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Research Article

Effects of Soil Organic Matter Fractions on Some Selected Physical and Chemical Properties of Forest Soils in Gashaka Local Government Area, Taraba State, Nigeria

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ABSTRACT
Soil organic matter fractions provide important insights into the mechanisms regulating soil carbon stabilization and nutrient dynamics in tropical ecosystems. This study investigated the distribution of soil organic carbon fractions and their relationships with selected soil physical and chemical properties in forest soils of Gashaka Local Government Area, Taraba State, Nigeria. Soil samples were collected from twenty-five auger sampling points at two depths (0–20 cm and 20–50 cm) using a systematic sampling approach within a 100-hectare forestland. A total of fifty soil samples were analyzed for total organic carbon (TOC), particulate organic carbon (POC), mineral-associated organic carbon (MOC), and selected soil physical & chemical properties using standard laboratory procedures. The results revealed clear vertical stratification of soil organic carbon fractions, with higher concentrations observed in the surface soil depth. Total organic carbon declined from 1.62% in the 0–20 cm depth to 1.21% in the 20–50 cm depth, while particulate organic carbon decreased from 0.46% to 0.38% with increasing soil depth. Mineral-associated organic carbon constituted the dominant carbon pool, accounting for approximately 71–73% of total organic carbon. The reduction in soil organic carbon fractions with depth corresponded with increases in bulk density and reductions in soil porosity, water holding capacity, and nutrient status. Surface soils with higher organic carbon concentrations also recorded greater total nitrogen and cation exchange capacity, indicating the important role of organic matter in nutrient retention and soil fertility. Generally, the findings highlight the importance of vegetation-derived organic inputs and organo-mineral interactions in regulating carbon stabilization and sustaining soil productivity in tropical savanna ecosystems.

Keywords: Carbon stabilization; Gashaka Nigeria; Mineral-associated organic carbon; Particulate organic carbon; Soil organic carbon fractions; Soil physicochemical properties; Tropical savanna soils

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INTRODUCTION

Soil organic matter (SOM) is widely recognized as one of the most important components of soil systems because it regulates a wide range of physical, chemical, and biological processes that sustain soil productivity and ecosystem stability. SOM contributes significantly to soil aggregation, nutrient availability, microbial activity, and water retention, thereby playing a central role in maintaining soil fertility and environmental sustainability. In tropical ecosystems, where high temperatures and intense rainfall accelerate organic matter decomposition, the maintenance of soil organic carbon (SOC) is particularly important for sustaining soil quality and agricultural productivity (Lal, 2018; Minasny *et al.*, 2019).

Globally, soils constitute the largest terrestrial carbon reservoir and store more carbon than the atmosphere and terrestrial vegetation combined. Consequently, understanding the mechanisms governing SOC storage and stabilization has become a major focus of soil science and climate change research. However, total SOC alone does not adequately explain the dynamics of carbon stabilization in soils because SOC is composed of different fractions with varying stability and turnover rates (Cotrufo *et al*., 2019; Lehmann *et al*., 2020).

To better understand soil carbon dynamics, SOC is commonly fractionated into functional pools, particularly particulate organic carbon (POC) and mineral-associated organic carbon (MOC). These fractions represent distinct pathways of carbon stabilization in soils. Particulate organic carbon consists largely of partially decomposed plant residues and organic debris that are relatively labile and responsive to environmental changes. Due to its rapid turnover, POC is often considered an indicator of recent organic inputs and short-term soil management effects. In contrast, mineral-associated organic carbon forms stable complexes with fine soil minerals such as clay and silt particles, which protect organic matter from microbial decomposition and contribute to long-term carbon sequestration (Lavallee *et al*., 2020; Liang *et al*., 2019).

The relative distribution of these SOM fractions provides valuable insight into the mechanisms controlling carbon persistence in soils. Previous studies have demonstrated that soil texture, aggregation processes, microbial activity, and vegetation inputs strongly influence the balance between particulate and mineral-associated carbon pools. Fine-textured soils often promote the formation of stable organo-mineral complexes that enhance carbon stabilization, whereas coarse-textured soils typically contain a higher proportion of labile organic matter fractions (Six *et al*., 2018; Wiesmeier *et al*., 2019).

In tropical savanna ecosystems, soil organic carbon dynamics are particularly sensitive to environmental conditions and land management practices. High temperatures, seasonal rainfall variability, and frequent disturbances such as cultivation and grazing often accelerate organic matter decomposition and reduce carbon storage. Nevertheless, natural ecosystems such as forests and grasslands can enhance soil carbon stabilization through continuous organic inputs from litter deposition and root turnover, which promote the formation of stable SOM fractions (Bossio *et al*., 2020; Sanderman *et al*., 2018).

In many parts of sub-Saharan Africa, including northeastern Nigeria, soils are generally characterized by relatively low organic matter content and limited nutrient reserves. The predominantly sandy loam soils found in tropical savanna regions often have a lower capacity for mineral-associated carbon stabilization compared with clay-rich soils. Consequently, understanding how SOM fractions interact with soil physical and chemical properties is essential for evaluating soil fertility and carbon stabilization processes in these environments (Obalum *et al*., 2017; Chude *et al*., 2020).

