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Spatial and Depth-Wise Variability of Soil Organic Carbon and Associated Soil Properties for Land Capability and Crop Suitability in the Northern Guinea Savanna, Nigeria

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Abstract

Soil Organic Carbon (SOC) is pivotal indicator of soil health, fertility, and land productivity, particularly in tropical savanna systems prone to degradation. In Niger State, Nigeria, continuous cultivation, low organic inputs, and climate variability have accelerated soil quality decline, affecting crop performance and land capability. However, depth resolved assessments linking SOC, soil physical and chemical properties, and crop suitability remain limited. Soil samples were collected from Gidan Kwano (GK) Campus, Federal University of Technology, Minna, and Umaru Sanda Ahmadu College of Education (COE), Minna, across three depths (0–20, 20–40, 40–60 cm). A total of 54 composite samples were analyzed for pH, electrical conductivity (EC), SOC, total nitrogen (N), phosphorus (P), potassium (K), and cation exchange capacity (CEC), as well as particle size distribution. Descriptive statistics, independent samples t-tests, and repeated measures ANOVA were applied to evaluate site and depth effects. Land capability and crop suitability for maize, soybean, and millet were assessed using the USDA framework and FAO parametric approach. COE soils exhibited higher SOC (11.1–13.97 g kg^{-1}), K (1.85–2.52 cmol kg^{-1}), and CEC (6.46–7.66 cmol kg^{-1}) compared to GK soils (SOC 8.85–10.77 g kg^{-1}; K 1.59–3.48 cmol kg^{-1}; CEC 6.35–7.33 cmol kg^{-1}). pH was significantly higher at COE (6.40–6.79) than GK (5.31–6.20). EC and available P were low across both sites (0.04–0.18 dS m^{-1}; 0.09–0.10 mg kg^{-1}). Depth trends revealed decreasing SOC and CEC with increasing depth. Soil texture varied, with GK soils being sandy (72.9–80.8 % sand) and COE soils finer (61.2–78.8 % sand). Land capability classification indicated moderate to severe limitations (Classes II–III), and crop suitability assessments showed maize and soybean mostly moderately suitable (S2), while millet tolerated lower fertility but with reduced yield potential. Spatial and depth wise variability in SOC, pH, texture, and CEC strongly influenced land capability and crop-specific suitability. Targeted management practices such as SOC restoration, residue retention, and balanced fertilization are recommended to enhance productivity and improve long term soil health in the Northern Guinea Savanna.

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1. Introduction

Soil organic carbon (SOC) is a fundamental indicator of soil health, land productivity, and ecosystem resilience, particularly in tropical savanna systems that are highly susceptible to degradation (Ngait et al., 2021; Taylor et al., 2021). SOC regulates nutrient retention, aggregate stability, water-holding capacity, infiltration, and biological activity, and it functions as a major terrestrial carbon reservoir with important implications for climate change mitigation. In Sub-Saharan Africa, declining SOC stocks have been associated with reduced crop yields, increased erosion risk, and progressive declines in land capability, underscoring the need for systematic soil assessments that connect carbon dynamics with agricultural productivity and sustainable land management (Kadiri et al., 2023).

Niger State, located in the Northern Guinea Savanna of Nigeria, is a major food-producing region dominated by rainfed maize, soybean, and millet systems (Peter-Jerome et al., 2022). Continuous cultivation, residue removal, limited organic inputs, and increasing climate variability have accelerated soil fertility decline, reflecting broader degradation trends across savanna agroecosystems (Jimoh et al., 2025). Although several studies have evaluated soil fertility in the region, most investigations have concentrated on surface soils with limited attention to vertical variability in SOC and related physicochemical properties. This limitation represents a critical research gap because depth-resolved information is necessary to understand nutrient stratification, rooting conditions, and long-term land capability.

Soils in the Northern Guinea Savanna exhibit marked spatial and vertical heterogeneity influenced by parent material, land use, and management intensity (Ojanuga, 2006; Yakubu & Panti, 2024). Variations in SOC, cation exchange capacity, nitrogen status, texture, and pH occur across landscapes and depths, with surface horizons generally richer in organic matter and nutrients than subsoil layers (Ippolito et al., 2021; Maqbool et al., 2025). Available phosphorus is frequently limiting, whereas electrical conductivity typically indicates non-saline conditions (Kadiri et al., 2023). These soil characteristics strongly influence land capability classification and crop performance. Maize is particularly sensitive to SOC, texture, and pH; soybean partially compensates for nitrogen limitations through biological fixation; and millet tolerates lower fertility conditions, although with reduced yield potential (Jimoh et al., 2025; Peter-Jerome et al., 2022).

