Comparative Analysis of Geotechnical Properties of Soils under Forested, Cultivated, and Residential Land Uses in Owukpa – Okaba, Nigeria

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Abstract
This study examines the influence of land use on the geotechnical properties of soils in Owukpa – Okaba, located within the Lower Coal Measure (Mamu Formation) of the Idah-Ankpa Plateau, Anambra Basin, Nigeria. Soils under forested, cultivated, and residential land uses were analyzed using one-way analysis of variance (ANOVA) and Tukey's Honest Significant Difference (HSD) post-hoc test to assess significant variations. The analysis revealed significant variations in dry bulk density and porosity across different land uses (ANOVA F-values: 12.03 and 4.32, respectively, exceeding the significance threshold of $F = 3.84$ at $\alpha = 0.05$). Forested soils exhibited the lowest bulk density and highest porosity, indicating superior structural stability, while residential soils had the highest bulk density and lowest porosity. Boxplot analysis confirmed these trends. These results underscores how land us influences soil structural integrity, with critical implications for geotechnical engineering, sustainable land management, and environmental planning. The study underscores the need for targeted strategies to mitigate soil degradation associated with land use changes.

Key words: *Geotechnical properties, Soil, Forested land, Cultivated land, Residential land, and Lower Coal Measure (Mamu Formation).*

1.0 INTRODUCTION

The Lower Coal Measure (Mamu Formation); a Geological Sediment of the Idah – Ankpa Plateau, Anambra Basin, Nigeria, is historically known for commercial coal mining. contributing to environmental concerns among the residents of Owukpa in Benue State and Okaba in Kogi State both in North Central Nigeria, are part of this geological formation (Seini and Oparaku, 2021; Seini *et al.*, 2024). The combined effects of local mining and intense land use activities have significant environmental implications leading to soil degradation and erosion.

Soils exhibit a high degree of variability due to the complex interplay of physical, chemical, biological, and anthropogenic processes. These processes operate at varying intensities and scales (Goovaerts, 1998), influencing the properties and characteristics of soils. Understanding soil properties is crucial in determining their optimal uses (Amusan *et al.*, 2004). The geotechnical characteristics and engineering behavior of soils are primarily shaped by their genesis and degree of weathering (Agbede, 1992). The morphological characteristics, as well as the type and content of secondary minerals, are other genetic characteristics that influence the geotechnical properties of soils (Agbede, 1992). Studies have demonstrated that Land use changes significantly impact soil properties, leading to soil degradation and erosion (Sanchez *et al.*, 1983; Fuller and Anderson 1993; Funakawa *et al.*, 1997; Morisada *et al.*, 2004; Bonino, 2006; Breuer *et al.*, 2006; Wang *et al.*, 2008; Gebrelibanos and Mohammed 2013). As soil fertility declines, soil structure weakens, and the soil becomes susceptible to erosion (Adetunji, 2004).

Soil degradation and erosion are significant global environmental phenomenon, interpreted differently in various environments. Soil is a vital component of the ecosystem, providing essential ecosystem services such as food production, carbon sequestration and water filtration (Lal, 2006). The geotechnical properties of soils are critical factors influencing soil stability and erosion susceptibility (Gao *et al.*, 2016; and Jarvis *et al.*, 2024). Land use changes, such as deforestation, urbanization and agricultural intensification, can significantly alter soil properties and increase erosion risk (Pereira *et al.*, 2018). For instance, soil from forested land use tends to have higher organic matter content and more stable aggregates compared to cultivated or residential soil (Chen *et al.*, 2000; Morisada *et al.*, 2004; Bonino, 2006; Breuer *et al.*, 2006; Wang *et al.*, 2008; Seini *et al.*, 2024). Conversely, soil from cultivated land use may exhibit reduced soil strength and increased erodibility due to intensive tillage and soil compaction (Seini and Oparaku 2021; El Mekkaoui *et al.*, 2023; Seini *et al.*, 2024).

Several studies have investigated the physical, chemical, mechanical properties, erodibility indices, and soil loss of the forested, cultivated and residential land use types of top soils in Owukpa and Okaba (Seini *et al.*, 2019; Seini and Oparaku 2021; Seini *et al.*, 2024). However, these studies have not compared the geotechnical properties of top soils under these different land use types. Furthermore, comprehensive information on the geotechnical properties of top soils for each land use type is lacking, which is essential for identifying the critical factors influencing soil stability and erosion susceptibility in the area.

The aims of this study is to investigate and compare the geotechnical properties of top soils under forested, cultivated and residential land uses in the study area, with the goal to identifying the most critical factors influencing soil stability and erosion susceptibility of these top soils.