Despite the increasing interest in soil carbon dynamics globally, empirical studies on SOM fraction distribution in tropical forest soils of Nigeria remain limited. In particular, there is insufficient information on the relationships between particulate and mineral-associated organic carbon pools and key soil physical and chemical properties in forest ecosystems of northeastern Nigeria. Such information is essential for understanding carbon stabilization mechanisms and for developing sustainable soil management strategies aimed at improving soil fertility and ecosystem resilience. Therefore, this study investigates the distribution of soil organic matter fractions and their relationships with selected soil physical and chemical properties in forest soils of Gashaka Local Government Area, Taraba State, Nigeria. Specifically, the study aims to:

Determine the distribution of total organic carbon, particulate organic carbon, and mineral-associated organic carbon across soil depths, Evaluate the relationships between SOM fractions and selected soil physical properties and examined the interactions between SOM fractions and soil chemical properties that influence soil fertility and carbon stabilization.

Based on the ecological characteristics of tropical savanna soils, the study hypothesizes that:

(i) mineral-associated organic carbon constitutes the dominant carbon pool in forest soils of the study area; (ii) soil depth significantly influences the distribution of SOM fractions; and (iii) soil physical and chemical properties play an important role in regulating the stabilization of organic carbon in sandy loam tropical soils.

MATERIALS AND METHODS

Study Area

The study was conducted in Gashaka Local Government Area (LGA), Taraba State, Nigeria, located in northeastern Nigeria between latitudes 6°51′N and 8°00′N and longitudes 10°56′E and 11°57′E. Gashaka LGA occupies an estimated land area of approximately 8,521 km², making it one of the largest Local Government Areas in Taraba State. The area lies within the tropical savanna ecological zone of Nigeria and is influenced by the Mambilla Plateau highland system, which contributes to the ecological and climatic variability of the region.

The climate of the area is characterized as tropical wet and dry (Aw) according to the Köppen climatic classification. The region experiences two distinct seasons: a rainy season from April to October and a dry season from November to March. Mean annual rainfall ranges between 1,200 and 1,600 mm, while the mean annual temperature varies between 26 and 32°C. Relative humidity is generally higher during the rainy season and declines during the dry season due to the influence of the northeast trade winds (Harmattan) that dominate northern Nigeria during the dry months (Adebayo & Tukur, 1999; Nigerian Meteorological Agency, 2022).

Vegetation in the area is dominated by savanna woodland interspersed with grasses and scattered trees, with patches of gallery forest vegetation occurring along rivers and drainage channels. Typical tree species include *Isoberlinia*, *Daniellia*, and *Parkia* species commonly associated with the Guinea savanna zone of Nigeria. This vegetation contributes significant organic inputs into the soil through litter deposition, root biomass turnover, and microbial decomposition, which play an important role in soil organic matter formation and nutrient cycling processes in tropical ecosystems (Bationo *et al*., 2018; Lal, 2020).

Topographically, the landscape consists of gently undulating plains interspersed with hills and mountainous terrain, particularly toward the southern portions of the area near the Mambilla Plateau. Elevation variations across the landscape influence local drainage patterns, soil development, and vegetation distribution. The area is drained by several seasonal and perennial streams that form part of the Benue River drainage basin, which represents one of the major hydrological systems in northeastern Nigeria (Ofomata, 2002).

Geologically, the soils of the region are derived predominantly from weathered Precambrian basement complex rocks, including granite, gneiss, and migmatite formations. These parent materials undergo intense tropical weathering processes, leading to the development of relatively coarse-textured soils with moderate mineral weathering and low inherent nutrient reserves (Obalum *et al*., 2017).

The soils of the study area are predominantly sandy loam in texture, a characteristic common to many savanna soils in northeastern Nigeria. Such soils generally exhibit moderate drainage, relatively low clay content, and rapid organic matter mineralization rates due to high temperatures and microbial activity. These characteristics significantly influence soil fertility status, carbon stabilization mechanisms, and water retention within the soil profile (Adesodun *et al*., 2020; Bationo *et al*., 2018).

Based on international soil classification systems, the soils of the area are generally classified as Alfisols under the USDA Soil Taxonomy, while their equivalent classification under the World Reference Base (WRB) system corresponds mainly to Luvisols. These soils are characterized by subsurface clay accumulation (argic horizons), moderate base saturation, and relatively good agricultural potential when appropriately managed (IUSS Working Group WRB, 2015; Soil Survey Staff, 2014).

Sampling Design and Soil Collection

The study was conducted within a 100-hectare forestland selected to represent the dominant vegetation type of the study area in Gashaka Local Government Area, Taraba State, Nigeria. The forest site represents a secondary tropical savanna woodland, characterized by mixed indigenous tree species and natural regeneration with minimal recent anthropogenic disturbance. Based on local land-use history and vegetation structure, the forest stand is estimated to be approximately 25–30 years old.

Soil sampling was carried out in January 2025 during the dry season, a period characterized by relatively stable soil moisture conditions in tropical savanna environments. Sampling during this period helps reduce short-term variability associated with rainfall events and facilitates more consistent comparisons of soil organic carbon fractions and associated soil properties.

A systematic sampling design was adopted to ensure adequate spatial representation within the 100-hectare study area. A total of twenty-five (25) sampling point**s** were established across the forest site using a grid-based approach (Figure 3). The study area lies between 6°51′N–8°00′N latitude and 10°56′E–11°57′E longitude, and the geographic coordinates of each sampling point were recorded using a handheld Global Positioning System (GPS) receiver to enhance reproducibility and facilitate spatial analysis (see Appendix 1.

