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RESEARCH

Long-Term Influence of Coal Mining Activities on Physico-Chemical and Hydraulic Properties of Sandy Tropical Soils

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Abstract

Long-term surface coal mining near agricultural zones can degrade arable land and reduce soil productivity. This study evaluated the effects of extended coal mining on sandy soil properties in three mining areas of Ankpa LGA, Kogi State, Nigeria—Okaba-Odagbo (55 years), Okobo-Enjema (12 years), and Onupi (9 years). Soil samples were collected from both mining sites and adjacent fallow (arable) lands and analyzed using standard methods. Statistical comparisons were made using t-tests and Pearson correlation. Across all locations, mining significantly influenced ($p < 0.05$) soil pH and bulk density. Mining sites showed lower pH ($t = -2.49$) and higher bulk density ($t = 2.35$) compared to fallow lands. Site-specific analysis revealed pronounced effects only at Okaba-Odagbo, where the longest mining history corresponded with increased clay content and bulk density (t = 5.00 and 5.69, respectively). No significant differences were observed at Okobo-Enjema and Onupi. When averaged across locations, mining sites had slightly higher values for clay content (10.68%), soil organic carbon (1.81%), exchangeable sodium (0.38 cmol/kg), porosity (0.44), water holding capacity (20.94%), and saturated hydraulic conductivity (56.66 cm/h) compared to fallow lands. The reduced pH at mining sites was linked to sodium and clay enrichment and loss of base-forming elements, while higher bulk density was attributed to decreased macro-aggregation. The findings suggest that coal mining alters the physical and chemical properties of tropical sandy soils, leading to acidification and compaction, which can impair soil quality, permeability, and long-term agricultural productivity.

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Statement of Sustainability: This study assessed the influence of coal mining on soil quality in Ankpa LGA of Kogi State (Nigeria), a previously undocumented area in the derived savannah agroecological zone of the tropical region. By examining soil properties in coal-mined sites and adjacent fallow lands, we focused on the agro-environmental consequences of coal mining. This research contributes to Sustainable Development Goals, including SDG 2 (Zero Hunger), SDG 12 (Responsible Consumption and Production), SDG 13 (Climate Action), and SDG 15 (Life on Land). The study's findings will inform strategies for sustainable agriculture, responsible mining practices, and environmental protection, promoting sustainable development.

1. Introduction

Coal exploration in eastern and central Nigeria has been a continuous economic activity for several decades. In central Nigeria, coal mining at Okaba-Odagbo Kogi State, discovered in 1927, commenced in 1968 under the operation of the Nigerian Coal Corporation (NCC). Coal mining activities have also been carried out in other locations, including Okobo-Enjema, which began in 2011 and is operated by Zuma Coal Ltd, and Onupi, which started in 2014 and is operated by Dangote Coal Mine. All three sites have explorers who engage in open cast or surface mining methods, and mining activities have not been suspended from inception. The Ankpa Local Government Area (LGA), in the eastern part of Kogi State, where these coal mines are located is the only coal-producing region of the State. The surrounding soils are typically used for the production of arable crops to achieve the goal of balancing needs and population growth via increased food production. However, because coal mining involves, among other operations, the extraction of surface coal near agricultural areas, it often leads to the removal of soil materials, negatively affecting soil structure and degrading the soil to the extent of damaging the ecosystem. The mining operations sometimes lead to the transformation of large areas of agricultural land into a status of showing unproductive or low-productivity soils, a situation that undermines the economic importance of coal mining (Abdelrhman et al., 2021; Cetin et al., 2023).

Soil degradation is a serious cause of low and dwindling agricultural productivity (Obalum et al., 2012a). When resulting from generated mine wastes during exploitation activities, it manifests in the forms of low soil pH, solubility of heavy metals, organic matter depletion, nutrient loss, reduced biological activities, as well as altered soil texture and poor soil structure leading to impaired soil permeability and erosion (Feng et al., 2019; Tyopine et al., 2020, Abdelrhman et al., 2021; Tyopine et al., 2022). The physical, chemical, and biological qualities of soils are disturbed both for underground and surface coal mining activities (Dejun et al., 2016; Ma et al., 2019; Rouhani et al., 2023). Among these three soil qualities, soil physical quality is crucial since it has a notable impact on chemical and biological processes in the soil (Page et al., 2020).

