Pedology and Environment 2024, 34 (02), 125-140
doi.org/10.47114/j.pedoenv.2024.dec 1

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, with an emphasis on their characterisation 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 analysed for selected properties. Genetic classification was performed, and statistical procedures, such as correlation and Linear Discriminant Analysis (LDA), were applied to examine relationships between soil properties and horizon differentiation. Morphological analysis revealed variations in horizon depth and colour, with Ap horizons exhibiting darker colours and shallower depths in Pedon 2 (14 cm) compared to Pedons 1 and 3 (20–22 cm). Textural analysis revealed a transition from sandy loam in the surface horizons to sandy clay loam in the Bt horizons, indicating clay illuviation. 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 (e.g., 15.40 g kg^{-1} OC in P2) 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 Lixisols in the FAO system. Diagnostic features included the presence of anargillic horizon. 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.

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

Introduction

Soil variability is influenced by well-documented drivers, including 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 (Gilisanbe et al., 2017; 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. Localised studies exploring the interplay between soil genesis, horizon-specific properties, and the taxonomic classification of soils are

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essential for bridging knowledge gaps and developing site-specific management strategies, especially in tropical soils such as those in Wukari, Taraba State, Nigeria (Djikerman, 1974; Duman, 2017; Duman et al., 2023).

The soils of the Wukari area exhibit characteristics typical of highly weathered soils in tropical savanna regions, including advanced weathering, distinct horizon differentiation, and considerable nutrient depletion (Osujieke et al., 2020; Imadojemu, 2024). However, these soils also display unique features, such as variations in clay mineralogy, base saturation, and organic matter dynamics, necessitating detailed characterisation (Maniyunda, 2012). 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. Despite these findings, the lack of comprehensive morphological, physical, and chemical data on Wukari soils hinders the development of targeted management practices tailored to the region's specific challenges.

One major advantage of soil characterisation 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 fertilisation practices (Weil & Brady, 2017). In the context of global challenges such as land degradation and climate change, soil characterisation is critical due to the pivotal role soils play in key environmental processes such as carbon sequestration, water regulation, and biodiversity preservation (Karasn & 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 techniques, such as Linear Discriminant Analysis (LDA), provide powerful means of identifying patterns and relationships that may be missed by conventional approaches (Qu & Pei, 2024). In soil science, LDA has been applied in diverse contexts, including the assessment of soil suitability for effluent renovation (Carroll et al., 2006) and the discrimination of soil carbon fractions (Borges et al., 2018). However, its potential for enhancing soil characterisation, differentiating soil horizons, and linking soil properties to functional roles in ecosystems remains underutilised. Employing such tools can improve our understanding of soil in control sections and provide a platform for universally describing soil properties with regard 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 for systematic soil categorisation across diverse landscapes. 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; IUSSWG, 2022). Applying these classification systems to the soils of Wukari enhances the understanding of their functional characteristics and agricultural suitability, particularly for key regional crops such as maize, cassava, and yams. Furthermore, classification aids in diagnosing inherent limitations such as subsoil compaction, nutrient deficiencies, and inadequate drainage that commonly affect soil productivity in tropical environments.

The interrelationship between soil characterisation and classification highlights their critical role in advancing soil health management. This research aims to characterise and classify selected soil units in Wukari using a combination of morphological, physical, chemical, and statistical analyses, which seeks to enhance the empirical understanding of micro-variability between surface and control sections of soils within a similar agro-ecological region.

Materials and Methods

Study Area

This study was conducted on three soil units located within the Federal University Wukari, Taraba State, Nigeria, spanning a latitude range of 7°50'51.19" N to 7°50'36.65" N and a longitude range of 9°45'49.21" E to 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 characterised 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 Bureau of Statistics [NBS], 2009).

Soil Sampling and Profile Description

Three soil profile pits (P1, P2 and P3) were excavated on representative points within each land unit (Fig. 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 colour (using Munsell Soil Colour Charts), texture, structure, consistency, and root abundance. The horizons identified were delineated, and samples were collected from each horizon for laboratory analysis.