Despite these insights, few studies in the region have simultaneously integrated depth-wise SOC assessment with rigorous statistical analysis, land capability classification, and crop-specific suitability evaluation. The present study addresses this gap through a combined spatial and vertical assessment of SOC and associated soil properties linked directly to land capability and crop suitability using established evaluation frameworks. This integrated, profile-based approach contributes new evidence to support site-specific soil management strategies aimed at improving productivity and sustaining soil resources in the Northern Guinea Savanna.

1.1 Objectives of the Study

The objectives of the study were to:

1. Quantify soil organic carbon, nitrogen, phosphorus, potassium, cation exchange capacity, pH, and particle size distribution across three depth intervals in representative agricultural lands of GK and COE.
2. Evaluate spatial and depth-wise differences in soil properties.
3. Assess land capability following the USDA framework and determine crop suitability for maize, soybean, and millet.

2. Materials and Methods

This study employed a field-based soil sampling and laboratory analytical approach to evaluate spatial and depth-wise variability in soil physicochemical properties. The methodological framework integrated soil sampling design, laboratory analysis, statistical evaluation, and land capability classification to establish relationships between soil characteristics and crop suitability.

2.1 Description of the Study Sites

The study was conducted at Gidan Kwano (GK) Campus, Federal University of Technology, Minna (Latitude 9°31′52.32″ N, Longitude 6°27′18.60″ E; elevation 190–216 m) and Umaru Sanda Ahmadu College of Education (COE), Minna (Latitude 9°31′51.71″ N, Longitude 6°27′19.34″ E; elevation 225–247 m), located in the southern Guinea savanna zone of Nigeria. This region experiences a tropical wet-and-dry climate characterized by distinct rainy and dry seasons. Mean annual rainfall ranges from 1,200 to 1,300 mm, while average temperatures are approximately 30–32 °C (Ojanuga, 2006; Yakubu & Panti, 2024). Soils are primarily ferruginous tropical soils derived from Basement Complex rocks, coarse-textured, moderately acidic, and inherently of low fertility (Yakubu & Panti, 2024). The major crops cultivated in the study areas include maize, soybean, millet, cowpea, and yam.

2.2 Sampling Design, Depth Stratification, and Laboratory Analysis

A stratified random soil sampling design was adopted to capture spatial variability across land use, soil type, and agroecological conditions. A total of 54 composite soil samples were collected from nine representative sampling points at each site (three replicate points per location). At each replicate, soil samples were collected at three depth intervals (0–20 cm, 20–40 cm, and 40–60 cm), reflecting both surface and subsoil characteristics.

Soil samples were air-dried, gently crushed using a mortar and pestle, and sieved through a 2 mm mesh to obtain fine earth fractions. Laboratory analyses followed ISRIC/FAO (2002) guidelines. Particle size distribution was determined by the Bouyoucos hydrometer method, and soil pH in a 1:1 soil-to-water suspension was measured using a calibrated pH meter. Soil organic carbon (SOC) was analyzed using the Walkley-Black method, and total nitrogen (TN) was determined via Kjeldahl digestion. Exchangeable bases (Ca^{2+}, Mg^{2+}, K^+, Na^+) were extracted with 1 N ammonium acetate; Ca^{2+} and Mg^{2+} were quantified using atomic absorption spectrophotometry, and K^+ and Na^+ by flame photometry. Exchangeable acidity was measured by titration with standard NaOH, and cation exchange capacity (CEC) was determined using the neutral 1 N ammonium acetate saturation method.

2.3 Data Processing and Statistical Analysis

Laboratory data were organized by site and depth (0–20 cm, 20–40 cm, and 40–60 cm) to facilitate vertical and spatial comparisons. Descriptive statistics including mean, standard deviation, and standard error were computed to summarize soil chemical properties across GK and COE sites, providing baseline data for EC, SOC, TN, available phosphorus, potassium, and CEC. Depth trends and site variability were evaluated to highlight spatial heterogeneity and surface versus subsoil differences in key soil fertility parameters (Blackburn *et al.,* 2022; Wang *et al.,* 2025).