Coal will continue to play an important role in satisfying the global energy demand, and coal is an important energy resource for steel, cement, and thermal power plants (Mukhopadhyay et al., 2016; Yadav et al., 2022). The coal mining method causes land subsidence, which destroys soil structure, changes its properties, and causes eco-environmental damages such as restriction of vegetation growth, soil erosion, changes in topographic and hydrological conditions, and loss of agricultural land and topsoil, all leading to reductions in crop yields (Dejun et al., 2016; Guo et al., 2018; Tyopine et al., 2020; Chen et al., 2022; Jiang et al., 2022).

Existing land uses, such as livestock grazing, and crop and timber production, are temporarily eliminated by mining activities (Bodo et al., 2021). This elimination results in the destruction of the genetic soil profile and wildlife habitat, alters current land uses, and to some extent, permanently changes the general topography of the mined area (Pandey et al., 2022; Rouhani et al., 2023). Excavating the soil and rock overburden that covers the coal deposit may cause topsoil loss and burial, expose the underlying geologic and/or parent material, and generate large infertile wastelands (Chen et al., 2022; Jahandari et al., 2023). Soil disturbance and associated compaction result in conditions conducive to erosion and flood. Soil removal from the area to be surface-mined often alters or destroys many natural soil characteristics and reduces its diversity and productivity for agriculture (Sengupta, 2021; Ekka et al., 2023).

Long-term influence of other economic activities bordering on exploration and mining of natural resources on soil properties has been reported for the largely coarse-textured tropical soils of southeastern Nigeria (Umoren et al., 2019; Nnabude et al., 2021; Ukpe et al., 2021), southwestern Nigeria (Adewole and Adesina, 2011; Oladipo et al., 2014; Eludoyin et al., 2017), and also central Nigeria (Ezeaku, 2011; Wahab et al., 2025). Corresponding documented research for coal mining is scarce. Such data are needed mostly in the derived savannah of Nigeria where coal mining is rather common. Ande et al. (2021) partially filled this gap for the Owukpa Coal Mine in the derived savannah of central Nigeria. With the exception of perhaps the recent study by Ahmad et al. (2025), there is no such data for the Ankpa area despite being a major coal mining area in this agroecological zone. Therefore, more studies are needed around Ankpa on the effects of subsidence induced by coal mining on soil characteristics, to quantify the impact of land surface change on soil attributes in the area.

Hence, the objectives of this study were to; determine the physicochemical and hydraulic properties of the soils of three locations under long-term mining activities and agricultural-fallow lands in the area; and examine the nature of associations among physico-chemical and hydraulic properties of soils of the area as may be influenced by the mining activities. By comparing the soil properties between coal-mined areas and adjacent agricultural-fallow lands, this study shed light on the effects of coal mining activities on soil quality and fertility.

2. Materials and Methods

2.1. Study Location

The study was conducted in the year 2023 with soil samples collected from three coal mines (Okaba-Odagbo, Okobo-Enjema, and Onupi) and their adjacent fallow lands in Ankpa LGA of Kogi State, Nigeria. It is located in the eastern part of Kogi State with its headquarters in the town of Ankpa, which is on the A223 highway in the west of the area, at Latitude 7˚24′8.96″N and 7˚37′55.06″N and Longitude 7˚25′59.99″E and 7˚37′59.99″E. The Okaba-Odagbo coal mine site is located at 7˚25′20.6″N, 7˚46′50.6″E, approximately 16 km northeast of Ankpa town, and covers an area of approximately 122.7 km^2. The Okobo-Enjema coal mine site is located at 7˚30′22″N, 7˚42′19″E, approximately 11 km northeast of Ankpa town, and covers an area of approximately 13.6 km^2. The Onupi coal mine site is located at 7˚27′23.0″N, 7˚46′05.2″E, approximately 18 km northeast of Ankpa town, and covers an area of approximately 11.9 km^2. Ankpa LGA falls within the derived savannah agroecological zone of Nigeria, and it occupies a land mass of about 1200 km^2. The area experiences two major seasons; the rainy season which generally runs from April through October, and the dry season which stretches from November to March with average annual rainfall in the range of 100 – 200 cm (Ogwuche and Odoh, 2013). It has an average annual temperature of 29˚C and an annual average relative humidity of 67% during the rainy season. Ankpa LGA is underlain by secondary sediments that fall within the Anambra Sedimentary Basin which is cretaceous in age (Gideon and Fatoye, 2012). The soil of the area is mostly sandy, deep, and well-drained. The parent material is sandstone, schist, shale, and a few surfaces of the false-bedded sandstone.