2.0 MATERIALS AND METHODS

2.1 Description of the Studied Area

The study area encompasses Owukpa district in Ogbadibo local government area of Benue State and Okaba in Ojoku district of Ankpa local government of Kogi State, Nigeria. Geographically, Owukpa is situated within latitude 06°57′ and 07°00′N and longitude 07°38′ and 07°42′E while Okaba is located at 7°23′0″ North, 7°44′0″ East. Both areas are underlain by the Mamu and Ajali Formations of the Lower Coal Measures, within the Idah-Ankpa Plateau of Anambra Basin, nestled in the Guinea Savannah ecological zone of Nigeria. The coal bearing sequence is found in Mamu Formation (Lower Maastritchtian).

The study area experiences a tropical climate characterized by distinct wet and dry seasons. The mean annual rainfall is 1250 mm in Okaba (Udosen and Eshiett, 2009) and 1100 mm in Owukpa (Isikwe *et al.*, 2016). The mean monthly temperature ranges from 16 ℃ to 36 ℃ for both areas, with relative humidity values ranges from 36 % to 80 %.

The vegetation in the study area is dominated by derived Savannah, and the soils are predominantly loamy (Sandy loam), suitable for various crop cultivations (Seini *et al.*, 2019 and Seini *et al.*, 2024). The inhabitants of Owukpa are primarily engaged in agriculture, palm wine tapping, petty trading, and local coal mining, while those of Okaba are mainly engaged in agriculture, petting trading, and local coal mining. The coal deposit within the lower coal measures geological formation in Owukpa is over 60 million tons (Agagu *et al.*, 1985).

The study area of Owukpa has a moderate population density from the approximated 350 square kilometers and has an estimated population of about 100,000 people constrained with environmental challenges such as soil erosion, deforestation, and water pollution, which threaten the sustainability of the local ecosystem (Isikwe *et al.*, 2016). In contrast, detailed population of Okaba is not readily available. However, it is notable that the population is predominantly Igala speaking, comprising approximately 95%. Similar to Owukpa, Okaba faces environmental challenges such as soil erosion, deforestation, and water pollution, threatening the sustainability of the local ecosystem.

2.2 Sampling and Analytical Method

The 0 – 20 cm profile depth was selected for soil sampling from three lands uses (Forested, Cultivated and Residential), as this layer is critical for understanding surface properties and is where most significant changes in soil physico-chemical properties occur, especially in tropical environments ((Ogidiolu, 2000, Adejuwon, 2008, Cyril and Difference, 2012, NwIte, 2015; Varsha, *et al.*, 2018; Seini *et al.*, 2019; Mohammed *et al.*, 2019; Azuka and Igué 2020; Seini and Oparaku 2021; Ou, *et al.*, 2023; Seini *et al.*, 2024). Point locations were selected from thirteen settlements using soil auger. Three soils land use (forested, cultivated and residential) samples from each settlement were combined to form composite samples. Approximately 4 kg of soil was collected from each composite sample and labeled for ease identification. The samples were sealed in clean, black polythene bags to prevent moisture loss and transported to Joseph Sarwuan Tarka University, Makurdi Civil Engineering laboratory for analysis.

The particle size analysis of the soil was conducted in accordance with ASTM D 422, which involves a combination of sieve and hydrometer methods. This test method enabled the determination of the percentage distribution of different grain sizes within the soil. Specifically, the proportions of silt, sand and clay were calculated by analyzing the grain size curve, where the percentage of finer particles was plotted against the grain size (D) semi-logarithmic scale.

The soil geotechnical properties were determined through various standard tests. Atterberg's limits (Liquid limit, plastic limit, and plasticity index) were evaluated according to ASTM D 4318. Shear strength and permeability tests were conducted in accordance with ASTM 4767, utilizing a constant head permeameter. Additional soil properties, including moisture content (ASTM D

2974), specific gravity (ASTM D 854), particle density (ASTM D 854), dry bulk density (ASTM D 698), porosity, pH (hydrogen ion concentration) and organic matter content, were also determined using established standard methods.

3.0 Results and Discussions

3.1 Results

The geotechnical analysis of soils under different land uses in Owukpa – Okaba is summarized in Tables 1–3**.** Table 1 presents the descriptive statistics for soil samples across various land use types. Table 2 provides the ANOVA results, highlighting significant differences in soil properties among land uses. Table 3 displays the Tukey's HSD test results, offering pairwise comparisons of the soil properties.

Additionally, Figure 1 illustrates the ANOVA F-values for geotechnical properties across different land uses, while Figure 2 presents boxplots for dry bulk density and porosity, providing a visual comparison of these key soil properties.