At each sampling point, soil samples were collected using a soil auger at two depths: 0–20 cm and 20–50 cm. The 0–20 cm depth represents the surface soil layer where organic matter accumulation is typically

higher due to litter deposition, root activity, and microbial processes. In contrast, the 20–50 cm depth represents the subsurface soil layer where organic carbon stabilization processes and mineral associations often differ from those in the surface horizon (Lal, 2020).
In addition to auger sampling, undisturbed soil core samples were collected for bulk density determination at both depths using a cylindrical core sampler measuring 5 cm in diameter and 5 cm in height (approximately 98.2 cm^3 volume). At each sampling point, one core sample was collected per depth, resulting in a total of 50 bulk density cores (25 sampling points × 2 depths).
Overall, fifty (50) soil samples were collected from the twenty-five sampling locations across the two depths. The samples were placed in labelled polyethylene bags, properly sealed, and transported to the laboratory where they were air-dried and prepared for subsequent physicochemical and soil organic carbon fraction analyses.
For the soil organic carbon fractionation, laboratory analyses were performed on all fifty (50) soil samples to adequately capture the vertical distribution and spatial variability of particulate organic carbon (POC) and mineral-associated organic carbon (MOC) within the forest soil profile.

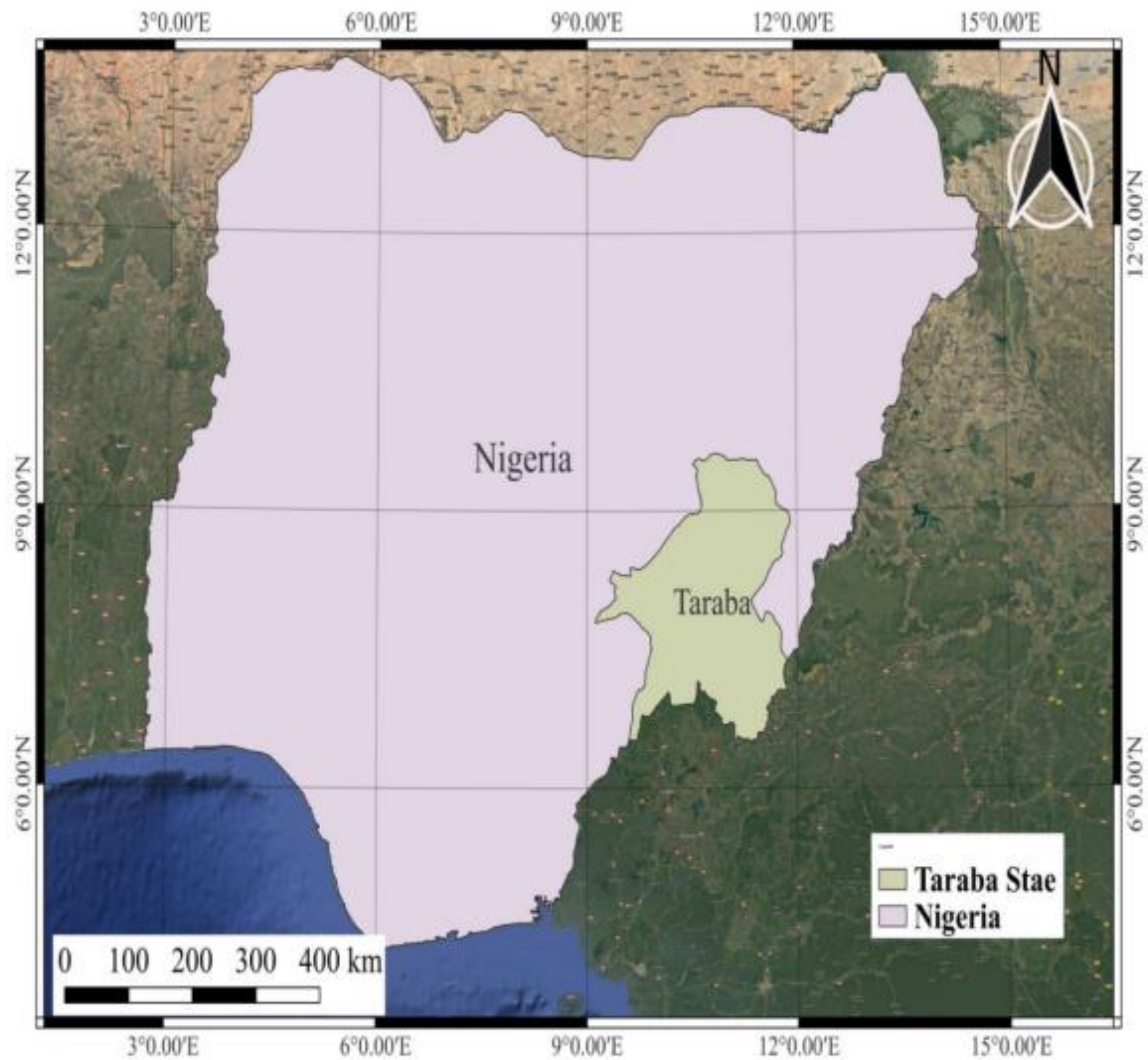

Figure 1: Map of Nigeria Showing Taraba State

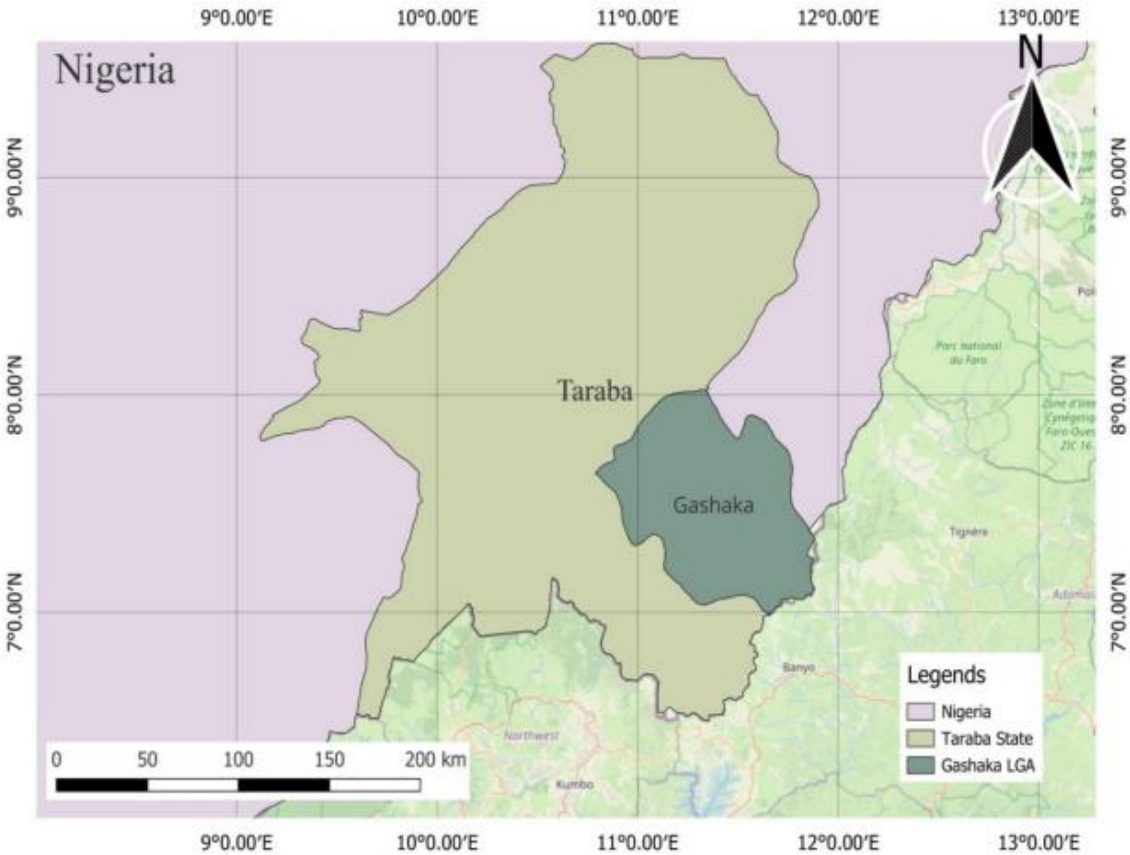

Figure 2: Map of Taraba State Showing Gashaka Local Government Area

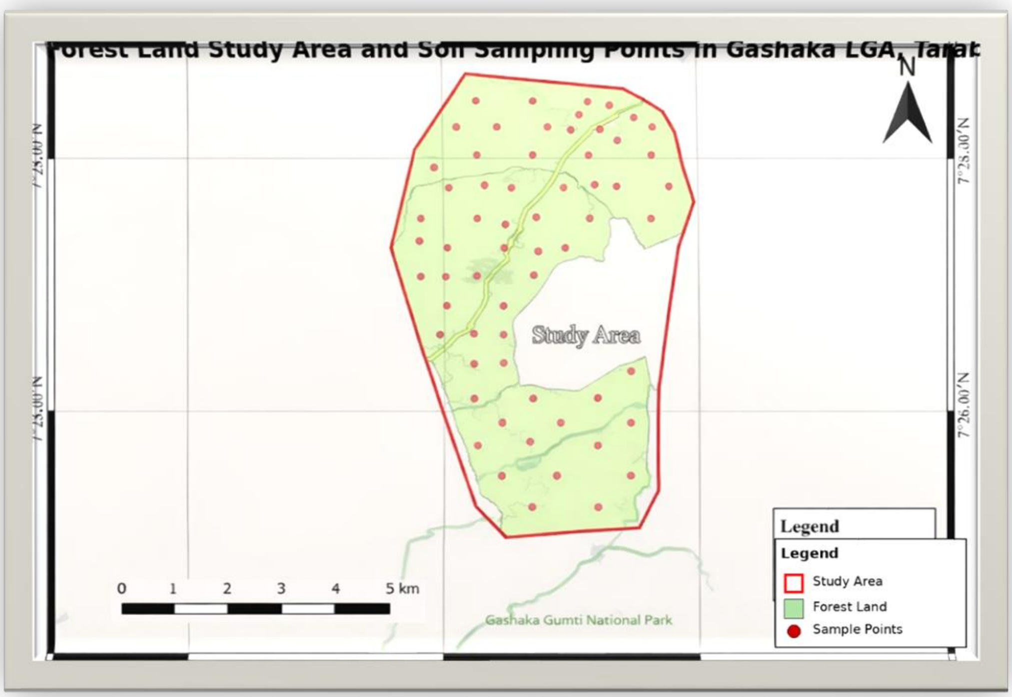

Figure 3: Map of the Study area showing sampling points

Sample Preparation

In the laboratory, soil samples were air-dried under room temperature conditions, gently crushed to break large aggregates, and passed through a **2-**mm **sieve** to remove coarse fragments, roots, and plant residues. The processed soil samples were then stored in clean sample containers prior to laboratory analyses (Chude *et al*., 2020; FAO, 2021).