Independent samples t-tests were performed to compare soil chemical properties between GK and COE, identifying statistically significant differences in soil pH, SOC, TN, and texture fractions. Repeated measures ANOVA was employed to assess the effects of site, depth, and their interaction on soil properties, accounting for correlations among repeated measurements and highlighting parameters critical for crop selection and land management. Partial eta-squared values were reported as effect sizes to indicate the proportion of variance explained by each factor.

2.4 Land Capability Classification and Crop Suitability Assessment

Soil textural classes were determined using the USDA textural triangle (Soil Survey Staff, 2014). Land capability classification followed the USDA framework (Klingebiel and Montgomery, 1961), integrating soil depth, texture, fertility, drainage, and erosion risk. Crop suitability for maize, soybean, and millet was assessed using the FAO parametric matching approach (FAO, 1976; FAO, 1983), combining chemical and physical soil parameters with known crop requirements. Suitability classes were assigned as follows:

- S1 (Highly suitable): Minor or no limitations
- S2 (Moderately suitable): Limitations reduce yield but do not preclude production
- S3 (Marginally suitable): Severe limitations restrict yield and profitability
- N (Not suitable): Limitations prevent economically viable cultivation

This methodological framework provides a direct link between observed soil properties, statistical analyses, and implications for crop selection and land management, aligning with results on descriptive statistics, t-test comparisons, and repeated measures ANOVA outcomes. Figure 1 shows the methodological framework for the study.

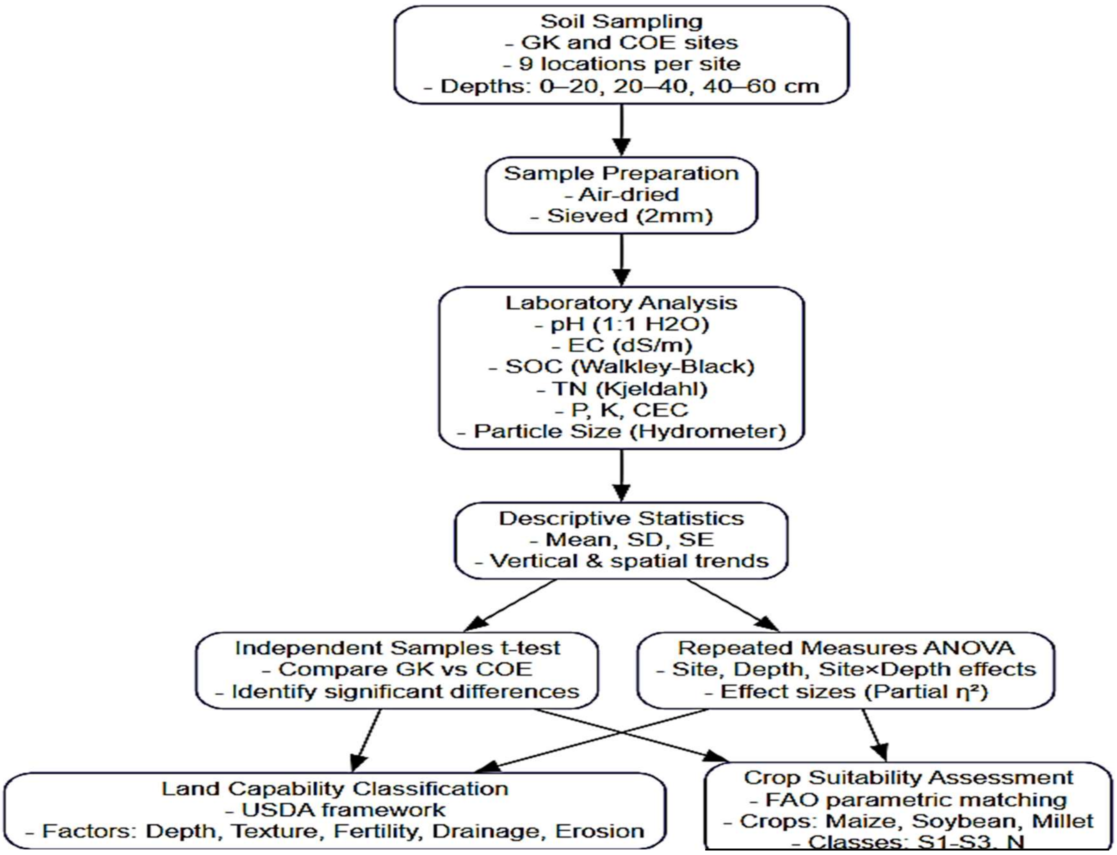

Figure 1: Methodological Framework

3. Results

Table 1 shows the descriptive statistics of soil chemical properties across GK and COE sites.