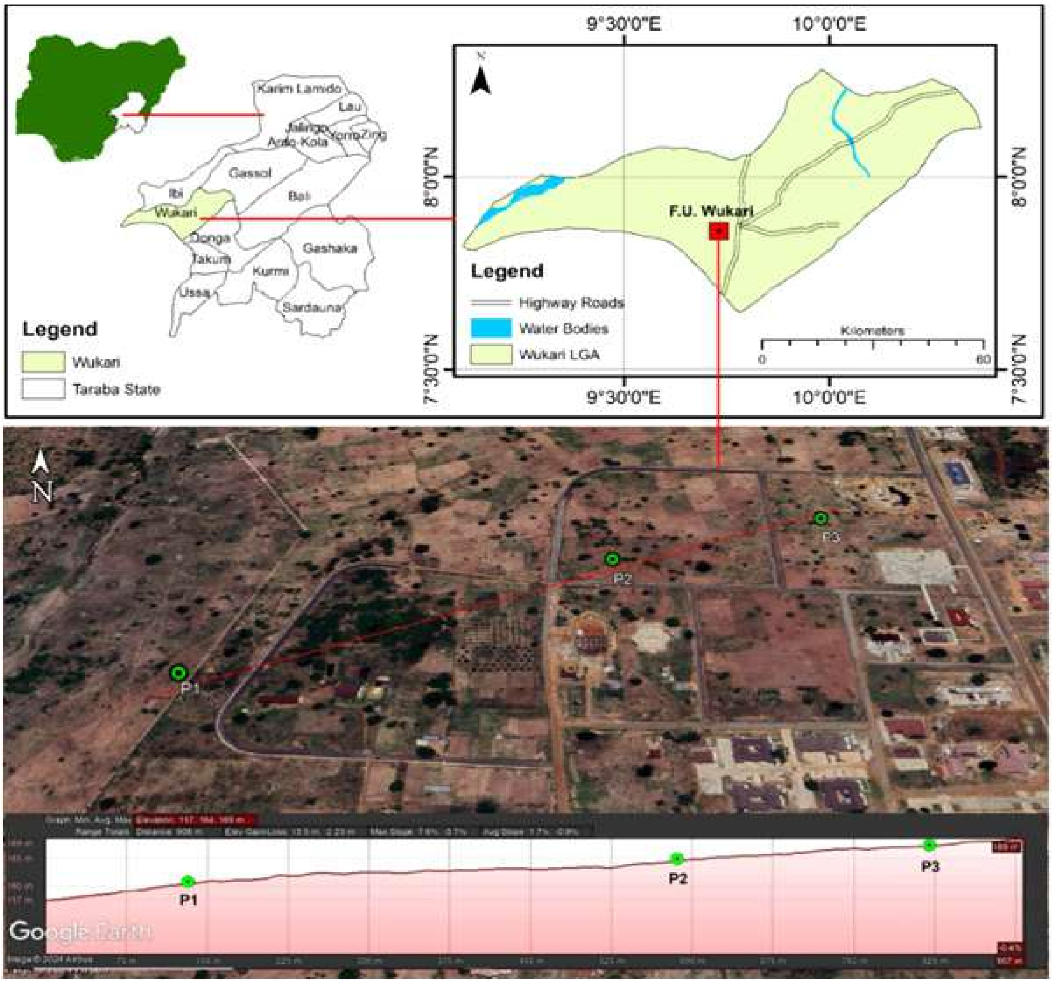

Fig. 1: Location of Study Pedons

Laboratory Analyses

Soil samples collected from the genetic horizons were routinely processed and used to carry out laboratory analysis such as particle size distribution (PSD), bulk density (BD, from 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 analysed 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:

$$Li(x) = w_i^T x + b_i \quad (1)$$

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 maximise separability, LDA optimises the ratio of between-class variance (S_B) to within-class variance (S_W):

$$J(w) = \frac{w^T S_B w}{w^T S_w w} \quad (2)$$

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

$$\Pr oportion\ of\ Trace = \frac{\lambda_i}{\sum j\lambda j} \quad (3)$$

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:

$$OA = \frac{Number\ of\ Correct\ \Pr edictions}{Total\ Number\ of\ \Pr edictions} \times 100 \quad (4)$$

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.