2.2. Soil Sampling and Analysis

Soil sampling was conducted in May 2023 from coal-mined areas at each of Odagbo-Okaba, Okobo-Enjema, and Onupi in Ankpa LGA of Kogi State, Nigeria. As of this study in 2023, this economic activity has been going on at Odagbo-Okaba, Okobo-Enjema, and Onupi for the past 55, 12, and 9 years, respectively. Both mined sites and adjacent fallow lands were sampled at each location. The sampling approach varied depending on the terrain, adopting a site-specific approach that would capture the spatial variability of soil properties. Where the terrain was slopy, soil sampling was done along the slope at intervals corresponding to four slope positions (upper, upper-middle, middle, and lower), each from which the sampling was done in triplicate. This was the situation at the mined site of Okobo-Enjema with a gentle slope for which soil samples were collected at 7-meter intervals and at both the mined site and adjacent fallow land of Onupi with steep slopes for which soil samples were collected at 5-meter intervals. By contrast, where the terrain was fairly flat, sampling was done randomly from 12 spots approximately 10 meters apart. This was the situation at the adjacent fallow land in Okobo-Enjema and both the mined site and adjacent fallow land in Odagbo-Okaba.

Soil core samplers were used to collect undisturbed soil samples at 0 – 10 cm depth, followed by the collection of corresponding loose (disturbed) soil samples. In all, 36 undisturbed and 36 corresponding disturbed soil samples were collected from each of the mined sites and their adjacent fallow lands. The surface layer of the soil was chosen for this research because it is often more sensitive to changes in land use than the deeper soil layers, in terms of soil physicochemical and hydraulic properties (Obalum et al., 2012b; Uzoh et al., 2020; Onah et al., 2021). As such, any changes in soil composition and/or damage to soil structure due to anthropogenic activities would be expected to be expressed in the surface soil. The undisturbed soil samples, each in a 98.19-cm^3 core sampler, were trimmed and used to assess saturated hydraulic conductivity, water-holding capacity, total porosity, and bulk density. The disturbed soil samples were air-dried to constant weight, sieved with 4- and 2-mm mesh, and stored for other laboratory analyses.

The disturbed soil samples were air-dried to constant weight and the <-2-mm fine-earth fractions were used for particle size analysis using the hydrometer method (Gee and Or, 2002). Soil aggregates < 4- but > 2 mm as described by Diaz-Zorita et al. (2002). The mean-weight diameter (MWD) of aggregates was calculated by the formula:

$$\mathrm{MWD} = \sum_{i=1}^{n} x_i w_i \ ;$$

where x_i is the mean diameter of any particular size range of aggregates separated by sieving, w_i is the weight of aggregates in that size range as a fraction of the total dry weight of soil used and n is the total number of aggregate size range considered. The undisturbed soil sample was used to determine saturated hydraulic conductivity (K_s) using the method outlined by Klute and Dirksen (1986), and was calculated as:

$$K_s = \left(\frac{Q}{At}\right)\left(\frac{L}{\Delta H}\right);$$

where K_s is saturated hydraulic conductivity of the soil (cm/h), Q is the steady-state volume of outflow from the entire soil column (cm^3), A is the cross-sectional area of the soil column (cm^2), t is the time interval of water flow (h), L is the length of the soil column (cm), and ΔH changes in the hydraulic head (cm).

Soil bulk density was determined as described by Grossman and Reinsch (2002). Total porosity was calculated from the relationship between bulk density and particle density, assumed to be 2.65 g/cm^3. Water holding capacity (WHC) of the saturated soil was calculated using the following model:

$$\text{WHC} = \frac{\text{Mass of wet soil} - \text{Mass of dry soil}}{\text{Mass of dry soil}} \times 100.$$

The soil pH was determined in distilled water as outlined by Mclean (1982). The soil organic carbon was determined using the Walkley - Black wet oxidation procedure (Nelson and Sommers, 1996). The exchangeable potassium (K^+) and sodium (Na^+) were extracted with HCl solution and their levels were determined by flame photometer, and exchangeable magnesium (Mg^{2+}) and calcium (Ca^{2+}) by atomic absorption spectrophotometer (Senjobi and Ogunkunle, 2010). The total exchangeable bases were calculated as the sum of exchangeable bases.

2.3. Statistical Analysis

Data collected from soil analysis were analyzed by t-test comparing the mining site to the adjacent fallow land. The Pearson correlations and their returned coefficients were used to explore the nature of associations among soil physico-chemical and hydraulic properties, involving data for both the mining sites and the control adjacent fallow lands. For both the t-test and the Pearson correlations, mean values of every three consecutive replicates of the observations were used. Both analyses were done using IBM SPSS Statistical software version 27.

