



TOPOGRAPHIC INFLUENCE ON SOIL VARIABILITY AND AGRICULTURAL SUITABILITY ALONG A TOPOSEQUENCE IN NORTEASTERN NIGERIA

Ibrahim Z. Talha¹, I. Adamu¹, Ibrahim B. Buji¹

Department of Soil Science, Faculty of Agriculture, University of Maiduguri, Borno State,
Nigeria

*corresponding author: email: zannahtalha@gmail.com, +2348032455460,
+2349014684990

ABSTRACT

Knowledge of soil characteristics with respect to their slope position is fundamental for land evaluation and sustainable agricultural systems. Such variability will affect pedogenic processes, soil redistribution, and nutrient dynamics, thereby affecting land capability. The study examined soil morphological, physical, and chemical characteristics, as well as land capability. After profiling according to standard procedures, eight pedons were identified, and samples were collected from each pedon at upper-, middle-, and lower-slope positions on the landscape. Particle size, bulk density, soil reaction, organic carbon, total nitrogen, available phosphorus, and cation exchange capacity were analysed. Principal component analysis (PCA) was applied to identify dominant controls on soil variability, while land capability classification was conducted using the FAO Framework for Land Evaluation. Soil pH ranged from 6.17 to 6.81, indicating slightly acidic to neutral conditions suitable for crop production. However, organic carbon ($0.31\text{--}0.98\text{g kg}^{-1}$), total nitrogen ($0.01\text{--}0.32\text{g kg}^{-1}$), and available phosphorus ($0.35\text{--}10.85\text{mg kg}^{-1}$) were generally low, reflecting major fertility constraints. Principal component analysis (PCA) identified two principal components explaining 72% of the total variance. The PC1 represented a fertility gradient associated with clay, organic carbon, total nitrogen, and cation exchange capacity, while PC2 reflected soil physical quality, controlled mainly by sand content and bulk density. Upper slope soils were classified mainly as Capability Classes IIIe and IVe because of erosion susceptibility and low fertility, whereas lower slope soils were classified predominantly as Classes II and III. Therefore, land management strategies should be site-specific to promote sustainable land use.

Keywords: Land capability classification; principal component analysis; semi-arid soils; soil–landscape relationships; toposequence

INTRODUCTION

Interactions among climate, parent material, biota, time, and topography govern soil variability and pedogenesis. Among these soil-forming factors, topography exerts a particularly strong influence on the lateral redistribution of soil materials, including clay and organic matter, through processes of erosion, transport, and deposition. As a result, soil properties often vary systematically along slope positions, producing distinct toposequences or soil catenas that extend from erosional upper slopes to depositional lower landscape positions (Schaetzl and Thompson, 2015; Huggett and Shuttleworth, 2022; Yuan *et al.*, 2019). The relief-driven redistribution processes strongly influence soil development, nutrient dynamics, and fertility status, particularly within semi-arid agricultural landscapes where topographic controls on water movement and sediment transfer are pronounced.

Land capability assessment provides an important framework for evaluating the suitability, productive potential, and limitations of soils for sustainable agricultural use and environmental management. The FAO land evaluation framework offers a systematic basis for determining the extent to which land characteristics satisfy the ecological requirements of specific use through the integration of key soil physical, chemical, and topographic attributes influencing productivity and sustainability (FAO, 1976; FAO, 2022). Land capability is largely determined by soil depth, texture, drainage condition, nutrient availability, organic matter content, erosion susceptibility, and landscape position, all of which regulate water retention, nutrient cycling, root development, and crop performance (Hillel, 2004; Shukla, 2023).

Assessment of land characteristics along topographic gradients is particularly important because geomorphic processes operating across slope positions strongly influence the spatial variability of soil characteristics and fertility status (Schaetzl and Thompson, 2015; Omokaro, 2023). Toposequential variations significantly affect pedogenic development, nutrient dynamics, and agricultural capability within an agroecosystems (Begna, 2020; Daura *et al.*, 2023).

Soil fertility constraints remain among the major limitations to agricultural productivity in regions where soils are generally characterized by low organic matter content, rapid mineralization under high temperatures, and inadequate nutrient replenishment (Masso *et al.*, 2017; Nord *et al.*, 2022). Deficiencies in soil organic carbon and essential nutrients adversely

affect aggregate stability, water-holding capacity, and nutrient buffering functions, thereby constraining sustainable crop production (Bashir *et al.*, 2021; Ahmad *et al.*, 2025). Consequently, land capability evaluation provides a scientific basis for identifying soil limitations, guiding land-use planning, and developing appropriate soil management strategies for sustainable agricultural intensification in semi-arid regions.