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.

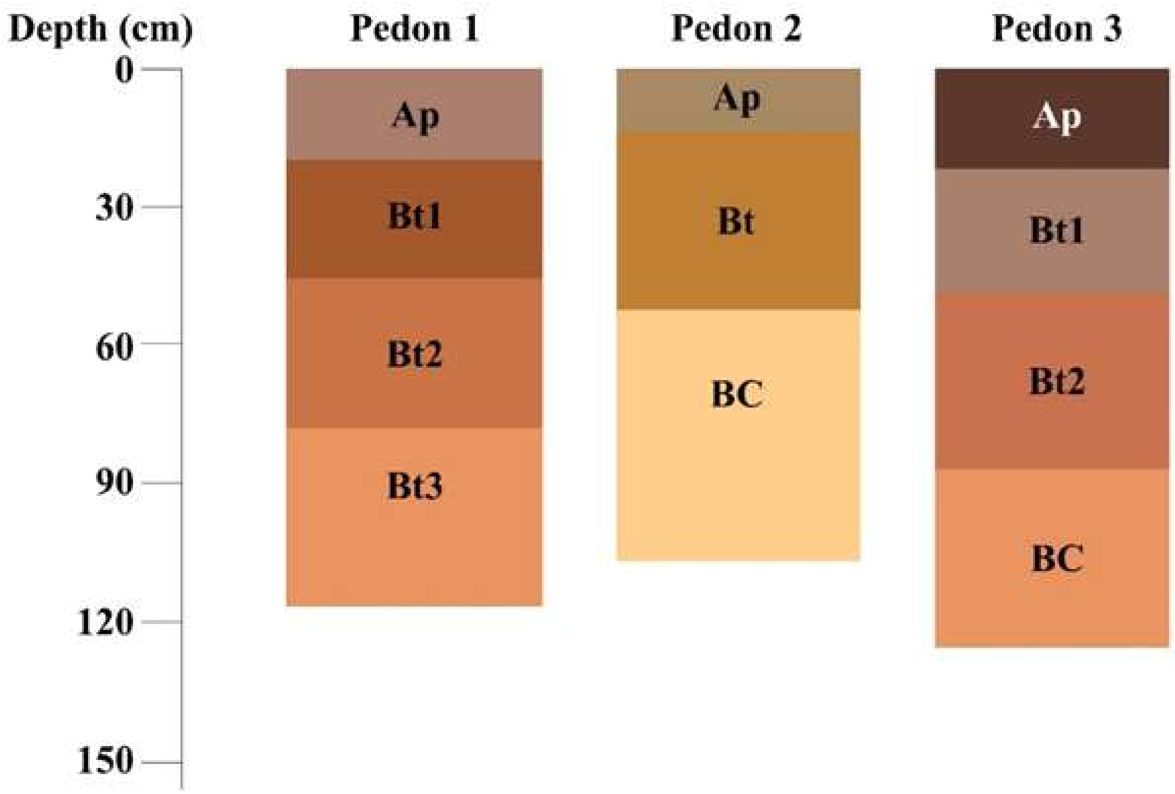

Fig. 2: Visual Representation of Horizon Colours and Thickness for the three Pedons

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 (fg) structure, which is characteristic of cultivated soils with higher organic matter, showing evidences of bioturbation. In contrast, the Bt horizons exhibited subangular blocky structures (msbk, fsbk). Horizon boundaries ranged from gradual (dg) to distinct (ds) and wavy (dw) 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. The clay content was lowest at 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 ratio (Si/C) was largely lower than 0.5 in most horizons, with the exception of 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 observed in the subsurface layers (range, 5.84–6.15) compared to the surface layers (range, 5.05–5.60). In all cases, the pH values in KCl were lower than those in water, resulting in negative ΔpH values, ranging from -0.20 to -0.85. Organic carbon (OC) was highest in the Ap horizon of P2 (15.40 g kg^{-1}), while total nitrogen (TN) was highest in surface horizons (0.70 – 1.31 g kg^{-1}) and declined with depth. Available phosphorus (av. P) ranged from 7.50 to 15.40 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}). The effective cation exchange capacity (ECEC) ranged from 9.61 to 10.99 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 (89.1 – 90.2%).