Determination of Soil Physical Properties

Particle size distribution was determined using the hydrometer method, which separates soil particles based on sedimentation rates in suspension. The proportions of sand, silt, and clay were used to determine soil textural classes according to the USDA soil textural classification system (Soil Survey Staff, 2017).

Bulk density was determined using the core sampling method, in which undisturbed soil samples were collected using cylindrical cores of known volume, oven-dried at **105°C**, and weighed to determine soil mass per unit volume. Particle density was determined using the pycnometer method, and total porosity was calculated from the relationship between bulk density and particle density. Water holding capacity (WHC) was determined using the saturation and drainage method, which measures the amount of water retained in soil after gravitational drainage (FAO, 2021; Hillel, 2020).

Determination of Soil Chemical Properties

Soil pH was determined in a **1:2.5** soil–water suspension using a digital pH meter, while electrical conductivity (EC) was measured using a conductivity meter in the same extract.

Total organic carbon (TOC) was determined using the wet oxidation method, which measures oxidizable organic carbon in soil samples. This method remains widely used in tropical soil studies due to its reliability and suitability for routine laboratory analysis (Nelson & Sommers, 2018; Chude *et al*., 2020).

Total nitrogen (TN) was determined using the Kjeldahl digestion method, while exchangeable bases including Ca^{2+}, Mg^{2+}, K^{+}, and Na^{+} were extracted using ammonium acetate solution at pH 7. Calcium and magnesium were determined using atomic absorption spectrophotometry**,** while potassium and sodium were determined using flame photometry. Cation exchange capacity (CEC) was determined using the ammonium acetate extraction method (FAO, 2021).

Fractionation of Soil Organic Matter

Soil organic carbon was fractionated into particulate organic carbon (POC) and mineral-associated organic carbon (MOC) using a particle-size fractionation method, which is widely employed in soil carbon studies to distinguish between labile and stabilized carbon pools (Cotrufo *et al*., 2019; Lavallee *et al*., 2020).

For the fractionation procedure, 20 g of air-dried soil (<2 mm) was placed in a 250-mL polyethylene bottle and dispersed using 50 mL of 5 g L^{-1} sodium hexametaphosphate ($(NaPO_3)_6$) solution as a chemical dispersant. The soil–solution suspension was mechanically shaken for 16 hours at approximately 150 rpm using a reciprocal shaker to ensure adequate dispersion of soil aggregates. Following dispersion, the suspension was passed through a 53 µm sieve to separate the coarse particulate fraction from the fine mineral fraction. The material retained on the sieve represents the particulate organic matter (POM) fraction, which mainly consists of partially decomposed plant residues and organic particles. This fraction was carefully washed with distilled water, oven-dried at 50°C, and subsequently analyzed for carbon concentration using standard procedures to determine particulate organic carbon (POC).

The fraction passing through the 53 µm sieve represents the mineral-associated fraction, which contains organic carbon stabilized through interactions with fine mineral particles such as clay and silt. The carbon associated with this fraction was estimated as mineral-associated organic carbon (MOC) and calculated by difference as:

$$MOC=TOC-POC$$

where TOC represents total organic carbon measured in the bulk soil sample.

To ensure adequate aggregate dispersion, mechanical shaking was used without sonication, as prolonged shaking in the dispersing solution is generally sufficient to disrupt macro-aggregates during particle-size fractionation procedures (Cotrufo *et al*., 2019). The recovery rate of the fractionation procedure ranged between 90 and 105%, which falls within the acceptable range for soil carbon fractionation studies.

Data Analysis

Data obtained from laboratory analyses were subjected to analysis of variance (ANOVA) to evaluate the effect of soil depth (0–20 cm and 20–50 cm) on soil organic carbon fractions and selected soil physical & chemical properties. The statistical analysis was performed using Statistix version 8.0 statistical software (Analytical Software, Tallahassee, USA).

Since soil depth represented the only experimental factor with two levels, comparisons between the surface and subsurface soil layers were conducted using one-way ANOVA, which is statistically equivalent to a two-sample t**-test**. Differences between treatment means were considered statistically significant at the 5% probability level ($p \leq 0.05$).

Mean values are presented together with their standard deviations (± SD) to indicate the variability among sampling points. Where significant differences were detected, means were separated using the Least Significant Difference (LSD) test at $p \leq 0.05$.

To further examine the interactions between soil organic carbon fractions and soil properties, Pearson correlation analysis was conducted to determine the relationships between total organic carbon (TOC), particulate organic carbon (POC), mineral-associated organic carbon (MOC), and selected soil physical and chemical properties. In addition, simple linear regression analysis was performed to quantify the strength of association between soil organic carbon fractions and key soil attributes.

RESULTS AND DISCUSSION

Distribution of Soil Organic Matter Fractions Across Soil Depths

The distribution of soil organic carbon fractions across the two sampling depths is presented in Table 1. The results revealed that total organic carbon (TOC), particulate organic carbon (POC), and mineral-associated organic carbon (MOC) were significantly higher ($p \leq 0.05$) in the surface soil layer (0–20 cm) compared with the subsurface layer (20–50 cm).