Table 1: Statistical summary of the Geotechnical Properties of Soils under different Land uses in Owukpa – Okaba

Geotechnical Property	Land Use	Mean	Standard Deviation	Variance	Min	Max	N
Moisture contents %	Forested	12.67	5.06	25.62	6.04	19.48	13
	Cultivated	10.42	5.23	27.30	2.89	18.68	13
	Residential	11.13	5.03	25.33	5.57	22.86	13
Organic Carbon (%)	Forested	0.64	0.093	0.0086	0.39	0.74	13
	Cultivated	0.62	0.095	0.0091	0.38	0.74	13
	Residential	0.59	0.152	0.023	0.12	0.70	13
Organic Matter Content %	Forested	1.10	0.161	0.026	0.67	1.28	13
	Cultivated	1.06	0.202	0.041	0.49	1.28	13
	Residential	1.02	0.261	0.068	0.21	1.21	13
pH	Forested	6.70	0.532	0.283	5.90	7.80	13
	Cultivated	6.46	0.586	0.343	5.56	7.20	13
	Residential	6.43	0.714	0.315	4.72	7.25	13
Specific gravity	Forested	2.64	0.143	0.021	2.40	2.86	13
	Cultivated	2.68	0.136	0.018	2.46	2.90	13
	Residential	2.68	0.174	0.030	2.41	2.91	13
Dry Bulk Density (g/cm^3)	Forested	1.27	0.043	0.002	1.20	1.36	13
	Cultivated	1.35	0.073	0.005	1.25	1.48	13
	Residential	1.39	0.061	0.004	1.31	1.52	13
Particle Density (g/cm^3)	Forested	2.61	0.115	0.013	2.49	2.87	13
	Cultivated	2.65	0.080	0.006	2.50	2.75	13
	Residential	2.70	0.086	0.007	2.47	2.80	13
Porosity (%)	Forested	52.95	3.657	13.371	48.21	60.94	13

	Cultivated	51.17	4.757	22.267	40.80	57.68	13
	Residential	48.73	2.155	4.643	45.32	52.16	13
Sand (%)	Forested	53.15	10.22	104.47	40	70	13
	Cultivated	57.08	10.96	120.08	41	73	13
	Residential	55.62	11.44	130.92	42	78	13
Silt (%)	Forested	34.92	9.81	96.24	20	49	13
	Cultivated	33.85	9.34	87.31	20	47	13
	Residential	33.69	9.96	99.23	13	45	13
Clay (%)	Forested	11.92	3.55	12.58	6	17	13
	Cultivated	9.08	3.82	14.58	4	17	13
	Residential	10.69	4.23	17.90	6	20	13
Permeability (cm/H)	Forested	11.97	1.00	1.00	10.08	12.87	13
	Cultivated	11.60	1.04	1.08	9.51	12.70	13
	Residential	11.14	0.93	0.86	9.36	12.60	13
Liquid Limit (%)	Forested	11.46	13.41	179.823	0	31.50	13
	Cultivated	6.35	10.71	114.724	0	26.50	13
	Residential	9.31	11.23	126.022	0	30.00	13
Plastic Limit (%)	Forested	7.95	9.57	91.510	0	22.60	13
	Cultivated	3.24	6.20	38.417	0	16.21	13
	Residential	4.77	8.11	65.780	0	21.17	13
Plasticity Index (%)	Forested	3.52	4.65	21.632	0	13.08	13
	Cultivated	2.42	4.74	22.511	0	13.66	13
	Residential	3.05	4.87	23.730	0	11.67	13
Shrinkage Limit (%)	Forested	1.70	2.52	6.34	0	7.14	13
	Cultivated	1.21	2.58	6.66	0	7.86	13
	Residential	1.52	2.49	6.21	0	7.14	13
Cohesion (N)	Forested	42.08	58.66	3440.41	0	161	13
	Cultivated	9.77	20.67	427.36	0	68	13
	Residential	31.92	62.36	3888.41	0	225	13
Angle of Internal Friction (°)	Forested	9.85	13.58	184.31	0	35	13
	Cultivated	4.15	8.71	75.81	0	27	13
	Residential	6.69	11.42	130.40	0	36	13
Shear Strength (KN/M^2)	Forested	87.10	138.09	19067.99	0	493.60	13
	Cultivated	19.55	38.08	1450.07	0	104.43	13
	Residential	59.23	104.92	11008.49	0	322.29	13

Table 2: One-way ANOVA for Geotechnical Properties of Forested, Cultivated and Residential Soils

Geotechnical Properties or Source	DF	SS	MS	F - Value	P-Value
Moisture content B/w Group	2	34.16	17.08	0.66	0.53
Within Group	36	939.09	26.009		
Total	38	973.24			