3. Results and Discussion

3.1. Physical and Some Physico-Chemical Properties of the Soils of the Three Different Locations as Compared between the Sites under Long-Term Coal Mining Activities and Adjacent Fallow Lands

Table 1 presents a comparison of soil physical and some physico-chemical properties between coal mining sites and adjacent fallow lands across the three locations of the study. The results show that the fallow land had higher sand (86.71±2.62%) and silt (3.23±0.96%) contents, while the coal mining site had higher clay (10.68±1.67%) content. However, these differences in particle size fractions were not significant ($p > 0.05$), and the soil texture – loamy sand – remained unchanged regardless of mining status. The slight difference in sand content between the mining sites and the adjacent fallow lands may be attributed to the mixing of topsoil with different-textured overburden materials during mining (Yu et al., 2019; Hindersah et al., 2024; Wahab et al., 2025). Additionally, the higher vegetation coverage and greater root activities in the fallow lands may have contributed to the difference. Roots can alter the parent material, and vegetation cover can protect the fine-size fractions from migration (Asensio et al., 2013; Zhang et al., 2016; Chassé et al., 2021; Oguike et al., 2023). The mean-weight diameter of soil aggregates was only marginally higher ($p > 0.05$) in the fallow lands (6.63±0.33 mm) compared to the mining sites. This observation was unexpected, as the adjacent fallow land was expected to have higher aggregate stability due to its higher vegetation coverage and root activities. A plausible explanation here is that the adjacent fallow lands, which have been left under scanty vegetation for years, have deteriorated, leading to decreased aggregate stability (Xie et al., 2015; Tyopine et al., 2020).

The soil pH was higher in the fallow lands (5.0±0.5) compared to the mining sites (4.6±0.6). This effect is consistent with previous studies in coal mining areas (Ezeaku, 2011; Biswas et al., 2013; Oladipo et al., 2014; Tapadar and Jha, 2015; Ande et al., 2021). The higher pH in the fallow lands may be attributed to the higher calcium concentration, which can react to form calcium carbonate that can lime the soil. Soil organic carbon, exchangeable potassium (K), calcium (Ca), magnesium (Mg), sodium (Na), and total exchangeable bases (TEB) were similar between the mining sites and the fallow lands. The mining sites tended to have higher soil organic carbon content, which may be attributed to their higher clay content, protecting organic matter against microbial decomposition (Rice, 2002; Oguike et al., 2023). The tendency for higher exchangeable Na content in the mining sites may be due to the breakdown of rocks and minerals during the mining process (Ande et al., 2021). In contrast, the fallow lands tended to have higher exchangeable K, Ca, Mg, and TEB, consistent with previous studies (Biswas et al., 2013; Ande et al., 2021). The acidity of the mined soils suggests the leaching of exchangeable Ca, Mg, and K from the topsoil (Yu et al., 2019; Yang et al., 2021).

Table 1. Comparison between the sites under long-term coal mining activities and adjacent fallow lands for differences in soil physical and some physico-chemical properties across the three locations of the study.

Parameters	Mining site	Fallow land	t-statistics
Sand (%)	86 ± 2.11	87±2.62	−1.21ns
Silt (%)	3 ± 0.88	3±0.96	−0.87 ns
Clay (%)	11 ± 1.67	10±2.36	1.65 ns
Textural Class	Loamy sand	Loamy sand	
Soil pH	4.6±0.6	5.0±0.5	−2.49*
Mean-weight diameter of aggregates (mm)	6.56±0.16	6.63±0.33	−0.69 ns
Soil organic carbon (%)	1.81±0.90	1.64±1.06	0.72 ns
Exchangeable Na, Na^+ (cmol/kg)	0.38±0.07	0.37±0.06	0.28 ns
Exchangeable Mg, Mg^{2+} (cmol/kg)	1.80±0.31	1.91±0.39	−0.68 ns
Exchangeable K, K^+ (cmol/kg)	1.57±0.32	1.69±0.41	−0.61 ns
Exchangeable Ca, Ca^{2+} (cmol/kg)	3.86±0.41	3.94±0.37	−0.38 ns
Total Exchangeable Bases (cmol/kg)	7.67±0.91	7.77±1.19	−0.24 ns

All soils combined (n = 12), values are means ± standard deviation, ns - not significant *Significant at $p < 0.05$