Total organic carbon decreased from 1.62 ± 0.12% in the surface soil to 1.21 ± 0.10% in the subsurface layer. Similarly, particulate organic carbon declined from 0.46 ± 0.05% at 0–20 cm to 0.38 ± 0.04% at 20–50 cm. Mineral-associated organic carbon also showed a significant reduction with depth, decreasing from 1.16 ± 0.09% in the surface horizon to 0.83 ± 0.08% in the subsurface soil. The higher concentrations of organic carbon fractions in the surface soil can be attributed to greater accumulation of plant residues, litter fall, and root biomass, which are predominantly deposited in the upper soil layer of forest ecosystems. These organic inputs provide substrates for microbial activity, resulting in the formation and accumulation of both labile and stabilized carbon fractions. In contrast, the lower carbon content observed in the subsurface layer reflects reduced organic matter inputs and increased decomposition of organic materials as soil depth increases.

Particulate organic carbon represents the labile fraction of soil organic matter, which is mainly composed of partially decomposed plant residues and organic debris. The significant decline in POC with increasing soil depth observed in this study suggests that fresh organic inputs are concentrated in the surface soil, where biological activity and litter deposition are highest. Similar patterns of decreasing POC with soil depth have been reported in tropical forest soils where organic inputs are largely confined to the upper soil horizons (Cotrufo *et al*., 2019; Lavallee *et al*., 2020).

Mineral-associated organic carbon constituted the dominant proportion of total organic carbon in the study area, accounting for approximately 70–72% of the SOC pool across the soil depths. This dominance indicates that organo-mineral interactions play a major role in stabilizing soil carbon in the sandy loam soils of the study area. Mineral-associated carbon is generally considered the more stable carbon pool because it is protected from microbial decomposition through interactions with clay and silt particles.

The observed depth-related decline in SOC fractions is consistent with findings from other tropical ecosystems, where soil organic carbon typically decreases with depth due to the stratification of organic matter inputs and microbial activity within the soil profile (Lal, 2020; Bationo *et al*., 2018). These results highlight the importance of surface vegetation and litter dynamics in maintaining soil carbon stocks in forest soils of the savanna region.

Table 1: Distribution of Soil Organic Carbon Fractions Across Soil Depths

Soil Depth (cm)	TOC (%)	POC (%)	MOC (%)
0–20	1.62 ± 0.12^a	0.46 ± 0.05^a	1.16 ± 0.09^a
20–50	1.21 ± 0.10^b	0.38 ± 0.04^b	0.83 ± 0.08^b

Values are mean ± SD

Values followed by different letters within columns indicate significant differences at $p \leq 0.05$.

Note: TOC: total organic carbon; POC: particulate organic carbon and MOC: mineral organic carbon

Analysis of Variance of Soil Organic Matter Fractions

The analysis of variance (ANOVA) revealed that soil depth had a significant influence on the distribution of soil organic matter fractions in the study area (Table 2). The results show that total organic carbon (TOC), particulate organic carbon (POC), and mineral-associated organic carbon (MOC) varied significantly across soil depths, indicating vertical stratification of carbon pools within the forest soils.

Total organic carbon recorded a highly significant difference across soil depths (F = 14.21, p = 0.001). This result suggests that the concentration of organic carbon is strongly influenced by depth, with surface soils generally exhibiting higher carbon accumulation due to continuous litter deposition, root biomass input, and reduced decomposition constraints near the soil surface. In tropical forest ecosystems, surface horizons typically receive substantial organic inputs from plant residues and root exudates, leading to higher carbon concentration compared with subsurface layers (Lal, 2018; Cotrufo *et al*., 2019).

Similarly, particulate organic carbon (POC) showed a significant variation with soil depth (F = 9.37, p = 0.004). Particulate organic carbon represents the relatively labile fraction of soil organic matter derived primarily from partially decomposed plant residues. The significant depth effect observed for POC suggests that this carbon pool is highly sensitive to surface organic matter inputs and decreases with increasing soil depth due to reduced biological activity and limited fresh organic residue incorporation. Previous studies have reported similar vertical declines in POC in tropical soils, emphasizing the influence of litter accumulation and microbial activity in the upper soil horizons (Six *et al*., 2018).

Mineral-associated organic carbon (MOC) also showed significant variation with soil depth (F = 11.52, p = 0.002). Although MOC represents the more stable fraction of soil organic carbon that is protected through interactions with soil minerals and aggregates, its distribution may still reflect the influence of organic inputs and stabilization processes within the soil profile. The significant depth effect observed in this study suggests that organo-mineral interactions and carbon stabilization mechanisms vary along the soil profile, potentially influenced by changes in microbial processing and mineral surface availability.

Overall, the significant ANOVA results indicate that soil depth is a major controlling factor influencing the distribution of soil organic carbon fractions in the forest soils of the study area. The observed stratification of TOC, POC, and MOC highlights the importance of surface organic matter inputs and mineral stabilization processes in regulating carbon dynamics in tropical forest soils.

Table 2: Analysis of Variance (ANOVA) for Soil Organic Matter Fractions across Soil Depths

Parameter	F-value	p-value
TOC	14.21	0.001
POC	9.37	0.004
MOC	11.52	0.002

Note: TOC: total organic carbon; POC: particulate organic carbon and MOC: mineral organic carbon

Relationship between Soil Organic Matter Fractions and Selected Soil Properties

Pearson correlation analysis was conducted to evaluate the relationships between soil organic matter fractions—total organic carbon (TOC), particulate organic carbon (POC), and mineral-associated organic carbon (MOC) and selected soil physical and chemical properties (Table 3). The results indicate that soil organic matter fractions are strongly associated with several key soil quality indicators, particularly water retention, nutrient availability, and soil structure.