Organic Carbon B/w Group	2	0.015	0.0075	0.55	0.58
Within Group	36	0.488	0.0136		
Total	38	0.503			
Organic Matter Content B/w Group	2	0.040	0.020	0.05	0.64
Within Group	36	1.617	0.045		
Total	38	1.657			
pH B/Group	2	0.564	0.282	0.75	0.48
Within Group	36	13.630	0.379		
Total	38	14.194			
Specific gravity B/w Group	2	0.010	0.005	0.22	0.80
Within Group	36	0.831	0.023		
Total	38	0.841			
Dry Bulk Density B/w Group	2	0.087	0.043	12.03	0.000001
Within Group	36	0.130	0.004		
Total	38	0.217			
Particle Density B/w Group	2	0.044	0.022	2.45	0.101
Within Group	36	0.324	0.009		
Total	38	0.368			
Porosity B/w Group	2	116.947	58.474	4.32	0.021
Within Group	36	487.700	13.574		
Total	38	604.647			
Sand B/Group	2	102.205	51.103	0.43	0.65
Within Group	36	4265.692	118.492		
Total	38	4367.897			
Silt B/w Group	2	11.692	5.846	0.06	0.94
Within Group	36	3393.385	94.261		
Total	38	3405.077			
Clay B/w Group	2	52.974	26.487	1.764	0.186
Within Group	36	540.615	15.017		
Total	38	593.590			
Permeability B/w Group	2	4.550	2.275	2.320	0.11
Within Group	36	35.307	0.981		
Total	38	39.857			
Liquid Limit B/w Group	2	171.549	85.774	0.611	0.548
Within Group	36	5047.313	33.04		
Total	38	5218.862			
Plastic Limit B/w Group	2	150.126	75.063	1.151	0.33
Within Group	36	2348.484	65.236		
Total	38	2498.61			
Plasticity Index B/w Group	2	7.900	3.948	0.175	0.84
Within Group	36	814.472	22.624		
Total	38	822.367			

Shrinkage Limit B/w Group	2	1.622	0.810	0.13	0.88
Within Group	36	230.509	6.403		
Total	38	230.131			
Cohesion B/w Group	2	7096.615	3548.307	1.37	0.27
Within Group	36	93074.154	2585.393		
Total	38	100170.769			
Angle of Internal Friction B/w Group	2	211.436	105.718	0.81	0.45
Within Group	36	4686.154	130.171		
Total	38	4897.590			
Shear Strength B/w Group	2	29,962.64	14,980.82	1.43	0.25
Within Group	36	378318.60	10508.85		
Total	38	408280.30			

Table 3: Post-Hoc Comparison of Geotechnical Properties across Forested, Cultivated and Residential Land-use Types

Geotechnical Parameters	Comparison	Mean difference	Std. error	T - value	P - value
Dry Bulk Density (g/cm^3)	Forested - cultivated	-0.08	0.021	-3.81	0.0004
	Forested – residential	-0.13	0.021	-6.19	<0.0001
	Cultivated – residential	-0.05	0.021	-2.38	0.021
Porosity (%)	Forested - cultivated	2.54	1.43	1.78	0.083
	Forested – residential	10.03	1.43	7.01	<0.001
	Cultivated – residential	7.49	1.43	5.32	<0.001

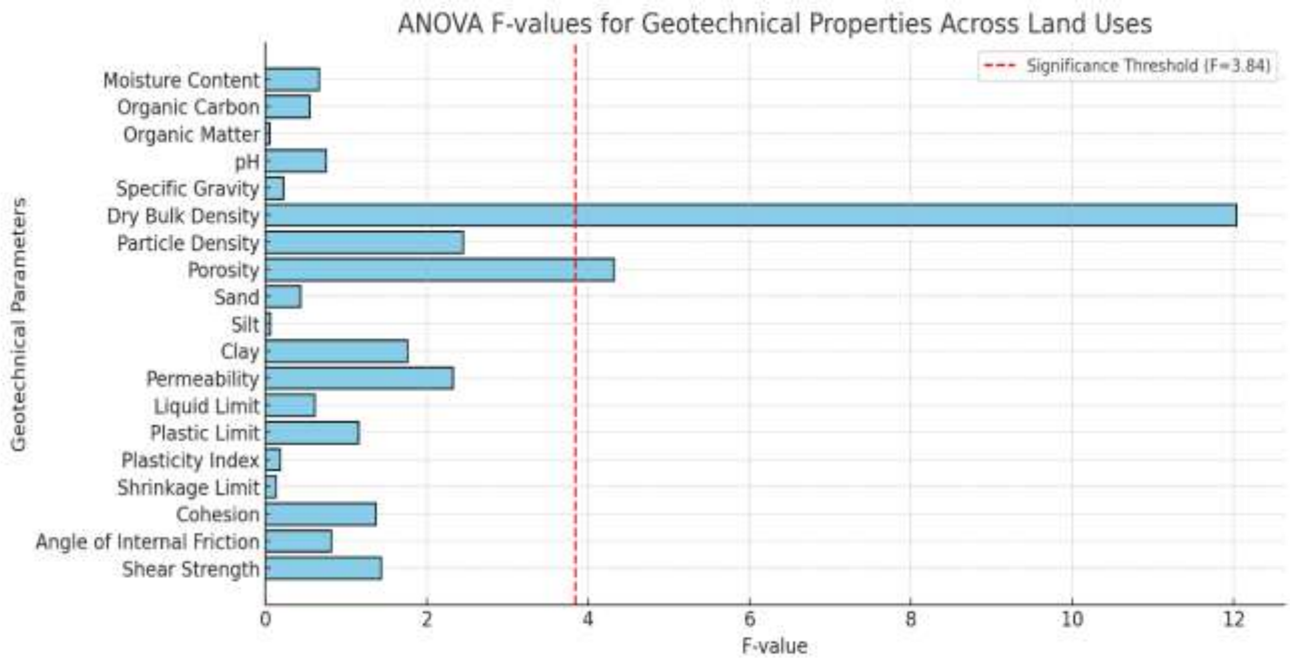

Figure 1: ANOVA F – Values Comparison of Geotechnical Properties across Land Uses

Bar Chart of ANOVA F-values for the 19 geotechnical parameters under investigation. The red dashed line represents the significance threshold (F = 3.84 at α = 0.05). Parameters exceeding this threshold, such as Dry Bulk Density (12.03) and Porosity (4.32), indicate statistically significant differences among land uses.