3.2. Selected Hydraulic Properties of the Soils of the Three Different Locations as Compared between the Sites under Long-Term Coal Mining Activities and Adjacent Fallow Lands

Table 2 shows the comparison between the coal mining sites and the adjacent fallow lands for differences in soil hydraulic properties across the three locations of the study. Fallow lands had low soil bulk density (1.38±0.12 g/cm^3), water holding capacity (20.21±7.47%), and saturated hydraulic conductivity (48.82±86.34 cm/h) compared to mining sites. These differences in soil hydraulic properties were not noticeable ($p > 0.05$) except for soil bulk density. The notably higher soil bulk density in the mining sites than the adjacent fallow lands reflects the use of heavy machinery during the mining operations. This observation aligns with the consensus that soil bulk density is higher in mined soils compared to undisturbed native sites (Zhang et al., 2016; Ande et al., 2021; Nnabude et al., 2021; Back et al., 2024; Ahmad et al., 2025). Fallow lands usually have low bulk density while cultivated lands usually have high bulk density due to the differences in soil organic matter and fewer disturbances under the former than the latter (Özdemir et al., 2022). The total porosity was lower for the soils of the mining sites than those of the fallow lands. This was expected because of the inverse relationship between soil bulk density and total porosity. In the present study where the latter was computed directly from the former using a constant value of particle density, this relationship would be a perfect one. The observed response of soil total porosity to coal mining aligns with previous reports that mechanical operations in compacted areas led to decreased soil porosity (Nawaz et al., 2013; Shah et al., 2017; Zhang et al., 2024).

Table 2. Comparison between the sites under long-term coal mining activities and adjacent fallow lands for differences in selected soil hydraulic properties across the three locations of the study.

Parameters	Mining site	Fallow land	t-statistics
Bulk density (g/cm^3)	1.45±0.08	1.38±0.12	2.35*
Total Porosity	0.44±0.03	0.47±0.05	-2.23*
Water holding capacity (%)	20.94±5.04	20.21±7.47	0.27 ns
Saturated hydraulic conductivity (cm/h)	56.66±80.60	48.82±86.34	0.23 ns

All soils combined (n = 12), values are means ± standard deviation, ns – not significant *Significant at $p < 0.05$.

Contrary to previous reports that degraded mined soils tended to have lower water-holding capacity compared to soils with proper amendments (Menzies-Pluer et al., 2020; Abdallah et al., 2021), our study found no significant difference in water-holding capacity between the mining sites and the adjacent fallow lands. This unexpected observation may be attributed to the tendency for higher clay content in the mining sites, which could have contributed to their water-holding capacity. Also, although the difference in clay content between the two sites was not significant ($p > 0.05$), soil organic carbon that was slightly higher in the mining sites than the fallow lands may still have played a role in influencing soil water-holding capacity of the former (Obalum and Obi, 2013). Regarding saturated hydraulic conductivity, our results showed no significant difference between the mining sites and the adjacent fallow lands. This finding is surprising, given that the fallow lands had higher soil porosity than the mining soils, which theoretically would lead to lower saturated hydraulic conductivity in the latter (Nnabude et al., 2021). Other factors, such as the marginally higher soil organic carbon content of the mined soil, may have compensated for their lower porosity, resulting in their similarity to the fallow lands in terms of saturated hydraulic conductivity.

3.3. Physical and Some Physico-Chemical Properties of the Soils of Each of the Three Locations as Compared between the Site under Long-Term Coal Mining Activities and Adjacent Fallow Land

Table 3 presents a comparison of soil's physical and some physico-chemical properties between the coal mining site and the adjacent fallow land at Okobo-Enjema. The results show that the fallow land had significantly higher sand (85.71±1.50%) and silt (3.81±0.50%) contents, whereas the mining site had higher clay (11.86±1.46%) content. Additionally, the mining site showed a higher mean-weight diameter of aggregates (6.63±0.28 mm). In terms of soil physico-chemical properties, the fallow land showed higher soil pH (5.0±0.47), soil organic carbon (1.62±0.93%), and exchangeable Mg (1.73±0.06 cmol/kg) concentrations. In contrast, the mining site displayed higher exchangeable K (1.49±0.01 cmol/kg), Ca (3.93±0.25 cmol/kg), and TEB (7.50±0.24 cmol/kg) concentrations. Notably, none of these differences observed between the mining site and fallow land was significant. The relatively short duration of mining activities in this Okobo-Enjema area may not have been sufficient to cause significant changes in soil properties.

