Nigerian Journal of Soil Science
Journal Homepage: www.soilsjournalnigeria.com

Characterization and Classification of Selected Soils Formed on a Planar Surface in Wukari, Nigeria

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Abstract

This study investigates the properties and variability of selected pedons in Wukari, Nigeria, focusing on their characterization and classification. Field soil profile description and laboratory analyses were conducted to assess morphological, physical, and chemical properties. Soil samples were collected from identified horizons and analyzed for selected properties. Genetic classification was performed, and statistical procedures such as correlation and Linear Discriminant Analysis (LDA) were applied to examine soil property relationships and horizon differentiation. Morphological analysis revealed variations in horizon depth and color, with Ap horizons exhibiting darker colors and shallower depths in Pedon 2 (14 cm) compared to Pedons 1 and 3 (20–22 cm). Textural analysis showed a transition from sandy loam in surface horizons to sandy clay loam in Bt horizons, indicating clay translocation. Bulk density increased with depth (1.21–1.45 Mg m^{-3}), while porosity declined due to compaction. Organic carbon and total nitrogen were highest in Ap horizons (10.9 - 14.40 g kg^{-1} and 1.17 – 1.31 g kg^{-1} respectively) and decreased with depth. High base saturation (>85%) across all horizons indicated strong nutrient retention. The soils were classified as Alfisols (Typic Haplustalfs and Typic Paleustalfs) in the USDA system, corresponding to Haplic Luvisols in the FAO system. Key classification indicators included the presence of an argillic horizon and base saturation exceeding 50%. Statistical analysis effectively differentiated soil horizons, with sodium content and total nitrogen as key discriminants. The LDA model achieved 81.82% accuracy, emphasizing the importance of horizon-specific management for sustainable soil use even in planar surfaces.

Keywords: Characterization, Classification, Linear Discriminant Analysis, Soil Variability, Tropical Soils, Wukari, Nigeria

Introduction

Soil variability is influenced by well-documented drivers such as parent materials, climatic conditions, and intensive human activities. These factors interact to create complex soil systems that are highly stratified, often exhibiting distinct physical and chemical variations across horizons (Awwal *et al*., 2022). While the importance of these factors is well established in pedological literature, the nuances of how these processes manifest in specific landscapes to create micro-variability remain a subject of ongoing research. Although many studies emphasize variability along toposequences and lithosequences, relatively uniform geomorphic settings such as planar surfaces provide a controlled context for examining vertical soil differentiation with minimal lateral redistribution effects. Localized studies exploring the interplay between soil genesis, horizon-specific properties, and the taxonomic classification of soils are essential for bridging knowledge gaps and developing site-specific management strategies, especially in tropical soils such as those in Wukari, Taraba State, Nigeria (Duman, 2017; Duman *et al*., 2023).

The soils of the Wukari area exhibit characteristics typical of highly weathered soils in tropical savanna regions, including horizon differentiation and nutrient depletion (Osujieke *et al*., 2020; Awwal & David, 2024). However, these soils also display variations in clay mineralogy, base saturation, and organic matter dynamics, necessitating detailed characterization (Maniyunda, 2012). Even within planar landscapes, such differences may persist despite the absence of pronounced slope gradients, reflecting the influence of pedogenic processes and subtle environmental heterogeneity. Studies like Awwal (2021) and Aliyu (2023) have highlighted the stratification of soil horizons in tropical ecosystems, noting that properties such as clay content, cation exchange capacity (CEC), and bulk density significantly influence agricultural productivity. Yet, limited site-specific data for Wukari soils constrains the development of targeted management practices suited to these conditions.

One major advantage of soil characterization is that it provides actionable insights for effective soil management (Shi *et al*., 2021). For instance, understanding the distribution of bulk density and porosity across horizons can inform interventions to reduce compaction risks, while assessments of pH and exchangeable bases can guide liming and fertilization practices (Weil and Brady, 2017). In the context of global challenges such as land degradation and climate change, soil characterization is critical due to the pivotal role soils play in key environmental processes such as carbon sequestration, water regulation, and biodiversity preservation (Karas and Oguz, 2017; Shi *et al*., 2021).

While existing knowledge on tropical soils provides a foundation for understanding their variability and functionality, a growing need exists to focus on the finer details that differentiate specific soils. Advanced statistical tools such as Linear Discriminant Analysis (LDA) offer unique opportunities to uncover patterns and relationships that traditional methods may overlook (Qu and Pei, 2024). The application of LDA in soil studies has been explored in contexts such as soil suitability for effluent renovation (e.g., Carrol *et al*., 2006) and carbon fractionation (e.g., Borges *et al*., 2017). However, its potential for enhancing soil characterization, differentiating soil horizons, and linking soil properties to functional roles in ecosystems remains underutilized. This is particularly relevant in geomorphically uniform settings, where variability is less apparent and requires robust analytical approaches to resolve. Employing such tools can improve our understanding of soil in control sections and provide a platform for universally describing soil properties with regards to their depth within the soil profile.

Taxonomic classification frameworks like the USDA Soil Taxonomy and the FAO World Reference Base have been extensively employed to categorize soils globally. These systems rely on diagnostic horizons and measurable criteria, such as base saturation, cation exchange capacity (CEC), and texture, to classify soils into taxonomic classes (Soil Science Division Staff, 2017; IUSS Working Group, 2022). Applying these frameworks in Wukari can elucidate soil functionality and suitability for key crops in the region, including maize, cassava, and yams. Moreover, soil classification helps identify potential limitations such as subsoil compaction, low fertility, and poor drainage, which are prevalent in tropical soils.

Integrating soil characterization with formal classification provides the necessary framework for improving soil health. This study minimizes topographic variability and emphasizes intrinsic pedogenic differentiation within the soil profile by focusing on a relatively planar surface. This research aims to characterize and classify selected soil units in Wukari using a combination of morphological, physical, chemical, and statistical analyses, with emphasis on micro-variability within a geomorphically uniform setting, which seeks to enhance the empirical understanding of micro-variability between surface and control sections of soils within similar a region.