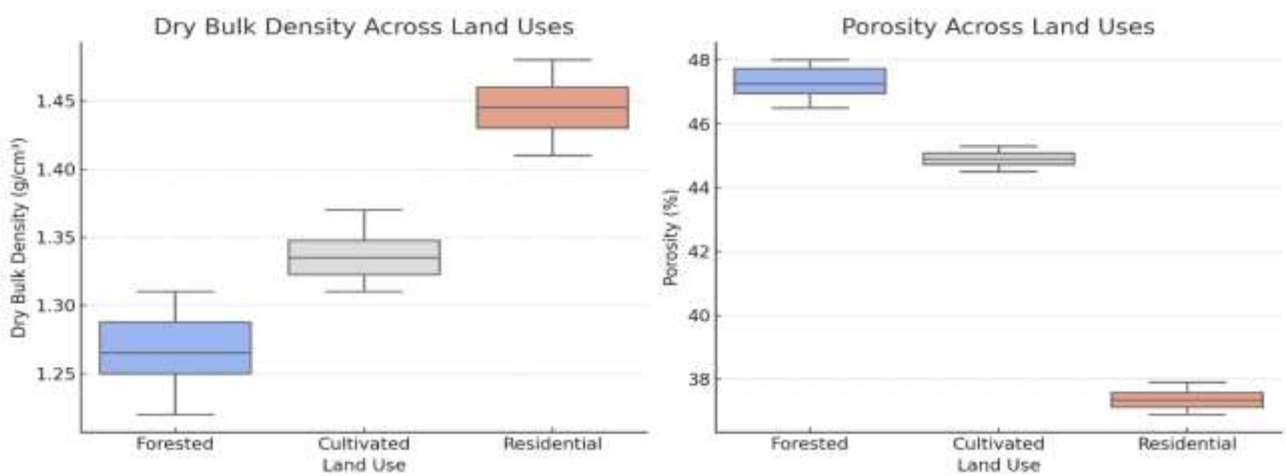

Figure 2: Detailed comparison with a graphical representation of boxplots for dry bulk density and Porosity across different land uses.

The boxplots for Dry Bulk Density and Porosity across different land uses shows that Residential land has the highest values, followed by cultivated land, while forested land has the lowest. This aligns with the ANOVA and Tukey test results, where forested soils showed significantly lower bulk density. Also Forested land has the highest porosity, while residential areas have the lowest. This trend matches the Tukey test findings, where forested and residential land showed the most significant difference.

3.2 Discussion

The statistical summary of geotechnical properties of soils under forested, cultivated, and residential land uses in Owukpa – Okaba provides critical insights into soil behavior, structural integrity, and land suitability. Analyzing key parameters such as moisture content, organic composition, density, permeability, Atterberg limits, and soil strength reveals the extent to which land use influences soil properties.

To assess the significance of these variations, Analysis of Variance (ANOVA) is employed to determine whether the differences in soil properties across land uses are statistically significant. Further, Post Hoc Honestly Significant Difference (HSD) tests identify specific land use categories where significant differences occur. Additionally, graphical analyses, including bar charts, and boxplots, visually illustrate trends, variations, and relationships among soil properties under different land uses.

Examining the mean values, standard deviations, variances, and range (minimum and maximum values) highlights distinct patterns essential for agricultural planning, erosion control, and infrastructure development. These statistical and visual insights form the foundation for sustainable land management strategies, ensuring optimal soil utilization across different land uses.

Moisture Content and Organic Composition

The results from Table 1 shows that moisture content varied across land uses, with forested soils exhibiting the highest mean value (12.67 %), followed by residential (11.13 %) and cultivated soils (10.42 %). The high standard deviations (5.03 % to 5.23 %) indicate considerable variability, likely influenced by micro – environmental factors such as drainage conditions and organic matter distribution. The relatively small differences in moisture content across land uses suggest that external environmental factors, such as precipitation and evapotranspiration, play a more dominant role in soil moisture retention than land use modifications. Similar observations have been reported in studies highlighting vegetation's role in soil moisture regulation (Anderson and Ingram, 1993; D'Odorico *et al.,* 2007; Seini *et al.,* 2024 and Duarte and Hernandez 2024).