Table 3: Chemical Properties of the Pedons

Horizon	pH (H_2O)	pH (KCl)	ΔpH	OC ($g\ kg^{-1}$)	TN	AvP ($mg\ kg^{-1}$)	Ca ($cmol\ kg^{-1}$)	Mg	K	Na	TEB	EA	ECEC	BS (%)
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

Soil Classification

According to the USDA Soil Taxonomy, the presence of an argillic horizon evidenced by a significant increase in clay content relative to the surface horizon and high base saturation values (>35%) (Table 3) place all three pedons within the Alfisols order. At the suborder level, the semi-arid climatic conditions and a moderate soil moisture regime, inferred from morphological features such as the presence of 2.5YR and 7.5YR hues (Table 1), support classification under the *Ustic* moisture regime, identifying the pedons as *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 Lixisols 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.

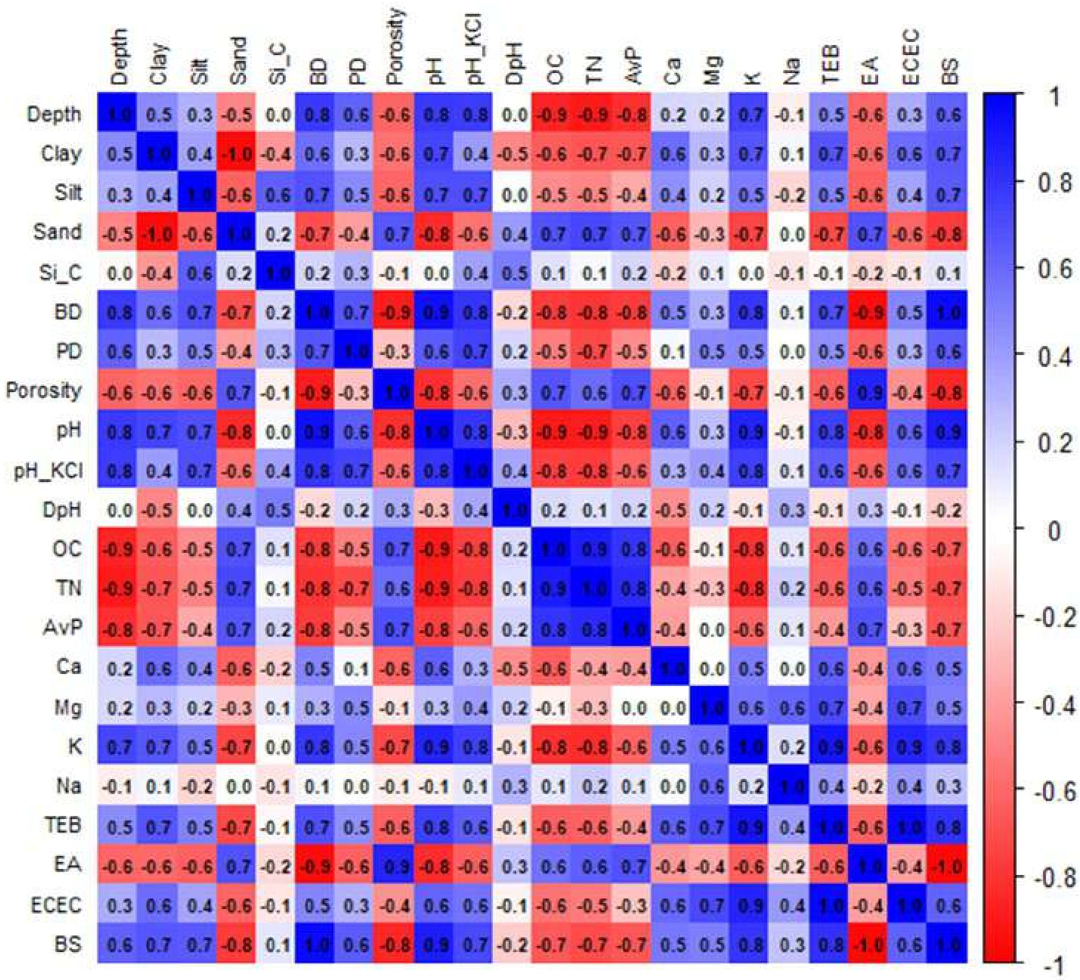

Fig. 3: Correlation heatmap of soil properties showing Pearson's correlation coefficients. Blue indicates positive correlations, while red represents negative correlations

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), indicating that higher pH levels enhance cation retention. A similar trend was observed between pH and exchangeable Ca (r = 0.7) and Mg (r = 0.6). Organic carbon (OC) exhibited a significant positive correlation with total nitrogen (TN) (r = 0.9) and available phosphorus (AvP) (r = 0.8), underscoring the role of organic matter in enhancing 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.

Linear Discriminant Analysis (LDA) of Soil Horizons

The Linear Discriminant Analysis (LDA) biplot (Fig. 4) illustrates the distribution of soil horizons along the first two linear discriminant (LD) axes, which account for 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.