Materials and Methods

Study Area

This study was conducted on three soil units located within Federal University Wukari, Taraba State, Nigeria, spanning between latitude 7°50'51.19" N, longitude 9°45'49.21" E and latitude 7°50'36.65" N, longitude 9°46'21.48" E with an average elevation of 163 m above sea level. This study was conducted in Wukari, located within the Guinea Savanna agro-ecological zone of Nigeria. Wukari experiences a tropical climate characterized by distinct wet and dry seasons, with annual rainfall ranging from 1,200 mm to 1,500 mm and mean temperatures of 25–30°C (David, 2024). The soils are predominantly derived from sedimentary parent materials and are subject to varying degrees of anthropogenic activities, including agriculture and grazing (National Geological Survey Agency [NGSA], 2006).

Soil Sampling and Profile Description

Three soil profile pits (P1, P2 and P3) were excavated on representative points within each land unit (Figure 1). Pedons 1 and 3 have been used for cultivating crops such as maize, cowpea and groundnut, while Pedon 2 is a bare land under exploration for agricultural usage. Each pit was situated on a near planar surface with similar geomorphology and was described in situ following the guidelines of the USDA Soil Survey Manual (Soil Science Division Staff, 2017), paying particular attention to morphological features such as color (using Munsell Soil Color Charts), texture, structure, consistency, and root abundance. The horizons identified were delineated, and samples were collected from each horizon for laboratory analysis.

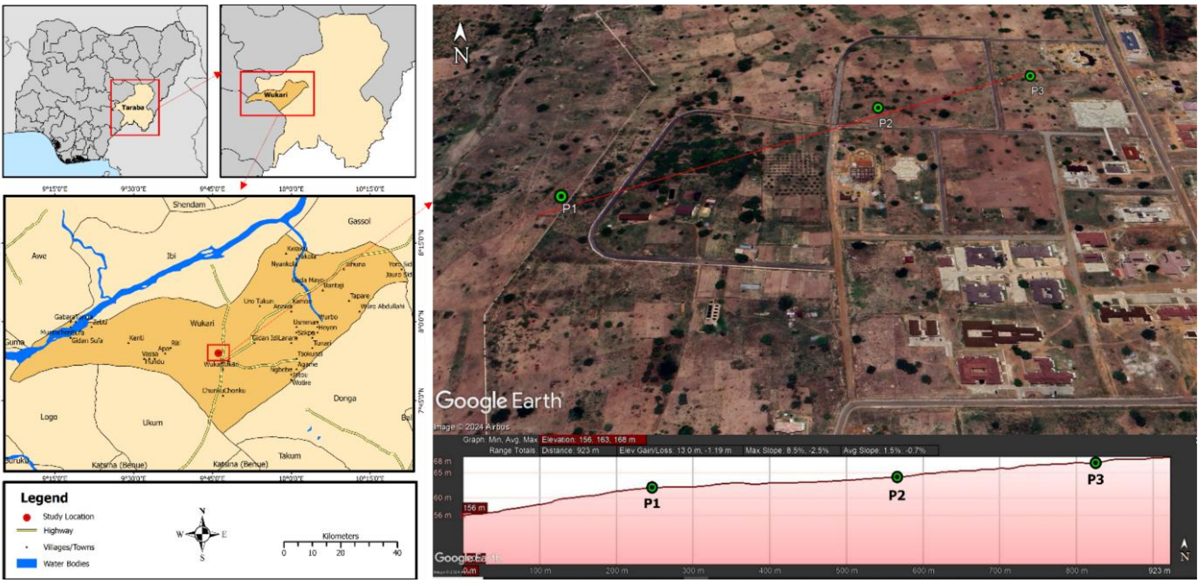


Figure 1: Study Area Showing Location of Study Pedons

Laboratory Analyses

Soil samples collected from the genetic horizons were routinely prepared and used to carry out laboratory analysis such as particle size distribution (PSD), bulk density (BD, undisturbed samples) and particle density (PD), following standard protocols described by Gee and Or (2002), after which total porosity was calculated from the relationship between BD and PD, as per Flint and Flint (2002). Soil pH was measured in water and 1 M KCl at a 1:2.5 soil-to-solution ratio using a glass electrode (FAO, 2020). Exchangeable bases (Ca^{2+}, Mg^{2+}, K^+, Na^+) were extracted with 1 M ammonium acetate and analyzed using an atomic absorption spectrophotometer (Ca and Mg) and a flame photometer (K and Na). Total nitrogen (TN) was determined by the Kjeldahl digestion method, while organic carbon (OC) was assessed using the Walkley-Black wet oxidation method. Available phosphorus (AvP) was extracted using the Bray-1 method. Total exchangeable bases (TEB), exchangeable acidity (EA), and effective cation exchange capacity (ECEC) were calculated accordingly, and base saturation (BS) was expressed as a percentage of ECEC.

Soil Classification

The soils were classified according to the USDA Soil Taxonomy (Soil Science Division Staff, 2017), using morphological and analytical data. This classification was correlated to the FAO World reference Base for Soil Resources classification methodology (IUSS Working Group, 2022).

Statistical Analysis and Evaluation Metrics

Descriptive statistics, including mean, standard deviation, and range, were calculated for all soil properties to summarize the variability within and across horizons. Pearson correlation coefficients were computed to assess the relationships between physical and chemical soil properties, highlighting significant interactions that influence soil functionality. Linear Discriminant Analysis (LDA) was performed to differentiate soil horizons based on their physical and chemical properties. The discriminant function is mathematically defined as:

$$L_i(x) = w_i^T x + b_i \qquad \text{- Equation (1)}$$

Where $L_i(x)$ represents the discriminant score for class i, w_i is the vector of discriminant coefficients, x is the input feature vector, and b_i is the bias term (Tharwat *et al.*, 2017). The classification rule assigns an observation to the class with the highest discriminant score.