Table 1: Descriptive Statistics of Soil Chemical Properties Across GK and COE Sites

Area	Latitude	Longitude	Parameter	Mean	SD	SE
GK 1	9.531024	6.455384	EC (dS/m)	0.093	0.072	0.042
			SOC (g/kg)	8.85	1.57	0.91
			N (g/kg)	0.51	0.09	0.05
			P (mg/kg)	0.093	0.006	0.003
			K (cmol/kg)	2.29	0.26	0.15
			CEC (cmol/kg)	7.22	0.55	0.32
GK 2	9.531031	6.455372	EC (dS/m)	0.116	0.114	0.066
			SOC (g/kg)	8.92	1.73	1.00
			N (g/kg)	0.56	0.08	0.046
			P (mg/kg)	0.100	0.010	0.006
			K (cmol/kg)	2.91	1.21	0.70

			CEC (cmol/kg)	7.33	1.80	1.04
GK 3	9.531201	6.455166	EC (dS/m)	0.043	0.011	0.006
			SOC (g/kg)	8.85	0.43	0.25
			N (g/kg)	0.59	0.03	0.017
			P (mg/kg)	0.093	0.006	0.003
			K (cmol/kg)	1.59	0.22	0.13
			CEC (cmol/kg)	6.35	0.61	0.35
COE 4	9.569292	6.578172	EC (dS/m)	0.067	0.011	0.006
			SOC (g/kg)	9.97	2.15	1.24
			N (g/kg)	0.49	0.07	0.04
			P (mg/kg)	0.100	0.006	0.003
			K (cmol/kg)	2.16	0.37	0.21
			CEC (cmol/kg)	7.10	0.91	0.53
COE 5	9.543253	6.583844	EC (dS/m)	0.060	0.023	0.013
			SOC (g/kg)	11.25	3.93	2.27
			N (g/kg)	0.42	0.03	0.017
			P (mg/kg)	0.090	0.000	0.000
			K (cmol/kg)	1.85	0.63	0.36
			CEC (cmol/kg)	6.58	0.64	0.37
COE 6	9.535051	6.578839	EC (dS/m)	0.060	0.011	0.006
			SOC (g/kg)	11.10	1.57	0.91
			N (g/kg)	0.53	0.11	0.064
			P (mg/kg)	0.093	0.006	0.003
			K (cmol/kg)	2.26	0.44	0.25
			CEC (cmol/kg)	6.46	0.68	0.39

The descriptive statistics of the soil samples from GK and COE indicate clear differences in chemical and physical properties. COE soils had higher mean soil organic carbon (12.0 g kg^{-1} ± 1.1 SE) and cation exchange capacity (7.3 cmol kg^{-1} ± 0.4 SE) compared to GK soils (SOC 8.9 g kg^{-1} ± 0.9 SE; CEC 6.5 cmol kg^{-1} ± 0.3 SE), indicating better nutrient retention and soil fertility potential. Nitrogen content was slightly higher in GK soils (0.56 g kg^{-1} ± 0.05 SE) than COE soils (0.49 g kg^{-1} ± 0.04 SE), suggesting localized differences in organic matter mineralization. Electrical conductivity was low at both sites (GK 0.12 dS m^{-1} ± 0.07 SE; COE 0.07 dS m^{-1} ± 0.01 SE), indicating non-saline conditions, and available phosphorus was similarly low (GK 0.10 mg kg^{-1} ± 0.01; COE 0.10 mg kg^{-1} ± 0.01). Potassium was moderately higher in COE soils (2.35 cmol kg^{-1} ± 0.12) relative to GK soils (2.18 cmol kg^{-1} ± 0.16), aligning with the higher SOC and CEC values.