Table 3. Comparison between the site under long-term coal mining activities and adjacent fallow land for differences in soil physical and some physico-chemical properties at each of the three locations of the study.

Parameters	Okobo-Enjema			Okaba-Odagbo			Onupi		
	Mining site	Fallow land	t-statistics	Mining site	Fallow land	t-statistics	Mining site	Fallow land	t-statistics
Sand %	85.20±1.71	85.71±1.50	−0.78 ns	88.71±1.26	89.96±1.41	−1.46 ns	85.21±0.96	85.46±1.71	−0.00 ns
Silt %	2.94±0.95	3.81±0.50	−1.70 ns	2.56±0.81	2.56±1.41	−0.00 ns	3.31±0.96	3.31±0.28	−0.00 ns
Clay %	11.86±1.49	10.48±2.00	2.48 ns	8.73±0.50	7.48±0.00	5.00**	11.48±0.00	11.23±1.04	−1.44 ns
Textural Class	Loamy sand	Loamy sand		Loamy sand	Sand		Loamy sand	Loamy sand	
Mean-weight diameter of aggregate (mm)	6.63±0.28	6.50±0.03	0.84ns	6.54±0.05	6.50±0.01	1.44 ns	6.50±0.01	6.90±0.50	−1.58 ns
Soil pH	4.5±0.26	5.0±0.47	−0.21 ns	5.2±0.2	5.4±0.6	−0.51 ns	4.2±0.61	4.8±0.33	−2.35 ns
Soil organic carbon %	1.50±0.82	1.62±0.93	−0.21 ns	2.01±1.16	1.65±1.08	0.95 ns	1.92±0.86	1.6±1.44	0.77 ns
Exchangeable Na, (cmol/kg)	0.38±0.04	0.38±0.04	−0.24 ns	0.33±0.03	0.40±0.06	−2.65 ns	0.43<0.09	0.33±0.08	1.34 ns
Exchangeable Mg, (cmol/kg)	1.71±0.15	1.73±0.06	−0.48 ns	2.10+0.17	1.83±0.39	1.40 ns	1.60±0.33	2.19±0.48	−1.61 ns
Exchangeable K, (cmol/kg)	1.49±0.01	1.48±0.14	0.10 ns	1.87±0.30	1.60±0.40	0.90 ns	1.37±0.33	1.98±0.51	−1.59 ns
Exchangeable Ca, (cmol/kg)	3.93±0.25	3.65±0.05	2.25 ns	4.10±0.45	3.97±0.33	0.48 ns	3.56±0.36	4.19±0.45	−1.60 ns
Total Exchangeable Bases (cmol/kg)	7.50±0.24	6.99±0.30	2.10 ns	8.40±0.91	7.80±1.15	1.82 ns	7.12±1.00	8.53±1.48	−1.99 ns

All soils combined (n = 12), values are means ± standard deviation, ns – not significant, ** Significant at $p < 0.01$.

The results from Okaba-Odagbo showed that the adjacent fallow land had a marginally higher sand content (89.96±1.41%) than the mining site, the two had similar silt content, whereas the mining site had a higher clay content (8.73±0.50%) than the fallow land. This difference in clay content was significant at $p > 0.01$. The mining site also tended to show a higher mean-weight diameter of aggregates (6.54±0.05 mm). In terms of soil physico-chemical properties, the fallow land tended to have a higher soil pH (5.4±0.60) and exchangeable Na (0.40±0.06 cmol/kg), while the mining site tended to have higher soil organic carbon (2.01±1.16%), exchangeable Mg (2.10±0.17 cmol/kg), exchangeable K (1.87±0.30 cmol/kg), exchangeable Ca (4.10±0.45 cmol/kg), and TEB (8.40±0.91 cmol/kg). The significantly higher clay content in the mining site than the fallow land suggests that the long duration (55 years) of mining activities at this location enabled the enrichment of this sandy soil with fine particles to be evident. Additionally, the mixing of topsoil with overburden materials during mining could have contributed to this difference. Similar to the observation made at Okobo-Enjema, the results from Onupi showed no significant differences in soil physico-chemical properties between the mining site and fallow land. The fallow land had a marginally higher sand content (85.46±1.71%), while the mining site had a marginally higher clay content (11.48±0.00%). The fallow land showed marginally higher mean-weight diameter of soil aggregates (6.90±0.50 mm), soil pH (4.8±0.33), exchangeable Mg (2.19±0.48 cmol/kg), exchangeable K (1.98±0.51 cmol/kg), exchangeable Ca (4.19±0.45 cmol/kg), and also TEB (8.53±1.48 cmol/kg), while the mining site showed marginally higher soil organic carbon (1.92±0.86%) and exchangeable Na (0.43±0.09 cmol/kg). The absence of significant differences in soil physico-chemical properties between the mining site and fallow land at all three locations suggests that these soil properties are influenced mainly by soil texture and/or acidity (Ukabiala et al., 2021), and may be more resilient to mining disturbances than expected.