To maximize separability, LDA optimizes the ratio of between-class variance (S_B) to within-class variance (S_W):

$$J(w) = \frac{w^T S_B w}{w^T S_W w} \quad \text{- Equation (2)}$$

The proportion of trace, which represents the variance explained by each discriminant, was calculated as:

$$Proportion\ of\ Trace = \frac{\lambda_i}{\Sigma_j \lambda_j} \text{- Equation (3)}$$

Here, λ_i is the eigenvalue associated with the i-th discriminant.

The analysis produced canonical linear discriminants, which were evaluated for their ability to classify horizons accurately. A confusion matrix was generated to assess classification performance (Gómez and Montero, 2011), and overall accuracy (OA), which quantifies the proportion of correctly classified instances out of the total observations, was calculated as:

$$OA = \frac{Number\ of\ Correct\ Predictions}{Total\ Number\ of\ Predictions} \times 100 \quad \text{- Equation (4)}$$

All statistical analyses were performed using R software (version 4.2.2), with packages such as ‘MASS’ for discriminant analysis, and ‘Hmisc’ for correlation analysis. Graphical outputs, including the correlation heatmap, and LDA scatter plot were generated to support data interpretation using the ‘ggplot2’ package (R Core Team, 2024).

Results

Soil Morphological Properties

The depth and differentiation of soil horizons across the studied pedons show varying degrees of pedogenic development (Table 1). The Ap horizons were shallow in P2, with a depth of 14 cm, compared to 20 to 22 cm in P1 and P3 respectively. Colour transitions between horizons corroborate pedological influences on horizon development, with the shift from darker hues in the Ap horizons (2.5YR 6/4) to lighter colours in the Bt horizons (7.5YR 7/8 in Bt3 of P1) as depicted in Figure 2.

Textural observation revealed that coarser textures of sandy loam (SL) and sandy clay loam (SCL) dominated all horizons in the study area. Generally, surface horizons were coarser (SL) in texture, overlaying relatively finer (SCL) subsurface layers. Soil structure showed similar variations, with weaker structures in the surface, and more aggregation in the subsurface. The Ap horizons predominantly displayed a fine granular structure, which is characteristic of cultivated soils with higher organic matter, showing evidences of bioturbation. In contrast, the Bt horizons exhibited subangular blocky structures. Horizon boundaries ranged from gradual to distinct and wavy and are more pronounced for BC horizons.

Soil Physical Properties

Sand-sized particles were the dominant fraction, comprising over 65% of the total distribution across all genetic horizons. In the Ap horizons, sand content ranged from 785.2 to 818 g kg^{-1}, while in subsurface horizons, it decreased to 668–798 g kg^{-1}. This reduction in sand content with depth corresponded to a progressive increase in clay-sized particles. Clay content was lowest

Table 1: Morphological Properties of Pedons

Horizon	Depth	Colour		Texture	Structure	Boundary	Other features
	(cm)	Dry	Moist				
P1: (7° 50' 37.70" N, 9° 45' 51.10" E)							
Ap	0-20	2.5YR 6/4	2.5YR 6/4	SL	1fg	dg	Common medium roots
Bt1	21-46	2.5YR 6/6	5YR 5/8	SCL	1msbk	ds	Common fine roots
Bt2	47-80	2.5YR 6/8	2.5YR 6/8	SCL	1fsbk	dw	Common medium roots
Bt3	81-120	7.5YR 7/8	5YR 7/8	SCL	2cp		Common medium roots
P2: (7° 50' 44.57" N, 9° 46' 7.18" E)							
Ap	0-14	2.5YR 6/4	7.5YR 6/4	SL	1fg	dg	Common fine roots
Bt1	15-54	7.5YR 6/6	7.5YR 6/8	SCL	1msbk	dg	Few fine roots
BC	55-110	7.5YR 6/8	7.5YR 8/6	SL	1mcr		Few medium roots
P3: (7° 50' 47.43" N, 9° 46' 16.16" E)							
Ap	0-22	2.5YR 6/4	2.5YR 4/3	SL	0fg	dg	Common medium roots
Bt1	23-50	5YR 7/6	2.5YR 6/4	SCL	1fg	dw	Few fine roots
Bt2	51-90	5YR 6/8	2.5YR 6/8	SL	2mcr	dg	Few medium roots
BC	91-130	5YR 7/8	2.5YR 8/8	SL	3cp		Common medium roots

Keys: textures = SL – sandy loam, SCL – sandy clay loam; boundaries = d – diffuse, g – gradual, s – smooth, w – wavy; structures = 0 - structureless, 1 - weak, 2 - moderate, 3 - strong, f - fine, m - medium, c - coarse, cr - crumb, g - granular, p - prismatic, sbk - subangular blocky structure.

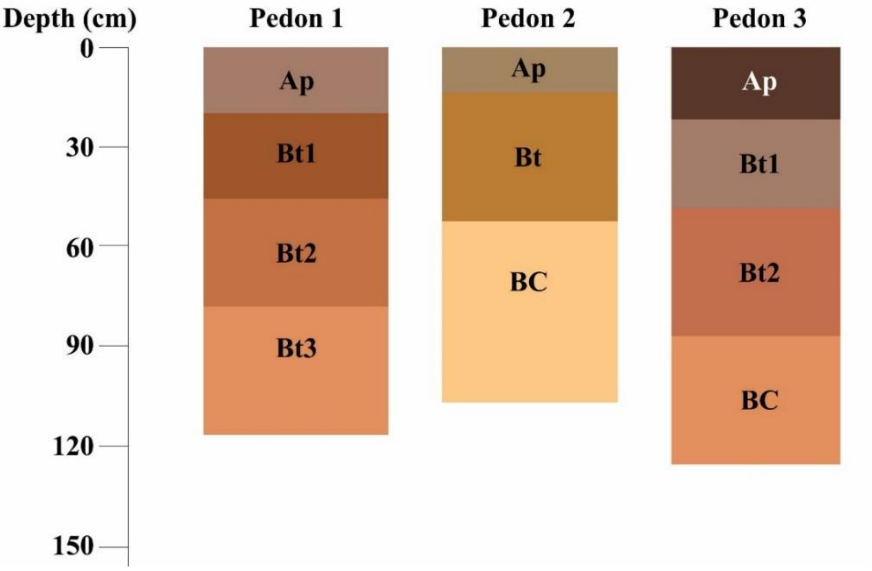


Figure 2: Visual Representation of Horizon Colours and Thickness for the three Pedons