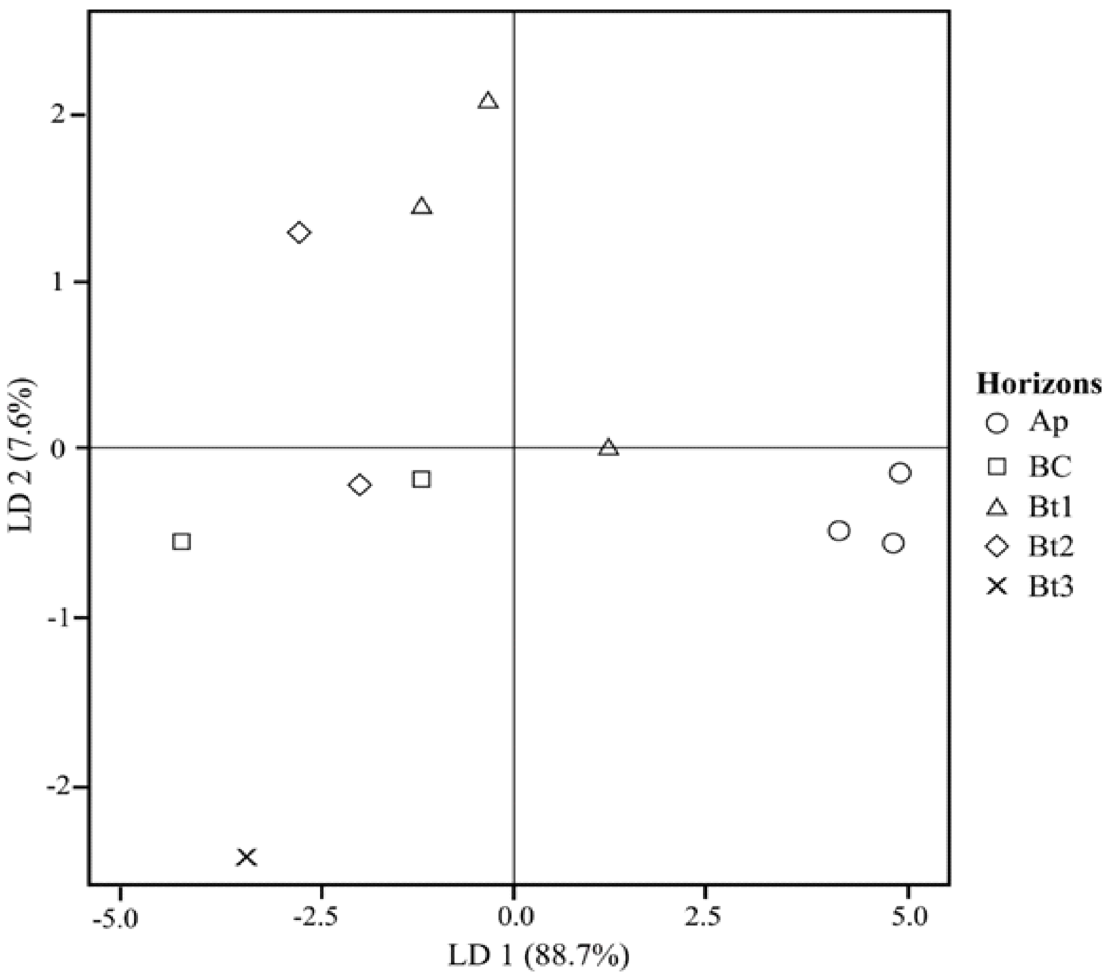

Fig. 4: Linear Discriminant Analysis biplot showing the distribution of soil horizons

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, emphasising 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, with no indication of restrictive layers - a characteristic typical of soils formed on planar geomorphic surfaces, where prolonged weathering occurs and surface erosion is minimal (Alem et al., 2015; Jimoh, 2021). In the Ap horizons, melanisation due to organic matter accumulation resulted in darker colours, corroborated by higher organic carbon content compared to subsurface layers (Table 3). Clay illuviation contributed to horizon-specific aggregation, as reflected in the variation of soil structure (Lopes et al., 2022). Increased aggregate strength and size in deeper horizons are consistent with the findings of Gilisanbe et al. (2017), who reported enhanced structural development with depth. Root distribution varied with depth, with common root presence in the Ap horizons of all pedons, highlighting the influence of biological activity in surface soil development, and a gradual decline in root abundance in deeper horizons. These morphological differences were quantitatively supported by the Linear Discriminant Analysis (LDA), where the Ap horizon was distinctly separated along LD1, primarily influenced by higher organic carbon and total nitrogen contents, as well as lower bulk density relative to subsurface horizonsThe 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 sandy loam (SL) texture observed in the Ap horizons of the pedons gradually transitions to sandy clay loam (SCL) in the subsurface horizons, indicating effective clay illuviation and accumulation. This textural differentiation reflects vertical translocation processes typical of horizon development in well-drained profiles(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 favoured. 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 widely used metric to indicate the intensity of weathering processes in soil (Ngongo & 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 (Fasina et al., 2015). 