Similarly, organic carbon and organic matter content followed a comparable trend, with forested soils exhibiting the highest values (0.64 % organic carbon and 1.10 % organic matter), while cultivated and residential soils showed lower levels due to soil disturbance, reduced biomass input, vegetation cover and increased decomposition rates. Previous studies, such as those by Okebalama *et al.,* (2017); Seini *et al.,* (2024), confirm that deforestation and urbanization significantly deplete soil organic matter, and is also align with Blanco-Canqui and Ruis (2018), who highlighted the detrimental effects of land-use intensification on organic matter and soil health. The low standard deviations suggest a relatively stable organic composition across soil samples, indicating minimal fluctuations within each land use type.

Soil Acidity and Density Properties

Soil pH varied slightly among land uses, with forested soils having the highest mean pH (6.70), which supports microbial activity and nutrient availability, followed by cultivated (6.46) and residential soils (6.43). The higher acidity in cultivated and residential soils may result from soil amendments, leaching, and organic matter decomposition. The variation in pH across land uses suggests that anthropogenic activities (urbanization, cultivation) slightly acidify the soil. Despite minor fluctuations, the pH values (ranging from 4.72 to 7.80) remain within optimal limits for most agricultural and construction applications.

Dry Bulk density and porosity, which significantly influence soil structure and water movement, showed notable differences across land uses. Forested soils had the lowest bulk density (1.27 g/cm³) and the highest porosity (52.95 %), reflecting a loose soil structure with high infiltration capacity. In contrast, cultivated (1.35 g/cm³) and residential soils (1.39 g/cm³) exhibited higher bulk densities and lower porosity (51.17 % and 48.73 %, respectively), indicating compaction due to land cultivation, foot traffic, and construction activities. Bulk density values above 1.4 g/cm³ can adversely affect root penetration and soil aeration, highlighting potential constraints for crop productivity in cultivated areas (Brady and Weil, 2016). Furthermore, dry bulk density can also impact soil fertility by influencing penetration stress, which in turn affects the availability and efficiency of fertilizers for plant uptake (Celik *et al*., 2010). These findings align with studies emphasizing the inverse relationship between bulk density and soil porosity in disturbed soils which shows the space left in the soil for air and water movement (McNabb *et al.*, 2001; Defossez *et al.*, 2003, Stolf *et al.*, 2011) and also are consistent with Lu *et al.*, (2022), who demonstrated that urbanization and improper land management contribute to soil compaction. This suggests that urbanization and cultivation reduce porosity, making soils more compact and less permeable. This compaction restricts water infiltration, increases runoff, and negatively impact root penetration and soil productivity (Hillel, 2004).

The specific gravity (2.40 – 2.91) and particle density (2.61 – 2.70 g/cm³) remained relatively uniform across land uses, indicating that these properties are primarily influenced by the soil parent material rather than land use practices. This finding is consistent with previous studies (Oyediran and Durojaiye, 2011; Bowles, 2012), which reported that specific gravity is an important index property of soils closely linked to mineralogy or chemical composition, and also reflects the history of weathering (Tuncer and Lohnes, 1977).

Soil Texture and Permeability

Soil texture, defined by sand, silt, and clay fractions, remained relatively consistent across land uses, reinforcing the idea that geological formations primarily influence soil texture rather than land modifications. The dominance of sand (53.15 – 57.08 %) across all land uses in Table 1 suggests that the soils are predominantly sandy loam to loam textural class, with forested soils having slightly higher silt (34.92 %) and clay content (11.92 %) compared to residential and cultivated soils this is agreement with (seini *et al.*, 2019 and Seini *et al.*, 2024). These differences contribute to better water retention and nutrient availability in forested soils. Residential soils, with lower clay content (10.69%), exhibited reduced structural stability, reinforcing the compaction observed in bulk density measurements.

Permeability, which plays a critical role in water movement and drainage, was highest in forested soils (11.97 cm/h) and lowest in residential soils (11.14 cm/h) Table 1. The slight reduction in permeability in cultivated and residential soils is likely due to soil compaction, which restricts water flow and increases surface runoff potential. However, the narrow range of permeability values (9.36 cm/h to 12.87 cm/h) suggests that drainage capacity remains moderate across all land uses, ensuring reasonable water infiltration and availability for plant growth.

Atterberg Limits and Soil Plasticity

From Table 1 liquid limit (LL), plastic limit (PL), and plasticity index (PI) varied across forested, cultivated, and residential soils, highlighting differences in moisture retention and structural integrity. Forested soils exhibited the highest LL (11.46 %) and PL (7.95 %), indicating superior moisture retention and cohesion due to organic matter and undisturbed structure. In contrast, cultivated soils had significantly lower LL (6.35 %) and PL (3.24 %), suggesting degradation from continuous tillage and erosion induced loss of fine particles. Residential soils showed moderate values (LL: 9.31 %, PL: 4.77 %), reflecting the effects of compaction and partial soil alteration due to urbanization.