in the surface of P3 (140.8 g kg^{-1}), while in horizons like Bt3 of P1, its content reached 270.8 g kg^{-1}. Silt content was the least abundant in the soils. The silt-clay ration (Si/C) where largely lower than 0.5 in most horizons, with exception to the Ap horizon in P3 (0.53). Bulk density (BD) increased with depth, with values such as 1.21 Mg m^{-3} in P1 (Ap horizon) and 1.45 Mg m^{-3} in P3 (Bt2 horizon). Particle density (PD) ranged from 2.41 to 2.60 Mg m^{-3} across the pedons, while porosity was higher in surface horizons (45.64 – 49.79%) and declined slightly with depth, with lower values in Bt1 of P1 (42.51%) and BC of P2 (42.91%).

Table 2: Physical Properties of Pedons

Horizon	**Particle Size Distribution (g kg^{-1})**			**Si/C**	**BD**	**PD**	**Porosity**
	Clay	**Silt**	**Sand**		**(Mg m^{-3})**	**(Mg m^{-3})**	**(%)**
Pedon 1: (7° 50' 37.70" N, 9° 45' 51.10" E)							
Ap	150.8	31.2	818	0.21	1.21	2.41	49.79
Bt1	200.8	81.2	718	0.40	1.42	2.47	42.51
Bt2	240.8	71.2	688	0.30	1.45	2.54	42.91
Bt3	270.8	61.2	668	0.23	1.43	2.56	44.14
Pedon 2: (7° 50' 44.57" N, 9° 46' 7.18" E)							
Ap	150.8	51.2	798	0.34	1.31	2.41	45.64
Bt1	250.8	81.2	668	0.32	1.39	2.51	44.62
BC	180.8	64	755.2	0.35	1.45	2.54	42.91
Pedon 3: (7° 50' 47.43" N, 9° 46' 16.16" E)							
Ap	140.8	74	785.2	0.53	1.33	2.56	48.05
Bt1	188	54	758	0.29	1.39	2.60	46.54
Bt2	198	84	718	0.42	1.41	2.57	45.14
BC	168	70	762	0.42	1.44	2.58	44.19

Keys: Si/C = silt-clay ratio; BD = bulk density; PD = particle density.

Soil Chemical Properties

The pH in water ranged from 5.05 to 6.15 across the horizons. Higher pH values were noted in the subsurface layers (range, 5.84 – 6.15), compared to the surface layers (range, 5.05 – 5.60). In all cases, the pH in KCl values were lower than the pH in water, leading to negative ΔpH values, ranging from -0.20 to -0.85. Organic carbon (OC) was highest in the Ap horizon of P2 (14.40 g kg^{-1}), while total nitrogen (TN) was highest in surface horizons (1.17 – 1.31 g kg^{-1}) and declined with depth. Available phosphorus (av. P) ranged from 4.45 to 11.32 mg kg^{-1}, with the highest values in the Ap horizon of P2.

Calcium was the dominant exchangeable cation in the area, with concentrations ranging from 3.88 to 4.46 cmol kg^{-1}. Magnesium was second in abundance, ranging from 2.04 to 2.64 cmol kg^{-1} in surface horizons. The highest total exchangeable bases (TEB) values were observed in the Bt2 horizon of P1 (9.98 cmol kg^{-1}). Effective cation exchange capacity (ECEC) ranged from 9.61 to 11.05 cmol kg^{-1}. Exchangeable acidity (EA) was low across the pedons, ranging from 1.01 to 1.51 cmol kg^{-1}. Base saturation was high across the study area, with higher values in the subsurface layers (85.4 – 90.8%).

Soil Classification

Based on the USDA Soil Taxonomy, the presence of an Argillic horizon characterized by significant clay accumulation compared to the surface horizon and high base saturation (>35%) (Table 3), all three pedons classify under the Alfisols order. At the sub-order level, the region's semi-arid conditions and moderate soil moisture regime, inferred from the morphological features such as the 2.5YR and 7.5YR hues (Table 1), classify as Ustic, placing the pedons under Ustalfs. The absence of a petrocalcic horizon, natric horizon, or other significant limiting subsurface features qualifies Pedons 1 and 3 as a Haplustalf, while evidence of extended weathering, with thick and well-developed Bt horizons extending deeper than in Pedons 1 and 3, characterize Pedon 2 as Paleustalfs. Furthermore, due to a lack of atypical characteristics, all pedons classify as Typic at the subgroup level. These correspond to Haplic Luvisols in the FAO World Reference Base, evidenced by the presence of an argic layer, high base saturation (>50%) and the absence of stagnic or gleyic features.