In addition, the increasing complexity and dimensionality of soil datasets have strengthened the application of multivariate statistical techniques, particularly principal component analysis (PCA), for identifying the dominant factors controlling soil variability and simplifying the interpretation of interrelationships among soil properties (Abuzaid *et al.*, 2022; Tomaz *et al.*, 2022; Kosma *et al.*, 2022; Agegnehu *et al.*, 2024). These analytical approaches provide robust tools for evaluating soil variability and elucidating landscape-scale controls on soil fertility in semi-arid environments.

Against this background, the present study assessed land capability along a representative soil toposequence in northeastern Nigeria. Specifically, the objectives were to: (i) characterize soil characteristics along the toposequence; (ii) identify the principal factors controlling soil variability using PCA; and (iii) evaluate land capability of the study area.

MATERIALS AND METHODS

Study Area

The study was conducted in the University of Maiduguri, the capital of Borno State in northeastern Nigeria, within the Sahel ecological zone. The climate is semi-arid with a mean annual rainfall of 550–650 mm concentrated between June and September (NIMET, 2021). Mean annual temperatures exceed 30 °C, and potential evapotranspiration consistently exceeds precipitation. (Fig. 1). The landforms in the area are predominantly gently undulating plains and depositional basins underlain by the Chad Formation, which is composed largely of unconsolidated sands, silts, and clayey sediments (Daura *et al.*, 2023). From these deposits, soils have developed that are predominantly sandy loam, with generally low inherent fertility and a high susceptibility to wind and water erosion (Talha *et al.*, 2025). The study was conducted along a landscape transect forming a soil toposequence. Sampling locations were georeferenced using a handheld GPS.