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 et al. (2018) 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 immobilised 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 4.03 to 4.22 cmol kg^{-1} and Mg ranging from 2.44 to 2.69 cmol kg^{-1} in surface horizons. These values suggest adequate base saturation (BSECEC), 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 a near-flat slope angle. The highest total exchangeable bases (TEB) values were observed in the Bt1 horizon of Pedon 1 (9.90 cmol kg^{-1}), which aligns with the relatively high clay content and soil structure in this horizon. The ECEC values ranged from 8.04 to 10.01 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). Notably, all three samples from the Ap horizons were correctly classified, underscoring their distinctiveness relative to subsurface horizons. This highlights the critical importance of conserving the Ap horizon, as its disturbance—through practices such as deep tillage or subsoiling may adversely affect soil structure and productivity. Similarly, the model achieved 100% classification accuracy for the Bt1 and Bt3 samples, further validating the discriminative strength of LDA in distinguishing morphologically and chemically differentiated soil horizons.

Table 5: Confusion matrix

Prediction \ Actual	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 confirm their distinctness in chemical and physical properties, likely due to their functional roles in the soil profile (e.g., Ap as the plough layer and Bt1 as a subsoil horizon). However, misclassification occurred between BC and Bt2 horizons, each having one incorrect prediction, reflecting 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 colour, horizon depth, and texture, with subsurface horizons showing signs of clay illuviation. The soils exhibited high base saturation, indicating a strong nutrient retention capacity; however, 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, emphasising the role of pedogenesis and land use in influencing soil properties in the area, which is critical for curating site-specific soil management practices to optimise agricultural productivity.

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Received: August, 2024 Accepted: October, 2024