Interaction between Soil Properties

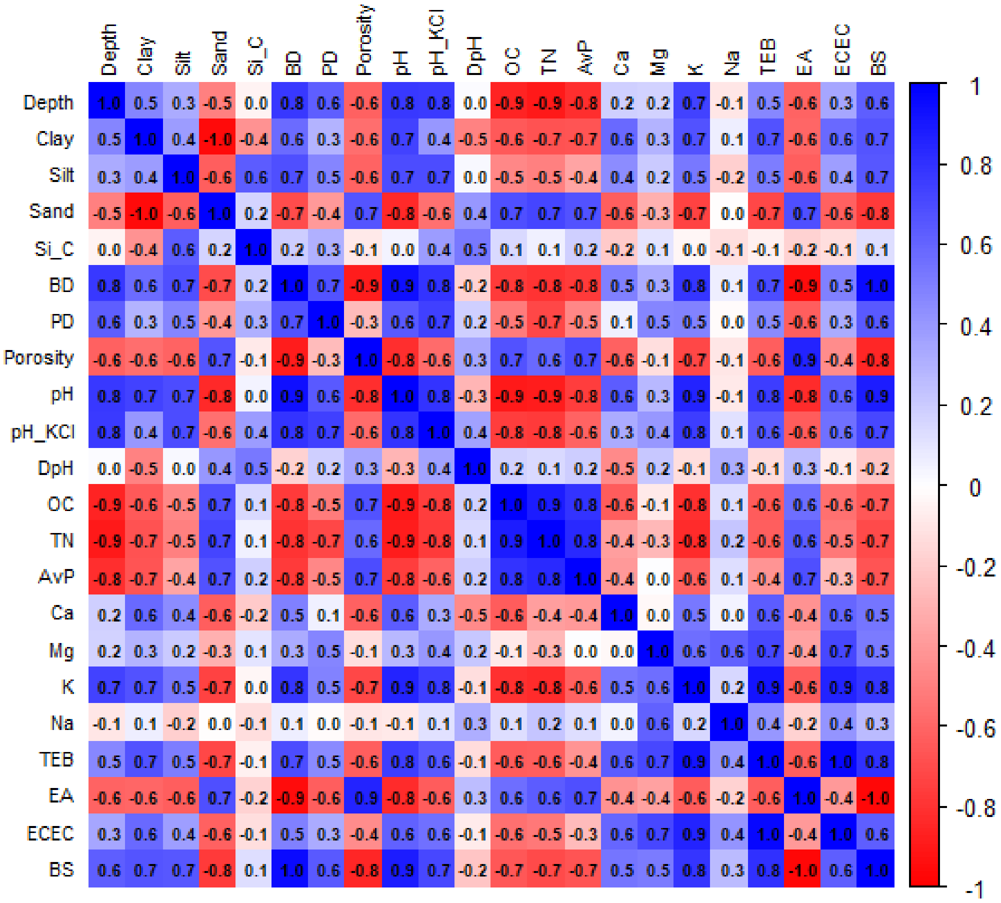
The correlation heatmap (Figure 3) illustrates the relationships among soil physical and chemical properties in the study area. Notable correlations include the strong positive relationship between horizon depth and bulk density (r = 0.8), indicating increased soil compaction with depth.

Conversely, clay content exhibited a negative correlation with porosity (r = -0.6), suggesting reduced pore spaces in finer-textured soils. Soil pH showed a strong positive correlation with base saturation (BS) (r = 0.9) and total exchangeable bases (TEB) (r = 0.8), suggesting that higher pH enhances cation retention. A similar trend was observed between pH and exchangeable Ca (r = 0.7) and Mg (r = 0.6). Organic carbon (OC) displayed a significant positive correlation with total nitrogen (TN) (r = 0.9) and available phosphorus (AvP) (r = 0.8), highlighting the role of organic matter in nutrient availability.

Among exchangeable cations, Ca and Mg were strongly correlated (r = 0.9), as were Mg and K (r = 0.8), indicating common sources and similar retention mechanisms. Effective cation exchange capacity (ECEC) also exhibited strong positive correlations with BS (r = 1.0) and TEB (r = 0.9), reinforcing the influence of base-forming cations on soil fertility.

Table 3: Chemical Properties of the Pedons

Horizon	**pH**	**pH**	**ΔpH**	**OC**	**TN**	**AvP**	**Ca**	**Mg**	**K**	**Na**	**TEB**	**EA**	**ECEC**	**BS**
	(H_2O)	**(KCl)**		**(g kg^{-1})**		**(mg kg^{-1})**	**(cmol kg^{-1})**							**(%)**
Pedon 1: (7° 50' 37.70" N, 9° 45' 51.10" E)														
Ap	5.05	4.85	-0.20	10.9	1.21	11.32	4.09	2.19	1.21	1.31	8.8	1.51	10.31	85.4
Bt1	6.05	5.62	-0.43	7.5	1.02	10.21	4.46	2.53	1.63	1.32	9.94	1.11	11.05	90.0
Bt2	6.10	5.60	-0.50	5.6	0.76	4.45	4.43	2.58	1.65	1.32	9.98	1.01	10.99	90.8
Bt3	6.15	5.70	-0.45	5.4	0.7	5.56	4.09	2.64	1.64	1.32	9.69	1.05	10.74	90.2
Pedon 2: (7° 50' 44.57" N, 9° 46' 7.18" E)														
Ap	5.23	4.55	-0.68	14.4	1.31	10.15	3.98	2.04	1.08	1.3	8.4	1.21	9.61	87.4
Bt1	6.05	5.50	-0.55	6.4	0.82	5.34	4.4	2.08	1.38	1.29	9.15	1.14	10.29	88.9
BC	6.00	5.87	-0.13	4.5	0.91	4.91	4.31	2.13	1.39	1.32	9.15	1.05	10.2	89.7
Pedon 3: (7° 50' 47.43" N, 9° 46' 16.16" E)														
Ap	5.60	5.35	-0.25	13.7	1.17	11.22	3.88	2.59	1.23	1.32	9.02	1.21	10.23	88.2
Bt1	5.84	5.25	-0.59	9.1	0.94	9.31	4.22	2.48	1.34	1.31	9.35	1.11	10.46	89.4
Bt2	6.15	5.70	-0.45	4.3	0.78	8.04	4.32	2.23	1.48	1.29	9.32	1.15	10.47	89.0
BC	6.05	5.85	-0.20	5.4	0.63	5.24	4.01	2.34	1.59	1.29	9.23	1.13	10.36	89.1