Among the physical properties, bulk density showed a significant negative correlation with TOC (r = −0.61, p < 0.05) and POC (r = −0.58, p < 0.05). This inverse relationship suggests that soils with higher organic carbon content tend to exhibit lower bulk density due to improved soil aggregation and increased pore space created by organic matter accumulation. Similar observations have been widely reported in tropical soils, where organic matter enhances soil structure and reduces compaction (Lal, 2018; Minasny *et al*., 2017). In contrast, particle density showed weak and non-significant correlations with the organic carbon fractions, indicating that mineral particle composition exerts a stronger control over this parameter than organic matter content.

Water holding capacity (WHC) exhibited the strongest positive correlation with TOC (r = 0.72, p < 0.01) and POC (r = 0.65, p < 0.01), while a moderate significant relationship was observed with MOC (r = 0.48, p < 0.05). This finding highlights the critical role of organic matter in improving soil water retention through enhanced aggregation, increased microporosity, and improved soil structure. Organic matter has a high specific surface area and strong affinity for water, thereby enhancing the soil's capacity to retain moisture, particularly in sandy loam soils typical of the study area (Six *et al*., 2018).

Similarly, soil porosity showed a significant positive correlation with TOC (r = 0.59, p < 0.05) and POC (r = 0.52, p < 0.05), indicating that increasing organic carbon levels contribute to improved pore development and soil aeration. However, the relationship with MOC was weaker, suggesting that particulate organic matter plays a more immediate role in influencing soil structural characteristics.

Among the chemical properties, total nitrogen exhibited a strong positive correlation with TOC (r = 0.76, p < 0.01) and POC (r = 0.69, p < 0.01). This relationship reflects the close association between soil organic carbon and nitrogen cycling since organic matter serves as a primary reservoir of nitrogen in soils. The significant relationship between MOC and total nitrogen (r = 0.55, p < 0.05) further suggests that stabilized carbon pools contribute to long-term nitrogen storage and nutrient cycling in forest ecosystems (Cotrufo *et al*., 2019).

Exchangeable bases such as calcium showed moderate positive correlations with TOC (r = 0.44, p < 0.05) and MOC (r = 0.47, p < 0.05), indicating that organic matter contributes to nutrient retention through the formation of organo-mineral complexes and improved cation exchange capacity. Although correlations with magnesium and potassium were positive, they were not statistically significant, suggesting that additional factors such as mineralogy and soil weathering may influence their distribution.

Furthermore, cation exchange capacity (CEC) showed strong positive correlations with TOC (r = 0.68, p < 0.01) and POC (r = 0.63, p < 0.01), as well as a significant relationship with MOC (r = 0.57, p < 0.05). This result underscores the fundamental role of soil organic matter in enhancing nutrient retention and buffering capacity, particularly in highly weathered tropical soils where organic matter contributes substantially to exchange sites (Lehmann and Kleber, 2015).

Overall, the correlation analysis demonstrates that soil organic matter fractions, particularly TOC and POC, play a central role in regulating both the physical and chemical properties of forest soils in the study area. The strong relationships with water holding capacity, bulk density, total nitrogen, and CEC highlight the importance of organic matter in maintaining soil fertility and ecosystem functioning in tropical forest environments.

Table 3: Pearson Correlation Coefficients between Soil Organic Matter Fractions and Selected Soil Properties

Variable	TOC	POC	MOC
Physical Properties			
Bulk Density	-0.61*	-0.58*	-0.43
Particle Density	-0.12	-0.09	-0.15
Water Holding Capacity	0.72**	0.65**	0.48*
Porosity	0.59*	0.52*	0.41
Chemical Properties			
pH	0.18	0.12	0.24
EC	0.31	0.28	0.26
Total Nitrogen	0.76**	0.69**	0.55*
Ca	0.44*	0.39	0.47*
Mg	0.41	0.37	0.42
K	0.36	0.31	0.29
CEC	0.68**	0.63**	0.57*

* Significant at p ≤ 0.05 & ** Significant at p ≤ 0.01

Integrative Perspective on Soil Organic Matter Fractions, Soil Structure, and Carbon Stabilization in Tropical Savanna Soils

The results of this study provide important insights into the interactions between soil organic matter fractions, soil structural properties, and carbon stabilization mechanisms in the forest soils of Gashaka Local Government Area. When interpreted within a broader regional and global context, the observed patterns are consistent with findings reported for tropical forest and savanna soils.

The surface soil total organic carbon (TOC) value of 1.62% observed in this study falls within the typical range reported for tropical forest soils (1–3%), suggesting that the soils of the study area possess moderate organic carbon status. Similar TOC values have been reported in forest soils of Ibadan and Benin in southern Nigeria, where surface soil organic carbon concentrations commonly range between 1.4% and 2.5% depending on vegetation cover and soil texture. Studies conducted in Nsukka forest ecosystems also reported comparable carbon concentrations in surface horizons, reflecting the influence of litter inputs and root biomass on organic carbon accumulation in Nigerian tropical soils (Nwite *et al*., 2016; Adeboye *et al*., 2019). The moderate TOC levels recorded in the present study therefore indicate that the forest soils of Gashaka maintain a reasonably stable organic matter status despite the rapid decomposition typical of tropical climates.