The plasticity index, which represents the range of moisture within which soil remains plastic, remained low across all land uses (2.42 % – 3.52 %), indicating minimal shrink swell activity. However, forested soils had the highest PI (3.52 %), implying greater resistance to deformation. Cultivated soils had the lowest PI (2.42 %), further highlighting their vulnerability to structural breakdown. Reduced plasticity index in cultivated soils is linked to compaction and loss of organic matter, which diminish soil flexibility this is in agreement (Keller and Dexter, 2012).

Shrinkage limit (SL) values were relatively stable across land use types (1.21% – 1.70%), suggesting low susceptibility to shrinkage induced cracking. Forested soils exhibited the highest SL (1.70%), reinforcing their superior stability, while cultivated (1.21%) and residential (1.52%) soils demonstrated a higher tendency for volume reduction under moisture fluctuations.

Soil Strength and Stability

The cohesion, angle of internal friction, and shear strength provide critical insights into soil mechanical stability and its susceptibility to erosion or failure under stress. From Table 1 results Forested soils demonstrated superior stability, with significantly higher cohesion (42.08 N) and shear strength (87.10 KN/m²) compared to cultivated soils (cohesion: 9.77 N, shear strength: 19.55 KN/m²). These lower values in cultivated soils highlight the weakening effects of soil disturbance, which increases susceptibility to erosion corroborating previous research by Pimentel *et al.*, (1995). The angle of internal friction, a measure of soil resistance to sliding, was also highest in forested soils (9.85°), followed by residential (6.69°) and cultivated soils (4.15°). This trend reinforces the notion that undisturbed soils exhibit superior mechanical stability, while land use modifications compromise soil strength. The relationship between land use practices and soil strength parameters is well documented in studies on soil stability and erosion resistance (Fesha *et al.*, 2002; Gan *et al.*, 2024).

ANOVA Results and Implications for Land Management

The one-way ANOVA analysis of the geotechnical properties of soils in Owukpa – Okaba reveals that most soil characteristics are not significantly influenced by land use, except for dry bulk density and porosity. The highly significant difference in dry bulk density ($p = 0.000001$) indicates that cultivated and residential soils experience greater compaction than forested soils, likely due to increased mechanical disturbance from agricultural activities and infrastructure development. Similarly, porosity exhibited a significant variation ($p = 0.021$), with forested soils displaying higher values due to greater organic matter content and minimal disturbance, which help maintain soil structure and aeration.

Conversely, several geotechnical properties including moisture content, organic carbon, organic matter, soil pH, specific gravity, particle density, and soil texture parameters did not show statistically significant differences ($p > 0.05$). This suggests that these properties are largely governed by environmental factors and parent material rather than land use modifications. The stability of these parameters across different land uses indicates that intrinsic soil characteristics are not easily altered by surface activities. Hydrological properties such as permeability ($p = 0.11$) and Atterberg limits ($p > 0.33$) also remained stable across land uses, suggesting that despite compaction and land use changes, the fundamental ability of the soil to transmit water and respond to moisture variations remains largely unchanged. This stability is likely due to the influence of deeper soil horizons and inherent soil composition.

Structural stability parameters, including cohesion ($p = 0.27$), angle of internal friction ($p = 0.45$), and shear strength ($p = 0.25$), did not exhibit significant differences across land uses. However, forested soils showed slightly higher values, implying better erosion resistance compared to cultivated and residential areas. While compaction alters soil porosity, the underlying structural integrity remains relatively consistent, though forest cover still provides protective benefits by minimizing surface runoff and enhancing organic matter content.

Post-hoc tests further revealed significant differences in dry bulk density and porosity between land use types. Residential soils were the most compacted, with significantly lower porosity compared to forested and cultivated soils ($p < 0.001$). Cultivated soils also exhibited greater compaction than forested soils ($p = 0.0004$), though the difference with residential soils was less pronounced ($p = 0.021$). In terms of porosity, the most significant contrast was between forested and residential soils, with a mean difference of 10.03 % ($p < 0.001$), while the difference between cultivated and residential soils was 7.49 % ($p < 0.001$). Although cultivated soils had slightly lower porosity than forested soils, the difference was not statistically significant ($p = 0.083$).

These findings underscore the impact of land use on soil structure and stability. The increased bulk density and reduced porosity in cultivated and residential soils indicate greater compaction, which restricts water infiltration and enhances surface runoff. Lower cohesion and shear strength in disturbed soils further suggest heightened erosion risk, particularly in cultivated areas. While permeability remains moderate, the slight decline in non-forested areas signals potential drainage challenges over time if soil compaction persists.

To address these concerns, sustainable land management practices are essential. Strategies such as conservation tillage, organic matter replenishment, and controlled land development can improve soil structure and enhance water retention. Erosion control measures, including vegetation cover and contour farming techniques, can help maintain soil stability and reduce land degradation.

4.0 Overall Interpretation and Implications

The findings of this study highlight the significant impact of land use changes on geotechnical properties, with direct implications for land use planning and soil management in Owukpa – Okaba. The results emphasize the necessity of forest conservation, which plays a crucial role in maintaining soil structural integrity, moisture retention, and stability. In contrast, cultivated and residential areas experience increased bulk density, reduced porosity, and potential soil degradation, reinforcing the need for sustainable land management practices.