	Depth	Clay	Silt	Sand	Si_C	BD	PD	Porosity	pH	pH_KCl	DpH	OC	TN	AvP	Ca	Mg	K	Na	TEB	EA	ECEC	BS
Depth	1.0	0.5	0.3	-0.5	0.0	0.8	0.6	-0.6	0.8	0.8	0.0	-0.9	-0.9	-0.8	0.2	0.2	0.7	-0.1	0.5	-0.6	0.3	0.6
Clay	0.5	1.0	0.4	-1.0	-0.4	0.6	0.3	-0.6	0.7	0.4	-0.5	-0.6	-0.7	-0.7	0.6	0.3	0.7	0.1	0.7	-0.6	0.6	0.7
Silt	0.3	0.4	1.0	-0.6	0.6	0.7	0.5	-0.6	0.7	0.7	0.0	-0.5	-0.5	-0.4	0.4	0.2	0.5	-0.2	0.5	-0.6	0.4	0.7
Sand	-0.5	-1.0	-0.6	1.0	0.2	-0.7	-0.4	0.7	-0.8	-0.6	0.4	0.7	0.7	0.7	-0.6	-0.3	-0.7	0.0	-0.7	0.7	-0.6	-0.8
Si_C	0.0	-0.4	0.6	0.2	1.0	0.2	0.3	-0.1	0.0	0.4	0.5	0.1	0.1	0.2	-0.2	0.1	0.0	-0.1	-0.1	-0.2	-0.1	0.1
BD	0.8	0.6	0.7	-0.7	0.2	1.0	0.7	-0.9	0.9	0.8	-0.2	-0.8	-0.8	-0.8	0.5	0.3	0.8	0.1	0.7	-0.9	0.5	1.0
PD	0.6	0.3	0.5	-0.4	0.3	0.7	1.0	-0.3	0.6	0.7	0.2	-0.5	-0.7	-0.5	0.1	0.5	0.5	0.0	0.5	-0.6	0.3	0.6
Porosity	-0.6	-0.6	-0.6	0.7	-0.1	-0.9	-0.3	1.0	-0.8	-0.6	0.3	0.7	0.6	0.7	-0.6	-0.1	-0.7	-0.1	-0.6	0.9	-0.4	-0.8
pH	0.8	0.7	0.7	-0.8	0.0	0.9	0.6	-0.8	1.0	0.8	-0.3	-0.9	-0.9	-0.8	0.6	0.3	0.9	-0.1	0.8	-0.8	0.6	0.9
pH_KCl	0.8	0.4	0.7	-0.6	0.4	0.8	0.7	-0.6	0.8	1.0	0.4	-0.8	-0.8	-0.6	0.3	0.4	0.8	0.1	0.6	-0.6	0.6	0.7
DpH	0.0	-0.5	0.0	0.4	0.5	-0.2	0.2	0.3	-0.3	0.4	1.0	0.2	0.1	0.2	-0.5	0.2	-0.1	0.3	-0.1	0.3	-0.1	-0.2
OC	-0.9	-0.6	-0.5	0.7	0.1	-0.8	-0.5	0.7	-0.9	-0.8	0.2	1.0	0.9	0.8	-0.6	-0.1	-0.8	0.1	-0.6	0.6	-0.6	-0.7
TN	-0.9	-0.7	-0.5	0.7	0.1	-0.8	-0.7	0.6	-0.9	-0.8	0.1	0.9	1.0	0.8	-0.4	-0.3	-0.8	0.2	-0.6	0.6	-0.5	-0.7
AvP	-0.8	-0.7	-0.4	0.7	0.2	-0.8	-0.5	0.7	-0.8	-0.6	0.2	0.8	0.8	1.0	-0.4	0.0	-0.6	0.1	-0.4	0.7	-0.3	-0.7
Ca	0.2	0.6	0.4	-0.6	-0.2	0.5	0.1	-0.6	0.6	0.3	-0.5	-0.6	-0.4	-0.4	1.0	0.0	0.5	0.0	0.6	-0.4	0.6	0.5
Mg	0.2	0.3	0.2	-0.3	0.1	0.3	0.5	-0.1	0.3	0.4	0.2	-0.1	-0.3	0.0	0.0	1.0	0.6	0.6	0.7	-0.4	0.7	0.5
K	0.7	0.7	0.5	-0.7	0.0	0.8	0.5	-0.7	0.9	0.8	-0.1	-0.8	-0.8	-0.6	0.5	0.6	1.0	0.2	0.9	-0.6	0.9	0.8
Na	-0.1	0.1	-0.2	0.0	-0.1	0.1	0.0	-0.1	-0.1	0.1	0.3	0.1	0.2	0.1	0.0	0.6	0.2	1.0	0.4	-0.2	0.4	0.3
TEB	0.5	0.7	0.5	-0.7	-0.1	0.7	0.5	-0.6	0.8	0.6	-0.1	-0.6	-0.6	-0.4	0.6	0.7	0.9	0.4	1.0	-0.6	1.0	0.8
EA	-0.6	-0.6	-0.6	0.7	-0.2	-0.9	-0.6	0.9	-0.8	-0.6	0.3	0.6	0.6	0.7	-0.4	-0.4	-0.6	-0.2	-0.6	1.0	-0.4	-1.0
ECEC	0.3	0.6	0.4	-0.6	-0.1	0.5	0.3	-0.4	0.6	0.6	-0.1	-0.6	-0.5	-0.3	0.6	0.7	0.9	0.4	1.0	-0.4	1.0	0.6
BS	0.6	0.7	0.7	-0.8	0.1	1.0	0.6	-0.8	0.9	0.7	-0.2	-0.7	-0.7	-0.7	0.5	0.5	0.8	0.3	0.8	-1.0	0.6	1.0

Figure 3: Correlation heatmap of soil properties showing Pearson's correlation coefficients. Blue indicates positive correlations, while red represents negative correlations

Linear Discriminant Analysis (LDA) of Soil Horizons

The Linear Discriminant Analysis (LDA) biplot (Figure 4) depicts the distribution of soil horizons along the first two linear discriminant (LD) axes, which explain 88.7% (LD1) and 7.6% (LD2) of the total variance. The separation of soil horizons along LD1 suggests strong differentiation based on soil properties, with Ap horizons clustering on the right side of the axis, while Bt and BC horizons are distributed towards the negative side of LD1.