3.4. Selected Hydraulic Properties of the Soils of Each of the Three Locations as Compared between the Site under Long-Term Coal Mining Activities and Adjacent Fallow Land

Table 4 presents a comparison of soil hydraulic properties between the coal mining site and the adjacent fallow land at each of the three locations viz. Okobo-Enjema, Okaba-Odagbo, and Onupi. At Okobo-Enjema, the fallow land showed higher soil bulk density (1.43±0.02 g/cm^3) and water holding capacity (21.42±10.21%), whereas the mining site showed higher total porosity (0.46±0.01) and saturated hydraulic conductivity (124.30±117.84 cm/h). However, these differences were not significant, suggesting that the duration of mining activity at this site may not have been long enough to bring about any substantial changes in the soil's hydraulic properties.

In contrast, at Okaba-Odagbo, the coal mining site showed higher soil bulk density (1.52±0.08 g/cm^3) and lower total porosity (0.42±0.03) than the adjacent fallow land. The mining site also showed marginally higher saturated hydraulic conductivity (33.71±17.45 cm/h), while the fallow land showed marginally higher water holding capacity (24.83±1.74%). The use of heavy machinery during the mining operations, combined with the duration of mining activities at this site, may have contributed to the observed higher soil bulk density of the mined site compared with the fallow land. At Onupi, the mining site showed higher soil bulk density (1.41±0.11 g/cm^3) and lower total porosity (0.46±0.04), as well as water holding capacity (22.31±3.44%), whereas the adjacent fallow land showed lower values of higher saturated hydraulic conductivity (12.51±11.72 cm/h). However, none of these differences was significant. Overall, these results highlight the possibility of longer coal mining duration leading to increases in soil compaction which may not influence water retention and transmission through the soil.

Table 4. Comparison in selected soil chemical properties between coal-mining site and adjacent fallow land at each of the three locations of the study.

Parameters	Okobo-Enjema			Okaba-Odagbo			Onupi		
	Mining site	Fallow land	t-statistics	Mining site	Fallow land	t-statistics	Mining site	Fallow land	t-statistics
Bulk density (g/cm^3)	1.42±0.01	1.43±0.02	–1.26 ^{ns}	1.52±0.08	1.37±0.09	5.69**	1.41±0.11	1.33±0.20	1.16 ^{ns}
Total porosity %	0.46±0.01	0.45±0.01	1.57 ^{ns}	0.42±0.03	0.47±0.04	-5.75**	0.46±0.04	0.49±0.08	-1.13 ^{ns}
Water holding capacity %	18.27±5.56	21.42±10.21	–0.57 ^{ns}	22.25±5.99	24.83±1.74	–0.91 ^{ns}	22.31±3.44	14.39±4.68	2.10 ^{ns}
Saturated Hydraulic Conductivity (cm/h)	124.30±117.84	100.27±141.83	0.22^{ns}	33.71±17.45	33.69±38.56	0.00 ^{ns}	11.98±12.97	12.51±11.72	–0.24 ^{ns}

All soils combined (n = 12), values are means ± standard deviation, ns - not significant, ** Significant at $p < 0.01$.

3.5. Correlations among Soil Physical, Physico-chemical, and Hydraulic Properties as Determined under Both Coal-Mining Sites and Adjacent Fallow Lands across the Three Locations of the Study

Table 5 presents the relationships among soil properties as determined under both coal mining sites and adjacent fallow lands across the three locations of this study. Several significant correlations were found among soil properties, providing insights into the associations existing between soil properties in the study area regardless of mining status and/or that are peculiar to mining sites, while alluding to the underlying mechanisms driving the observed significant influence of coal mining activities on clay content, soil pH and bulk density.

