close. The slightly higher value at the Okaba mine site could be due to the presence of iron-rich minerals in the mined areas. The concentration of Pb at all the sites (including control) was observed to be the same at 0.01ppm. Lead is a toxic heavy metal, and even small amounts can have harmful effects on plants, animals, and humans. The concentrations of Lead in all three sites are identical (0.01 ppm), with no variation between the mine sites and the control site. This indicates that the coal mining activities have not contributed to an increase in Lead levels in the soil. The measured concentrations are very low, suggesting that there is no immediate risk of lead contamination or toxicity in these areas. Studies by (Olabanji, Oluyemi, Fakoya, Eludoyin, & Makinde, 2015) have argued that heavy metals in soils may be absorbed by shallow rooted plants or washed into surface water, from where they may contaminate the food chain. Long term exposure and bioaccumulation some of these metals, including Pb and Zn have been linked to inhibition of blood cells formation and brain damage in children, while exposure to Cd has been implicated to cause softening of the bones and osteoporosis in both children and adults (World Health Organisation, 2010). Lo et al. (2012) linked an outbreak of lead poisoning among children in two villages in Zamfara State, Nigeria to gold mining activities in the area.

3.4 Heavy Metal Contamination

The P_s values for all metals are very low, indicating that the concentrations of these heavy metals at both the mined and control sites are well within the permissible limits. Zinc has the highest P_s values across all sites, but it remains far below any critical pollution threshold.

The results suggest minimal pollution risk from these heavy metals in the soil, whether in the mined or control sites. The P_s scores are very similar between the mined and unmined areas, further indicating that mining activities have not significantly induced heavy metal pollution levels.

Table 4. Specific contamination level of selected heavy metals based on the Nemerow pollution index

Element	Ika-Ogboyaga Mine Site	Okaba Mine site	Abache (Control)
Zinc (ppm)	0.0133	0.0134	0.0133
Copper (ppm)	0.0048	0.0047	0.0043
Iron (ppm)	0.000119	0.00012	0.00011
Lead (ppm)	0.0001	0.0001	0.0001

Table 5. ANOVA of Spatial Variation in the Physico-chemical characteristics of sampled soil

ANOVA						
Source of Variation	***SS***	***df***	***MS***	***F***	***P-value***	***F crit***
Between Groups	0.611094118	2	0.305547059	0.004499111	0.995511	3.190727
Within Groups	3259.812447	48	67.91275931			
Total	3260.423541	50				

3.5 Spatial Variation of Sampled Parameters

Table 5 shows that (F-value=0.00449; F-crit=3.1907; P-value=0.995511) there is no significant spatial variation in the soil physical and chemical properties between the mined and unmined sites. The differences observed between the sites are likely due to random variation rather than any impact of mining activities.

With a p-value of 0.9955, the study conclude that the soil physical and chemical properties are statistically similar across the Ika-Ogboyaga Mine, Okaba Mine, and Abache (Control) sites. Therefore, the mining activity in these areas does not appear to have significantly altered the soil physical properties compared to the unmined site.

4. CONCLUSION

The study concludes that coal mining activities in Kogi East, Nigeria, have had a relatively minor impact on soil physical and chemical properties. The consistency in soil texture (sandy clay loam) and the minimal variations in chemical properties, such as pH, organic matter, nitrogen, and cation exchange capacity, suggest that the soils remain largely unaffected by mining. However, the slightly higher bulk density in mined areas indicates some degree of soil compaction, which could affect soil porosity and water infiltration. Heavy metal concentrations, including zinc, copper, iron, and lead, were within safe limits, posing no immediate threat to soil quality or environmental health.

5. RECOMMENDATIONS

1. Soil Compaction Mitigation: To prevent further soil compaction in mined areas, it is recommended that post-mining soil restoration activities, such as tilling and organic matter incorporation, be undertaken to improve soil structure and porosity.
2. Vegetation Rehabilitation: Implementing a re-vegetation program with native plant species will help in stabilizing the soil structure, improving organic matter content, and enhancing nutrient cycling in post-mining sites.
3. Continuous Monitoring: Periodic monitoring of soil properties, particularly bulk density, cation exchange capacity, and heavy metal concentrations, should be conducted to assess long-term impacts of mining on soil health and guide appropriate remediation measures.
4. Awareness Campaigns: Awareness programs should be organized for local communities on the potential environmental effects of mining and sustainable land management practices.
5. Sustainable Mining Practices: Mining companies should be encouraged to adopt environmentally friendly practices that minimize soil disturbance and prevent heavy metal contamination.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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