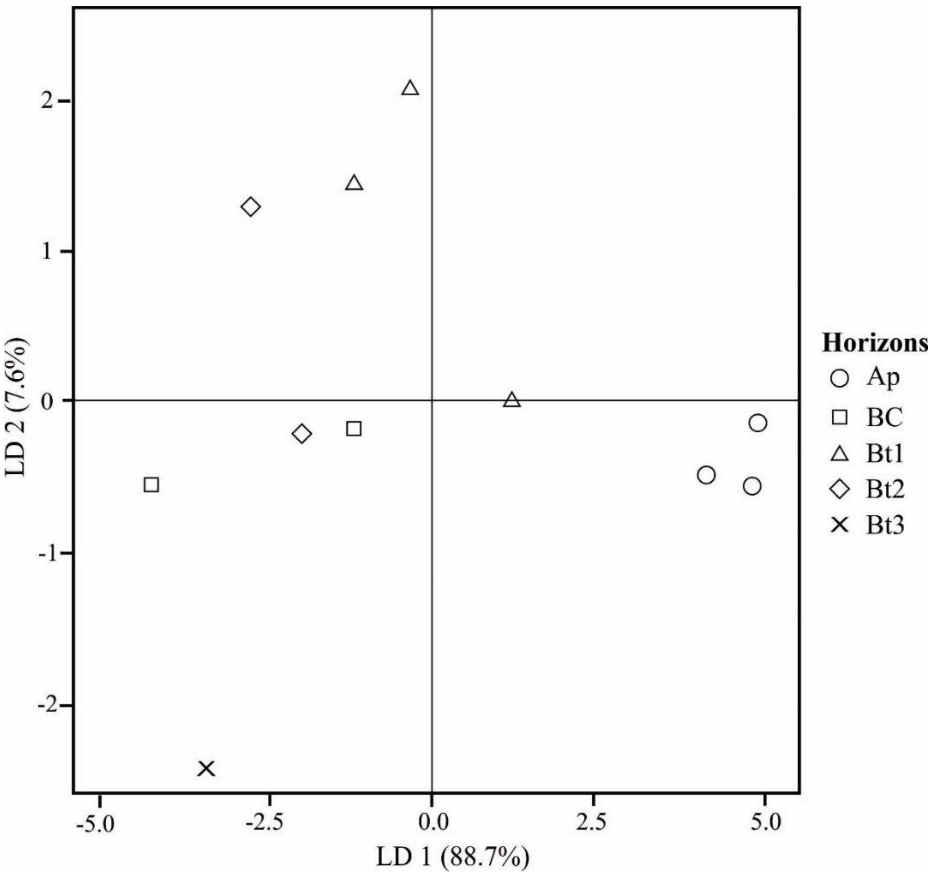


Figure 4: Linear Discriminant Analysis biplot showing the distribution of soil horizons

Factor loadings (Table 4) indicate that exchangeable Na (LD1: 10.749), total nitrogen (LD1: 2.529), and particle density (LD1: 1.831) are the strongest contributors to the first discriminant function, emphasizing their role in horizon differentiation. Conversely, bulk density (LD2: 1.065) and exchangeable Ca (LD2: 1.825) had significant loadings on LD2, suggesting their influence in further distinguishing between subsurface horizons.

Table 4: Linear Discriminants Factor Loadings of Soil Properties

	LD1	LD2	LD3	LD4
Depth	-0.030	-0.028	0.003	0.002
Clay	-0.006	0.005	-0.009	-0.001
Silt	-0.006	0.003	0.017	-0.002
Sand	0.006	-0.004	0.001	0.001
Si/C	-0.267	-0.197	2.421	-0.428
BD	-0.422	**1.065**	0.032	-3.987
PD	**1.831**	-1.917	-1.738	-0.977
Porosity	0.057	-0.072	-0.050	0.053
pH_{water}	-1.172	0.449	2.053	-0.501
pH_{KCl}	0.040	0.178	0.387	0.295
ΔpH	0.261	0.184	0.215	0.520
OC	0.006	-0.079	-0.124	-0.162
TN	**2.529**	**1.528**	1.949	0.070
AvP	0.072	-0.030	0.166	0.050
Ca	**0.562**	**1.825**	0.697	1.008
Mg	-0.167	-0.227	-0.783	0.059
K	**-2.180**	-0.086	-0.456	0.736
Na	**10.749**	**9.061**	-7.983	3.899
TEB	-0.261	0.149	-0.359	0.270
EA	-0.421	-0.442	0.716	1.762
ECEC	-0.301	0.106	-0.288	0.440
BS	0.017	0.059	-0.105	-0.130
Proportion of Trace	0.8871	0.076	0.035	0.001

The Ap horizon exhibited positive LD1 values, driven by higher base saturation and organic matter content. The Bt horizons were primarily characterized by negative LD1 values, reflecting their higher clay content and lower exchangeable sodium. The BC horizon displayed intermediate positioning, indicating transitional properties between Ap and Bt horizons.

Discussions

The soils were moderately deep without any evidence of restriction. This is characteristic of soils developed on planar surfaces, where weathering is more intense, and surface erosion that diminishes soil depth is limited (Alem *et al.*, 2015; Jimoh, 2021). Organic matter influenced soil color in the Ap horizon through melanization, giving it darker hues compared to subsurface layers, as evidenced by higher OC content recorded in the Ap horizons (Table 3). Clay accumulation promoted aggregation due to the horizonal variation in soil structure (Lopes *et al*., 2022). Deeper horizons showed more aggregation strength and size, which is consistent with the findings of Gisilanbe *et al*. (2017) on soil structure variation with depth. Root abundance and distribution varied among horizons, with common roots in the Ap horizons of all pedons, supporting the role of biological activity in surface soil development, and fewer roots with increasing depths. These morphological distinctions were quantitatively confirmed by LDA results, where the Ap horizon was distinctly separated on LD1, driven by higher organic carbon, total nitrogen, and lower bulk density compared to subsurface layers.