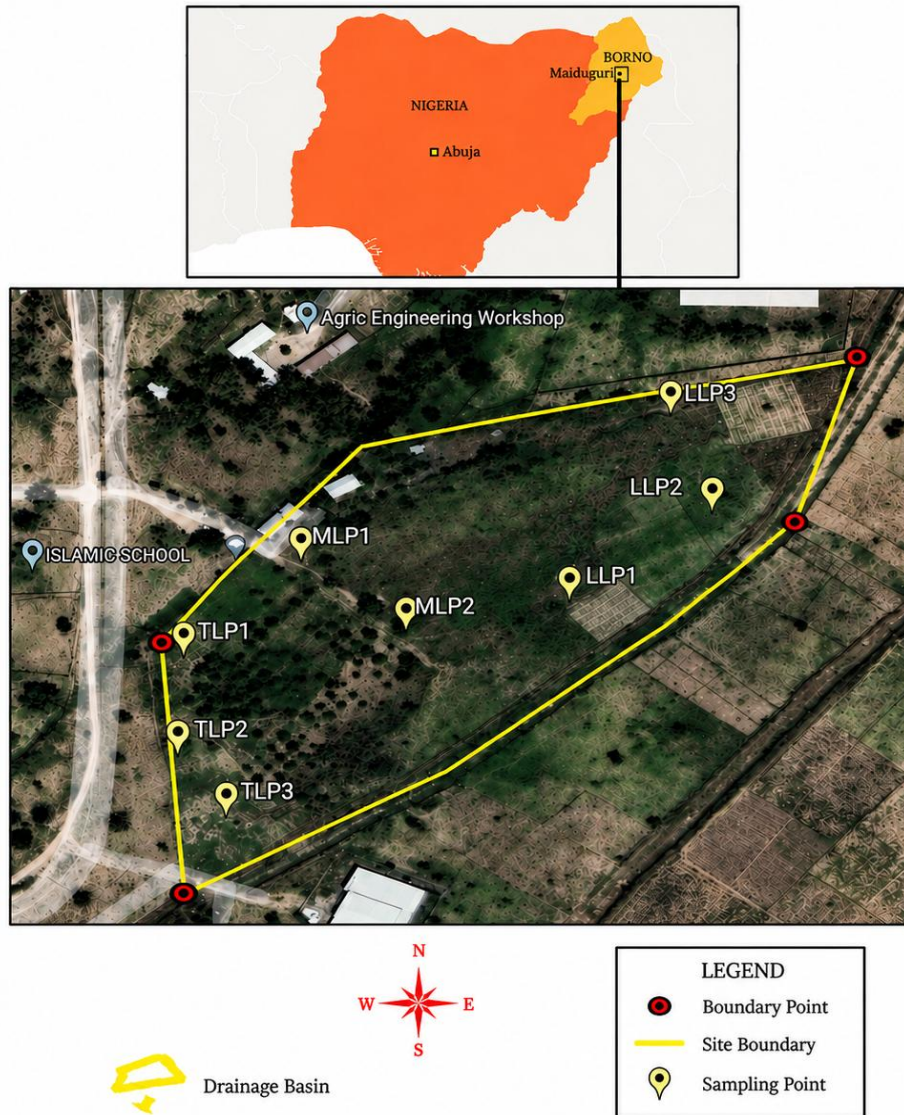


Fig. 1 Study area map showing the locations of sampling sites across the slope gradient.

Field Sampling and Soil Description

A representative toposequence with a gentle slope gradient (3–8%) was selected to examine soil variability across landscape positions. Following a reconnaissance survey, eight soil pedons were established along a transect. Three were located on the upper slope (TLP1–TLP3), two on the middle slope (MPL1–MPL2), and three on the lower slope (LLP1–LLP3). Pedon locations and slope segments were identified using standard soil survey procedures. Each pedon was described to a depth of 200 cm, or to a restrictive layer where encountered, in accordance with the FAO Guidelines for Soil Description (FAO, 2006). Soil colour was determined using the Munsell Soil Colour Charts.

Horizon-wise soil samples were collected from each pedon for laboratory analyses. In addition, undisturbed core samples were taken to determine bulk density and selected physical properties. All samples were properly labelled, sealed in polyethene bags, and transported to the laboratory for preparation and analysis.

Laboratory Analyses

Collected soil samples were air-dried at room temperature, gently crushed to break down aggregates, and passed through a 2-mm sieve to obtain the fine-earth fraction before laboratory analysis. The prepared samples were subsequently analysed for selected physical and chemical properties using standard soil analytical procedures.

Physical characteristics

Particle-size distribution (sand, silt, and clay fractions) was determined using the Hydrometer Method as described by Gee and Or (2002). Soil bulk density was measured using the Core Method following the procedure outlined by Grossman and Reinsch (2002). Soil textural classes were subsequently assigned based on the USDA Soil Textural Triangle.

Chemical characteristics

Soil pH was measured potentiometrically in a 1:2.5 soil–water suspension using a glass electrode pH meter. Soil organic carbon was determined using the Walkley–Black Method, while total nitrogen was analysed using the Kjeldahl Method as described by Bremner and Mulvaney (1982).

Available phosphorus (Bray 2) was extracted using the Method developed by Bray and Kurtz (1945). Exchangeable bases (calcium, magnesium, potassium, and sodium) were extracted and analysed using 1 M ammonium acetate (NH_4OAc) at pH 7.0. Cation exchange capacity (CEC) was determined with ammonium acetate, and base saturation was calculated as the ratio of total exchangeable bases to CEC.

Data Analysis

Principal component analysis (PCA) was performed in R version 4.4.1 (R Foundation for Statistical Computing, Vienna, Austria) using the FactoMineR package for multivariate analysis and the factoextra package for visualisation. Before analysis, the mean of the three replicate measurements for each of the 32 soil samples collected from the four pedons was calculated and used for statistical analysis. All variables were standardised to zero mean and unit variance (z-score transformation) to remove the effects of differing measurement scales. PCA was performed on the correlation matrix, and principal components with eigenvalues > 1.0 (Kaiser's criterion) were retained for interpretation. Variable loadings were used to

identify the soil properties contributing most strongly to each principal component, while score plots were used to evaluate similarities and differences among pedons and genetic horizons.

Land Capability Classification

Land capability classification (LCC) was done as described by Klingebiel and Montgomery (1961), which classifies land based on its suitability for sustained agricultural use. Characterised soils were classified using key physical and chemical characteristics. These included soil depth, texture, drainage, slope gradient, erosion risk, and fertility indicators such as organic carbon, total nitrogen, and cation exchange capacity. Based on these assessments, each pedon was classified into a capability class (I–VIII) according to the severity of production limitations.

RESULTS AND DISCUSSION

Soil Morphological Characteristics

Soil profile descriptions revealed distinct horizon sequences and colour variations across the toposequence, indicating strong topographic control on pedogenic processes (Table 1).