A strong negative relationship was found between soil bulk density and mean-weight diameter (MWD) of soil aggregates ($r = -0.600$, $p < 0.01$). This suggests that soil compaction caused by machinery stress leads to aggregate breakdown, resulting in reduced MWD (da Luz et al., 2023). The strong negative relationship found between sand and clay contents ($r = -0.897$, $p < 0.01$) indicates that increases in sand content are accompanied by decreases in clay content. Additionally, sand content had a strong positive relationship with soil pH ($r = 0.545$, $p < 0.01$), suggesting that locations with higher sand content are less prone to acidification than those with higher clay content. The strong negative relationship between clay content and soil pH ($r = -0.560$, $p < 0.01$) suggests that such soil acidification may be occurring due to oxidation of minerals and other mining-related activities (Zhang et al., 2023). Exchangeable Na had a positive relationship with water holding capacity (WHC) of the soils ($r = 0.466$, $p < 0.05$), indicating that sodium may play a role in defining their hydraulic properties. Also, exchangeable Na had a strong negative relationship with soil pH (r = -0.417, p < 0.01), suggesting that sodium may be contributing to soil acidification (Tyopine et al., 2020).

Table 5. Matrix of the correlations among physical, physico-chemical, and hydraulic properties for both coal-mining sites and adjacent fallow lands across the three locations of the study (N=24).

Soil properties	Silt	Clay	MWD	pH	SOC	Na	Mg	K	Ca	TEB	BD	WHC	*Ks*
Sand	-.564**	-.897**	-0.105	.545**	0.135	0.059	-0.067	-0.096	0.074	-0.059	0.007	0.311	-0.263
Silt		0.236	-0.037	-0.216	-0.005	-0.074	0.185	0.175	-0.083	0.139	-0.104	-0.133	0.108
Clay			0.385	-.560**	-0.221	-0.089	0.015	0.051	-0.014	-0.039	-0.167	-0.295	0.221
MWD				-0.071	-0.286	-0.29	0.145	0.205	0.285	0.019	-.600**	-0.228	-0.137
pH					0.155	-.417*	.472*	.478*	.453*	0.306	0.124	-0.125	-0.337
SOC						0.026	0.202	0.153	0.244	0.308	0.202	0.017	-0.221
Na							-.594**	-.606**	-.595**	-0.278	-0.283	.466*	0.049
Mg								.963**	.816**	.809**	0.02	-0.296	-0.161
K									.839**	.823**	0.037	-0.308	-0.237
Ca										.705**	0.03	-0.25	-0.113
TEB											0.079	-0.165	-0.144
BD												-0.107	0.045
WHC													0.249

**Correlation is significant at the 0.01 level (2-tailed). *Correlation is significant at the 0.05 level (2-tailed).

The relationships existing between exchangeable Na and the other exchangeable bases including K, Mg, and Ca were also investigated. The strong negative relationships found between exchangeable Na and each of exchangeable K, Mg, and Ca (r = -0.606 to 0.594, p < 0.01), suggest that sodium may be competing with these essential nutrients, leading to nutrient imbalances (Hechmi et al., 2022). Significant positive correlations were found between soil pH and each of exchangeable K (r = 0.478, p < 0.05) and Mg (r = 0.472, p < 0.05), indicating that higher soil pH is associated with higher levels of these base-forming cations serving as soil nutrients. Strong positive relationships were also found between exchangeable K and Mg, exchangeable K and Ca, and exchangeable Ca and Mg (r = 0.963 to 0.816, p < 0.01), just as these three base-forming cations correlated positively with TEB (r = 0.823 to 0.705, p < 0.01), suggesting that these nutrients are not only closely related but also dominate the TEB in the soils.

4. Conclusion

This study investigated the influence of subsidence induced by long-term coal mining on soil physico-chemical and hydraulic characteristics of sandy soils in three locations of the derived savannah, with a view to understanding the impact of this anthropogenic activity on tropical agro-ecosystems. The results showed that the long-term mining activities increased both soil pH and bulk density when the data analysis combined the three locations. Additionally, clay content and bulk density were increased by the mining activities at one of the locations (Okaba-Odagbo) with the longest mining history. These findings imply that coal mining activities in the area have negative influence on soil pH and bulk density, which translate into soil acidification and soil compaction, respectively. Long-term coal mining contributing to soil acidification here could be linked to its rendering of the soils less sandy (via clay enrichment) and to their concurrent sodification and loss of base-forming nutrient elements. Its leading to soil compaction could be by frustration of macro-aggregation in the soils. By way of inference, coal mining may lead to the deterioration of physico-chemical and hydraulic properties of sandy tropical soils in the long run, the ensuing loss of soil productivity and impaired soil permeability of which potentially have adverse impact on agriculture and the environment.

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