The domination of sand-size particles observed in the study area is common on soils developed on granitic parent material (Esu, 2010; Ihediuche *et al*., 2021). Typically, these coarse textures often lead to high permeability and low water retention capacity (Rêgo *et al*., 2016). This is further evident by the positive correlation between porosity and sand (r = 0.7). The SL texture noted on the Ap horizons of the pedons transitions gradually into SCL, signifying effective eluviation and deposition of finer particles in subsurface horizons, which is often encouraged by pedoturbation (Awwal, 2021). This suggests that moisture retention will be improved in the subsurface layer, which is a critical factor for crop selection, as crops with deeper taproots will be favored. Consequently, porosity was generally higher in the surface horizons and declined with depth due to variation in clay (r = -0.6) and organic carbon (r = 0.7) content. The LDA confirmed these textural and structural differences by distinctly clustering the Bt horizons along LD2, with particle density and sodium playing significant roles in their differentiation.

The silt-to-clay ratio (Si/C) is a popular metric used to indicate the intensity of weathering processes in soil (Ngongo and Langohr, 1992). Ratios below 0.5 in the Bt horizons of all pedons indicate advanced weathering and clay translocation, while, in contrast, higher Si/C ratios in the Ap horizons reflect a less altered surface. Bulk density (BD) increased with depth across all pedons, consistent with compaction and reduced organic matter content in the subsurface (Awwal, 2021). The lower BD in Ap horizons, such as 1.21 Mg m^{-3} in P1, favors root growth and water infiltration, while higher BD in Bt horizons, such as 1.45 Mg m^{-3} in Bt2 of P3, is typically due to improved structure and lower organic matter but remains non-restrictive for soil aeration and root elongation (Hillel, 1980).

Soil pH in water ranged from 5.05 to 6.25, indicating slightly acidic to near-neutral conditions across horizons. Similar values were reported by Imadojemu (2024) for soils of the Wukari series, attributed to increased exposure to acidic parent materials (Maniyunda, 2012). In all cases, pH in KCl was lower, resulting in a consistently negative ΔpH (-0.20 to -0.85), which suggests the presence of exchangeable Al^{3+} or H^+, reducing soil buffering capacity (Awwal, 2021). Available P correlated negatively (r = -0.8), while exchangeable K correlated positively (r = 0.9) with pH, reflecting pH's influence on their availability. Similarly, increasing depth (r = 0.8) and clay content (r = 0.7) also significantly increased pH.

The decline of OC, TN and av. P with depth is consistent with reduced organic matter inputs and microbial activity in the subsurface horizons, as is common in tropical soils (Shi *et al.*, 2021). Additionally, lower Av. P concentrations in subsurface horizons across the pedons are typical of soils in tropical regions, where P is immobilized by Al and Fe oxides or lost through leaching (Abdu, 2006). The role of total nitrogen (TN) in distinguishing the Ap horizon was further reinforced by LDA results, where TN was among the strongest differentiating variables on LD1.

Calcium and magnesium were the dominant cations, with Ca ranging from 3.88 to 4.09 cmol kg^{-1} and Mg ranging from 2.04 to 2.59 cmol kg^{-1} in surface horizons. These values suggest adequate base saturation, which exceeded 85% across all horizons. This high BS percentage suggests that the soils possess a high capacity to retain nutrients due to proper drainage and near-flat slope angle. The highest total exchangeable bases (TEB) values were observed in the Bt2 horizon of Pedon 1, which aligns with the relatively high clay content and soil structure in this horizon. The ECEC values ranged from 9.61 to 10.74 cmol kg^{-1}, again reflecting the soils' capacity to hold and exchange nutrients, while the EA values were generally low, consistent with the near-neutral soil reaction. The role of sodium (Na) and calcium (Ca) in distinguishing subsurface horizons was particularly evident in LDA results, where Na had the highest loading (10.749) on LD1, reinforcing the chemical differences among soil horizons.

Overall, the LDA results validated the observed soil property patterns, confirming that Ap horizons are distinct due to high OC, TN, and lower BD, with strong separation along LD1, Bt horizons exhibit differentiation due to clay content, bulk density, and exchangeable bases, clustering separately along LD2 and BC horizons are transitional, showing overlapping characteristics with both Ap and Bt, as indicated by their intermediate position on LD axes.

Confusion Matrix

To confirm the performance of the LDA, a confusion matrix was constructed (Table 5), revealing that the LDA achieved an overall accuracy of 81.82%, which is satisfactory for LDA-based classification (Tharwat *et al.*, 2017). All three samples from the Ap horizons were correctly classified, buttressing their difference from soils from the subsurface horizons. This points to the importance of conserving the Ap horizons to avoid its loss and to discourage deep tillage practices such as subsoiling, which may have marked effects on soil productivity. Similarly, the Bt1 and Bt3 samples were all accurately classified by the model.

Table 5: Confusion matrix

Actual

Prediction	Ap	BC	Bt1	Bt2	Bt3
Ap	3	0	0	0	0
BC	0	1	0	1	0
Bt1	0	0	3	0	0
Bt2	0	1	0	1	0
Bt3	0	0	0	0	1

These accurate classifications confirms their distinctness in chemical and physical properties, likely due to their functional roles in the soil profile (e.g., Ap as the plow layer and Bt1 as a subsoil horizon). However, misclassification occurred between BC and Bt2 horizons, each having one incorrect prediction, reflect some overlap in properties, potentially due to transitional characteristics or similar soil properties. This may be due to the similar clay content and chemical properties of the horizons.

Conclusion

Statistical methods are essential for understanding and elucidating soil variability. The soils in the study area were classified as Alfisols at varying stages of profile development, likely influenced by land use. Morphological and physical variations were evident in properties such as color, horizon depth, and texture, with subsurface horizons showing signs of clay illuviation. The soils exhibited high base saturation, indicating strong nutrient retention capacity, but organic carbon and total nitrogen contents were generally low, with the highest concentrations recorded in the surface (Ap) horizons. Pearson's correlation analysis identified clay content and organic carbon as key factors influencing critical soil properties such as exchangeable bases (sodium and potassium), total nitrogen, particle density, and bulk density, which were instrumental in differentiating soil horizons through LDA. Overall, this study demonstrates that the soils of the Wukari area exhibit significant micro-variability within soil profiles, emphasizing the role of pedogenesis and land use in influencing soil properties in the area, which is critical for curating tailored management practices to optimize agricultural productivity.

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