Spatially, GK soils (latitude ~9.531° N, longitude ~6.455° E) were more homogenous, while COE soils (latitude ~9.55° N, longitude ~6.58° E) displayed greater variability in key parameters, reflected in higher standard deviations for SOC (1.7 g kg^{-1}) and nitrogen (0.07 g kg^{-1}). Depth trends showed that surface layers (0–20 cm) contained higher SOC and N than subsoil layers (20–60 cm), with SOC decreasing from 10.8–8.0 g kg^{-1} in GK and 13.97–10.97 g kg^{-1} in COE, while CEC declined slightly with depth. These results highlight differences in nutrient availability and soil fertility potential between the two sites, which are important for land management and crop suitability assessments. Table 2 shows the summary of independent samples t-test comparing GK and COE soils.

Table 2: Iindependent samples t-test comparing GK and COE soils

Parameter	GK Mean	COE Mean	Mean Difference (GK–COE)	t-value	df	p-value
pH	5.82	6.30	-0.48	-3.41	16	0.004*
EC (dS m^{-1})	0.084	0.062	0.022	1.12	16	0.279
OC (g kg^{-1})	8.87	11.00	-2.13	-2.86	16	0.012*
N (g kg^{-1})	0.56	0.45	0.11	2.45	16	0.026*
P (mg kg^{-1})	0.10	0.10	0.00	0.38	16	0.710
Ca (cmol kg^{-1})	1.18	1.17	0.01	0.21	16	0.835
Mg (cmol kg^{-1})	0.70	0.66	0.04	0.74	16	0.470
Na (cmol kg^{-1})	1.52	1.73	-0.21	-1.32	16	0.206
K (cmol kg^{-1})	2.05	2.02	0.03	0.19	16	0.853
CEC (cmol kg^{-1})	6.97	6.71	0.26	0.84	16	0.413
Sand (%)	75.5	69.0	6.5	3.02	16	0.008*
Silt (%)	9.4	13.0	-3.6	-2.91	16	0.010*
Clay (%)	14.7	17.9	-3.2	-2.67	16	0.017*

*= Significant ($\alpha = 0.05$)

The independent samples t-test revealed statistically significant differences between GK and COE soils in selected physical and chemical properties. Soil reaction differed markedly between the two sites, with COE soils exhibiting significantly higher pH values (6.30) compared to GK soils (5.82) ($p = 0.004$), indicating that GK soils are comparatively more acidic. Soil organic carbon was also significantly greater in COE (11.00 g kg^{-1}) than in GK (8.87 g kg^{-1}) ($p = 0.012$), suggesting better organic matter status and potentially improved structural stability and nutrient retention in COE soils. In contrast, total nitrogen was significantly higher in GK (0.56 g kg^{-1}) than in COE (0.45 g kg^{-1}) ($p = 0.026$), although the magnitude of this difference was relatively small. No significant differences were observed in electrical conductivity, available phosphorus, exchangeable calcium, magnesium, sodium, potassium, or cation exchange capacity ($p > 0.05$), indicating broadly comparable fertility status with respect to these parameters.

Significant differences were also detected in soil texture fractions. GK soils contained a significantly higher proportion of sand (75.5%) compared to COE soils (69.0%) ($p = 0.008$), whereas COE soils had significantly higher silt (13.0%) and clay (17.9%) contents than GK soils (9.4% and 14.7%, respectively; $p < 0.05$). These findings demonstrate that GK soils are coarser in texture, while COE soils are relatively finer. The higher silt and clay contents in COE soils likely contribute to improved water holding capacity and stabilization of organic carbon, consistent with the observed higher organic carbon levels. Therefore, the results indicate that the principal distinctions between the two sites are related to soil reaction, organic carbon content, nitrogen status, and particle size distribution, all of which have important implications for land capability classification and crop suitability evaluation. Table 3 shows the site and depth effects on soil properties: repeated measures ANOVA and implications for crop selection.

Table 3: Site and Depth Effects on Soil Properties: Repeated Measures ANOVA and Implications for Crop Selection