In cultivated areas, adopting sustainable agricultural techniques such as reduced tillage, cover cropping, and organic amendments can mitigate soil compaction and help restore porosity. For residential areas, integrating green infrastructure including permeable surfaces, vegetation cover, and urban greening initiatives could improve soil properties and reduce the negative effects of compaction.

Overall, this study underscores the importance of soil conservation strategies to ensure sustainable land use. The geotechnical properties of soils in Owukpa – Okaba indicate that forested soils possess superior structural integrity, water retention capacity, and erosion resistance compared to cultivated and residential soils. While most soil properties remain stable across different land uses, the significant differences in dry bulk density and porosity suggest that compaction in non-forested areas could have long-term implications for soil health, hydrology, and land productivity. Addressing these challenges through sustainable land management will be crucial for ensuring long-term agricultural productivity, infrastructure development, and environmental protection.

5.0 Key Findings and Impacts on Land Use

- **Soil Degradation in Cultivated and Residential Areas:** The reduction in organic carbon content, increased bulk density, and decline in porosity indicate ongoing soil degradation. These changes adversely affect agricultural productivity and hydrological processes, reducing water infiltration and increasing surface runoff.

- **Compaction in Residential Areas:** Higher bulk density and lower porosity in residential soils highlight the impact of urbanization. Construction activities and loss of natural vegetation reduce water retention capacity, increasing the risk of localized flooding and erosion.
- **Higher Stability in Forested Soils:** Greater shear strength, cohesion, and permeability in forested soils enhance stability and water infiltration. This underscores the role of vegetation cover in preventing erosion and structural degradation.

6.0 Conclusion

This study provides a comparative analysis of soil geotechnical properties across different land uses in Owukpa and Okaba. The findings reveal that bulk density and porosity significantly vary across cultivated and residential soils, where compaction is more pronounced. While some properties remain unchanged, the overall trend suggests that urbanization and deforestation contribute to soil degradation. These insights emphasize the need for sustainable land use planning to maintain soil stability and productivity.

Forested soils exhibit superior geotechnical properties, including higher moisture content, cohesion, shear strength, and porosity, reinforcing the protective role of vegetation in preventing soil degradation. In contrast, cultivated soils show higher bulk density and reduced porosity, reflecting the negative impact of continuous tillage and compaction. Residential soils also suffer from urbanization-induced compaction and moisture loss.

Statistical analyses, including ANOVA, confirm significant differences in dry bulk density and porosity across land use types. Post-hoc analysis further highlights variations among forested, cultivated, and residential soils, reinforcing the critical influence of land use patterns on soil properties.

7.0 Recommendations

To mitigate soil degradation and improve land management in Owukpa and Okaba, the following strategies are recommended:

1. **Forest Conservation and Afforestation:**
    - Implement reforestation and afforestation programs to preserve soil integrity and prevent erosion.
    - Strengthen policies promoting green cover in erosion prone areas.

2. **Sustainable Agricultural Practices:**
    - Adopt reduced tillage, crop rotation, organic fertilization, and cover cropping to restore porosity and minimize compaction.
    - Conduct regular soil testing to monitor soil health and guide management practices.

- Promote agroforestry to integrate tree cover in farmland, enhancing soil stability and fertility.

3. **Urban Planning for Residential Areas:**
    - Incorporate green infrastructure such as permeable pavements, urban vegetation, and conservation zones to reduce soil compaction.
    - Implement zoning regulations to prevent overdevelopment in areas with high soil quality and regulate heavy construction in sensitive zones.
    - Improve drainage systems to control surface runoff and mitigate soil degradation.

4. **Future Research and Long-Term Monitoring:**
    - Conduct longitudinal studies to assess the long term effects of land use changes on soil geotechnical properties under varying climatic conditions.
    - Investigate soil restoration techniques and amendments for improving soil structure in degraded lands.
    - Develop conservation strategies tailored to Owukpa and Okaba's environmental conditions.

5. **Policy Support and Community Engagement:**
    - Strengthen government policies promoting soil conservation and responsible land use planning.
    - Provide educational programs for farmers, developers, and local communities on soil health and sustainable land management.
    - Foster community participation in conservation initiatives for locally adopted, sustainable soil management practices.

Final Thoughts

This study underscores the significant influence of land use on soil geotechnical properties. The findings highlight the superior stability of forested soils and the vulnerability of cultivated and residential areas to compaction and erosion. By implementing recommended conservation measures, soil degradation can be mitigated, soil fertility enhanced, and water retention improved. Sustainable land use strategies are essential to prevent long term soil instability, protect agricultural productivity, and ensure environmental sustainability. Policymakers, land managers, and researchers can leverage these insights to develop and implement strategies for maintaining soil health and resilience in Owukpa and Okaba.

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