The vertical decline in TOC and POC observed with increasing soil depth is also consistent with patterns reported across African savanna ecosystems, where organic carbon inputs are concentrated near the soil surface due to litter deposition and root turnover. Studies in West African savanna soils in Ghana and northern Nigeria have shown that surface soil horizons often contain significantly higher labile carbon fractions compared with subsurface layers because biological activity and residue incorporation are greatest in the upper soil profile (Bationo *et al*., 2018; Vågen *et al*., 2021). These findings reinforce the role of vegetation-derived inputs and microbial processing in regulating carbon distribution in tropical soils.

A particularly important finding of this study is the dominance of mineral-associated organic carbon (MOC), which accounted for approximately 71–73% of total organic carbon. This proportion is consistent with global observations indicating that mineral-associated carbon typically constitutes between 50% and 80% of total soil organic carbon in mineral soils. The relatively high contribution of MOC suggests that carbon stabilization in the studied soils is primarily controlled by organo-mineral interactions rather than by the persistence of particulate organic matter alone. Similar proportions of mineral-associated carbon have been reported in tropical soils of East Africa and the Congo Basin, where strong associations between organic compounds and clay minerals contribute to long-term carbon stabilization despite rapid organic matter turnover (Cotrufo *et al*., 2019; Six *et al*., 2018).

The relationships observed between soil organic matter fractions and soil physical properties further highlight the integrative role of organic matter in maintaining soil structure. The negative relationship between organic carbon fractions and bulk density, combined with the positive correlations with water holding capacity and porosity, suggests that organic matter contributes significantly to soil aggregation and pore formation. These structural improvements enhance water retention and aeration, which are particularly important in sandy loam soils typical of tropical savanna landscapes, where mineral particles alone provide limited structural stability.

From a nutrient dynamics' perspective, the strong associations between organic carbon fractions, total nitrogen, and cation exchange capacity indicate that soil organic matter acts as a central regulator of soil fertility in the study area. In highly weathered tropical soils, organic matter provides a substantial proportion of the exchange sites responsible for nutrient retention. Consequently, maintaining stable organic carbon pools is critical for sustaining nutrient cycling and long-term soil productivity.

Globally, the findings of this study demonstrate that soil organic matter fractions play a fundamental role in linking soil structure, nutrient dynamics, and carbon stabilization in tropical savanna soils. The dominance of mineral-associated organic carbon suggests that long-term carbon persistence in the forest soils of Gashaka is largely governed by mineral protection mechanisms, which are known to be a key pathway for soil carbon sequestration in tropical ecosystems. These results contribute to the growing body of evidence indicating that carbon stabilization in tropical soils depends not only on organic inputs but also on the capacity of soil minerals to protect organic compounds from rapid decomposition.

CONCLUSION

This study demonstrates that soil organic matter fractions play a critical role in regulating soil structural stability, nutrient dynamics, and carbon stabilization in the forest soils of Gashaka Local Government Area, Taraba State, Nigeria. The observed vertical stratification of organic carbon fractions indicates that surface-driven biological inputs remain the primary driver of soil carbon accumulation in tropical forest soils. More importantly, the dominance of mineral-associated organic carbon suggests that long-term carbon persistence in the sandy loam soils of the study area is largely controlled by organo-mineral interactions rather than by short-lived particulate carbon pools. This finding reinforces the growing understanding that carbon stabilization in tropical soils depends not only on organic matter inputs but also on the capacity of soil minerals to protect organic compounds from rapid decomposition.

From a land management perspective, the results emphasize the importance of maintaining continuous vegetation cover and minimizing soil disturbance in order to sustain soil organic matter inputs and promote aggregate stability. Land managers and conservation practitioners in tropical savanna environments should prioritize practices that enhance organic matter accumulation, such as preserving forest vegetation, promoting litter retention, and integrating organic residue management in adjacent land-use systems. Such practices can improve soil structure, increase water holding capacity, enhance nutrient retention, and ultimately strengthen the soil's capacity for long-term carbon sequestration.

Despite these insights, several research gaps remain. Future studies should investigate the influence of different land-use systems and vegetation types on the stabilization pathways of soil organic carbon fractions across broader tropical landscapes. In addition, long-term monitoring and advanced analytical approaches such as isotopic tracing and microbial community analysis could provide deeper understanding of the mechanisms governing carbon turnover and mineral protection in tropical soils. Addressing these research needs will improve our ability to design effective soil management strategies aimed at enhancing soil fertility and carbon sequestration under changing climatic conditions.

Finally, the study contributes to the growing body of knowledge on soil carbon dynamics in tropical savanna ecosystems and highlights the integrative role of soil organic matter fractions in linking soil structure, nutrient cycling, and long-term soil productivity.

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Appendix 1: Forestland USE Of the Study Area.

S/N	X	Y	Elv.(m)
FL1	757524	819528	381
FL2	757689	819576	394
FL3	757875	819583	397
FL4	758111	819774	472
FL5	758309	819818	477
FL6	758528	819825	473
FL7	758556	819973	474
FL8	758388	820122	477
FL9	758341	820388	396
FL10	758310	820579	391
FL11	758247	820750	370
FL12	758154	820982	359
FL13	758000	821187	361
FL14	757814	821231	357
FL15	757587	821318	355
FL16	757434	821395	351
FL17	757288	821409	350
FL18	757142	821416	348
FL19	757040	821413	350
FL20	756117	826032	473
FL21	757240	820408	474
FL22	758406	820115	477
FL23	757240	820408	396
FL24	757140	821433	350
FL25	756119	826022	473