Parameter	Source of Variation	F-value	df	p-value	Partial η²	Land Capability Class	Crop Suitability
pH	Site	12.47	1, 4	0.023*	0.757	II – III	Maize (S2), Soybean (S2), Millet (S2)
	Depth	2.35	2, 8	0.160	0.370	–	–
	Site × Depth	1.05	2, 8	0.394	0.208	–	–
EC (dS m⁻¹)	Site	0.91	1, 4	0.388	0.186	III – IV	Maize (S3), Soybean (S3), Millet (S3)
	Depth	0.76	2, 8	0.503	0.160	–	–
	Site × Depth	0.45	2, 8	0.656	0.101	–	–
OC (g kg⁻¹)	Site	10.36	1, 4	0.032*	0.722	II	Maize (S1), Soybean (S1), Millet (S1)
	Depth	8.14	2, 8	0.012*	0.671	–	–
	Site × Depth	6.07	2, 8	0.027*	0.603	–	–
N (g kg⁻¹)	Site	7.92	1, 4	0.048*	0.664	II – III	Maize (S2), Soybean (S2), Millet (S2)
	Depth	5.14	2, 8	0.040*	0.562	–	–
	Site × Depth	2.12	2, 8	0.182	0.346	–	–
P (mg kg⁻¹)	Site	0.21	1, 4	0.670	0.050	III – IV	Maize (S3), Soybean (S3), Millet (S3)
	Depth	0.84	2, 8	0.462	0.173	–	–
	Site × Depth	0.67	2, 8	0.541	0.143	–	–
Sand (%)	Site	10.92	1, 4	0.027*	0.732	III	Maize (S3), Soybean (S3), Millet (S3)
	Depth	6.84	2, 8	0.018*	0.631	–	–
	Site × Depth	5.07	2, 8	0.038*	0.559	–	–
Silt (%)	Site	9.47	1, 4	0.034*	0.703	II – III	Maize (S2), Soybean (S2), Millet (S2)
	Depth	5.63	2, 8	0.031*	0.585	–	–
	Site × Depth	2.11	2, 8	0.183	0.345	–	–
Clay (%)	Site	7.68	1, 4	0.050*	0.658	II	Maize (S2), Soybean (S2), Millet (S2)
	Depth	4.29	2, 8	0.053*	0.518	–	–
	Site × Depth	1.48	2, 8	0.285	0.270	–	–

*= Significant (α = 0.05)

The repeated measures ANOVA results indicate that soil properties at the GK and COE sites differed significantly for several parameters. Soil reaction (pH) showed a strong site effect (F = 12.47, p = 0.023, partial η^2 = 0.757), suggesting that COE soils are less acidic than GK soils, which may influence crop performance and nutrient availability. Similarly, soil organic carbon (OC) and total nitrogen (N) were significantly affected by site, with COE soils having higher OC (F = 10.36, p = 0.032) and GK soils slightly higher N (F = 7.92, p = 0.048), highlighting differences in organic matter content and fertility status. Soil texture fractions, including sand, silt, and clay, were significantly influenced by site, with GK soils coarse (higher sand content) and COE soils finer (higher silt and clay content). Depth had a significant effect on OC, N, and texture fractions, reflecting the typical stratification of soil nutrients and particle distribution, while most site × depth interactions were not significant, indicating that the site differences were largely consistent across soil depths. Parameters such as electrical conductivity (EC) and available phosphorus (P) showed no significant site, depth, or interaction effects, suggesting similar salinity levels and P availability across the study area.

Considerring land capability and crop suitability, the results show that soils with higher OC and finer textures, such as those at COE, correspond to more favorable land capability classes (II) and higher suitability ratings for crops such as maize, soybean, and millet (S1–S2). Conversely, the coarser, sandy soils at GK fall into slightly lower capability classes (II–III or III) and are moderately suitable (S2–S3) for the same crops. The significant differences in pH, OC, and texture are particularly important, as they influence water retention, nutrient availability, and structural stability, directly impacting both land use classification and crop performance. These findings are consistent with previous studies connecting soil organic matter and texture to land capability and crop suitability assessments in tropical savanna soils (FAO, 1976; USDA, 1961; Brady and Weil, 2017). However, the results emphasize that site-specific soil management strategies are critical to optimize agricultural productivity based on soil chemical and physical properties.

4. Discussion and Limitations

The observed differences between GK and COE soils align with previous findings that soil fertility and texture significantly influence land capability and crop productivity. Higher SOC and CEC in COE soils imply improved nutrient retention and water-holding capacity, which is critical for supporting crops such as maize, soybean, and millet (Brady and Weil, 2017; Inacio, *et al.* 2025). In contrast, the coarser texture of GK soils, coupled with lower SOC, may limit nutrient availability and water retention, necessitating targeted soil management and fertility enhancement (Sun, *et al.* 2025).

Depthwise variability indicates that organic matter and nutrient content are concentrated in the topsoil, decreasing with depth. This pattern is consistent with tropical savanna soils where surface layers receive organic inputs from crop residues and plant litter, while subsoil layers are less enriched (FAO, 2017; Sun, *et al.* 2025). The variability in COE soils may reflect differences in previous land management, micro-topography, or soil texture, suggesting that site-specific management practices are essential. Therefore, COE soils demonstrate higher potential for sustainable crop production, while GK soils may require interventions to improve fertility and enhance crop yield stability.

The significant variation in soil reaction between GK and COE sites underscores the critical role of pH in regulating nutrient availability and soil biochemical processes. The lower pH recorded in GK soils indicates comparatively higher acidity, which can reduce the availability of essential nutrients such as phosphorus and molybdenum while increasing the solubility of potentially toxic elements like aluminum (Bulenga, *et al.* 2023). Soil pH is widely described as a master variable influencing nutrient solubility, microbial activity, and overall soil productivity (Brady and Weil, 2017). In their seminal textbook, Brady and Weil (2016) emphasize that soils within a slightly acidic to near-neutral pH range generally provide optimal conditions for most arable crops. The significantly higher soil organic carbon (SOC) concentration observed in COE soils further suggests improved soil structural stability and nutrient retention. The protective role of fine particles in stabilizing organic matter has been extensively demonstrated by (Bulenga, *et al.* 2023), who showed that clay-associated organic matter is less susceptible to rapid decomposition, thereby enhancing long-term carbon storage and soil quality. Although COE soils contained significantly higher organic carbon, total nitrogen was slightly but significantly higher in GK soils. This apparent discrepancy may reflect differences in mineralization rates, residue management, or fertilizer inputs. The close interrelationship between soil organic carbon and nitrogen cycling has been highlighted by (Lal 2004; Bulenga, *et al.* 2023), they noted that nitrogen availability is strongly governed by organic matter turnover and microbial processes. The relatively small difference in nitrogen content suggests that both sites may experience moderate nitrogen limitations under continuous cultivation. Furthermore, the absence of significant differences in exchangeable bases (Ca, Mg, Na, K) and cation exchange capacity (CEC) indicates broadly comparable nutrient-holding capacities between the two locations. Cation exchange capacity is strongly influenced by clay mineralogy and organic matter content, as described by (Bulenga, *et al.* 2023), where they explain that both clay fraction and humus contribute substantially to exchange sites in soils.

The significant differences in particle size distribution provide further insight into the contrasting soil characteristics. GK soils were significantly sandy, while COE soils contained higher proportions of silt and clay (Yakubu & Panti 2024). Soil texture is a fundamental determinant of water retention, aeration, and nutrient dynamics, and thus plays a central role in land capability assessment and crop suitability evaluation. According to the land evaluation guidelines of the Food and Agriculture Organization (FAO, 1976), texture is a key criterion influencing agricultural potential due to its control over rooting depth, available water capacity, and erosion susceptibility. The finer texture and higher SOC observed in COE soils therefore suggest enhanced resilience and greater suitability for sustained crop production (Yakubu & Panti 2024). In contrast, the coarser texture of GK soils may limit water-holding capacity and nutrient retention, necessitating improved soil management practices such as organic amendments and integrated nutrient management to sustain productivity (Okoli, *et al.* 2023; Amanze *et al.* 2024). Therefore, the findings demonstrate that soil reaction, organic carbon status, nitrogen dynamics, and texture collectively determine differences in land capability and crop suitability between the two sites.

The results of the repeated measures ANOVA revealed significant differences in several physical and chemical soil properties between the GK and COE sites, with implications for land capability and crop suitability (Ajayi, *et al.* 2025). Soil reaction differed between the two sites, with COE soils exhibiting higher pH than GK soils. This indicates that GK soils are more acidic, which could affect nutrient availability, particularly for base-sensitive nutrients such as phosphorus and potassium (Brady and Weil, 2017; Abate and Anteneh, (2024). Soil organic carbon also showed significant differences across sites and depths, with COE soils having higher organic matter content. This reflects a greater organic matter status, which is linked to improved soil structure, water retention, and nutrient-holding capacity (Lal, 2004; FAO, 2017). Total nitrogen followed a similar trend, emphasizing the stratification of soil nutrients and the importance of organic matter in sustaining fertility (Brady and Weil, 2017). Other chemical parameters, including electrical conductivity and available phosphorus, did not differ significantly between sites, suggesting broadly comparable salinity and phosphorus availability across the study area.

Physical properties also differed between sites, particularly soil texture fractions. Sand content was higher in GK soils, whereas silt and clay were higher in COE soils. These differences indicate that GK soils are coarser and more prone to drainage and erosion, while COE soils, with higher silt and clay content, likely possess greater water-holding capacity and structural stability (Mengiste, *et al.* 2025; Brady & Weil, 2017). Depth effects were also significant for texture fractions, highlighting the vertical distribution of particles and organic matter in the soil profile. Linking these results to land capability and crop suitability, soils with higher organic carbon, silt, and clay at COE were classified as more suitable for crops such as maize, soybean, and millet, while GK soils were moderately suitable (Amanze *et al.* 2024). These findings are consistent with established relationships between soil chemical-physical properties, land evaluation, and crop productivity in tropical savanna ecosystems (FAO, 1976; USDA, 1961). The study underscores the necessity of site-specific soil management and fertility enhancement strategies to optimize crop performance and sustainable land use. This study was limited to two locations within a relatively small geographic range, which may constrain broader regional extrapolation. Seasonal variability was not assessed, and temporal dynamics of soil organic carbon were not evaluated.

5. Conclusions and Future Work

The study demonstrated significant spatial and depth-wise variability in soil chemical and physical properties across GK and COE sites, with clear implications for land capability and crop suitability. Soil organic carbon (SOC) levels were generally moderate but declined consistently with depth, confirming the critical role of surface horizons in nutrient retention and crop productivity. COE soils exhibited relatively higher SOC, cation exchange capacity (CEC), and slightly improved pH conditions compared to GK soils, indicating better nutrient holding capacity and overall fertility potential. In contrast, GK soils were comparatively coarser in texture and more acidic, factors that may limit nutrient retention and water availability. Electrical conductivity and available phosphorus were uniformly low across both sites, suggesting non-saline conditions but potential phosphorus constraints.

Land capability classification placed most of the assessed lands within Classes II and III, reflecting moderate limitations primarily associated with low SOC, coarse texture, and reduced nutrient retention capacity. Crop suitability analysis showed that maize and soybean were generally moderately suitable (S2), while millet demonstrated greater tolerance to fertility constraints but with comparatively lower productivity potential. The findings underscore the importance of integrating SOC, texture, soil reaction, and CEC in profile-based land evaluation. Enhancing SOC stocks and improving nutrient management are therefore essential to upgrading land capability, increasing crop productivity, and strengthening climate resilience in the Northern Guinea Savanna.

- Farmers should adopt integrated soil fertility management practices combining organic amendments (manure, compost, crop residues) with balanced mineral fertilization. Conservation tillage, residue retention, and legume-based crop rotations should be encouraged to improve SOC levels, soil structure, nutrient retention, and water holding capacity.
- Policymakers should promote soil organic carbon centered land use planning and provide incentives for conservation agriculture, residue retention, agroforestry systems, and sustainable nutrient management. Incorporating SOC monitoring targets into agricultural development and climate adaptation policies will support long-term soil health and productivity.
- Researchers should establish long term, depth-resolved soil monitoring programs across agricultural landscapes to track SOC dynamics and fertility trends. Further research on carbon stabilization mechanisms, including interactions among SOC, clay minerals, and soil microbial processes, is needed to inform targeted restoration strategies for Guinea savanna agro-ecosystems.

Conflict of Interest

The authors declare no conflicts of interest.

Author Contributions

Abubakar A. Panti: Conceptualization, Methodology, Supervision, Formal analysis, Funding acquisition, Writing – review and editing.

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Buhari Y.: Statistical analysis, Software, Data interpretation, Visualization.

Bokani M. Audu: Field sampling, Resources, Data curation, Project administration.

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Ethical Statements

This study did not involve human participants, human data, or vertebrate animals. Soil samples were collected from institutional agricultural lands with appropriate site authorization and in accordance with local research guidelines. Field sampling was conducted responsibly to minimize environmental disturbance, and no protected or restricted areas were affected. All laboratory analyses were performed following standard scientific procedures and institutional safety protocols. The authors adhered to principles of research integrity, transparency, and responsible data management throughout the study.

Data and Code Availability

The datasets generated and analyzed during the current study are available from the corresponding author upon reasonable request

Supplementary Materials

The materials are available from the corresponding author upon reasonable request.

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