Table 1: Selected soil morphological and physical characteristics of the study area

Horizon	Depth (cm)	Sand (g kg ⁻¹)	Silt (g kg ⁻¹)	Clay (g kg ⁻¹)	Texture Class	Colour (Moist)	Bulk Density (Mg m ⁻³)
Pedon 1 (TLP1)							
Ap	0–32	620	230	150	sandy loam	7.5YR 6/3	1.33
AB	32–61	550	280	180	sandy loam	7.5YR 5/3	1.32
Bw1	61–119	450	380	180	loam	7.5YR 5/4	1.12
Bw2	119–200	450	350	200	loam	7.5YR 4/2	1.23
Pedon 2 (TLP2)							
Ap	0–40	500	350	150	loam	7.5YR 5/4	1.33
AB	40–134	470	350	180	loam	7.5YR 6/3	1.27
Bw1	134–155	450	380	180	loam	7.5YR 7/6	1.25
Bw2	155–200	570	230	200	sandy loam	7.5YR 7/8	1.33
Pedon 3 (TLP3)							
Ap	0–50	320	520	160	silt loam	7.5YR 6/4	1.20
Bw1	50–88	520	300	180	loam	7.5YR 6/3	1.23

Horizon	Depth (cm)	Sand (g kg⁻¹)	Silt (g kg⁻¹)	Clay (g kg⁻¹)	Texture Class	Colour (Moist)	Bulk Density (Mg m⁻³)
Bw2	88–131	570	250	180	sandy loam	7.5YR 7/6	1.19
C	131–200	550	250	200	sandy loam	7.5YR 7/8	1.16
Pedon 4 (MPL1)							
Ap	0–34	550	270	180	sandy loam	10YR 5/4	1.32
Bw1	34–111	470	380	150	loam	7.5YR 6/3	1.35
Bw2	111–138	400	450	150	loam	7.5YR 8/2	1.20
Bw3	138–200	570	250	180	sandy loam	7.5YR 7/2	1.21
Pedon 5 (MPL2)							
Ap	0–34	650	170	180	sandy loam	7.5YR 6/4	1.39
Bw1	34–75	620	200	180	sandy loam	7.5YR 7/4	1.35
Bw2	75–123	600	270	130	sandy loam	10YR 6/6	1.32
Bw3	123–167	570	300	130	sandy loam	7.5YR 7/4	1.30
Bw4	167–200	420	430	150	loam	7.5YR 8/2	1.29
Pedon 6 (LLP1)							
Ap	0–30	570	250	180	sandy loam	7.5YR 5/3	1.33
Bw1	30–60	470	350	180	loam	7.5YR 6/3	1.22
Bw2	60–119	420	350	230	loam	7.5YR 6/4	1.13
Bw3	119–200	320	480	200	loam	7.5YR 8/6	1.26
Pedon 7 (LLP2)							
Ap	0–65	570	250	180	sandy loam	7.5YR 5/3	1.33
Bw1	65–160	450	330	220	loam	7.5YR 6/8	1.27
Bw2	160–200	440	380	180	loam	7.5YR 7/8	1.25
Pedon 8 (LLP3)							
Ap	0–70	550	250	200	sandy loam	7.5YR 6/3	1.20
Bw1	70–110	570	200	180	sandy loam	7.5YR 6/4	1.23
Bw2	110–140	600	220	180	sandy loam	7.5YR 6/3	1.19
Bw3	140–200	520	300	180	loam	7.5YR 7/6	1.16

Upper slope (TLP1–TLP3), Middle slope (MPL1–MPL2), and lower slope (LLP1–LLP3).

Soils on the upper slope were generally shallow with weakly developed horizons, likely due to continuous erosion and limited pedogenic development. At the mid- and lower-slope positions were deeper and more horizonated, which shows greater geomorphic stability and

progressive accumulation of transported materials along the landscape. These morphological differences are characteristic of classical soil catena development, in which erosion predominates on upper slope positions while depositional processes dominate lower slope areas (FAO, 2022).

Surface horizons exhibited relatively darker colours, including 7.5YR 5/3, 7.5YR 5/4, 7.5YR 6/3, 7.5YR 6/4 and 10YR 5/4, attributable to greater organic matter accumulation and enhanced biological activity within the epipedon. In the subsurface horizons, there were brighter and paler colours such as 7.5YR 6/3, 7.5YR 7/4 and related hues, showing reduced organic carbon content (Table 2) and a greater proportion of mineral constituents (Gerasimova and Lebedeva, 2018). Moist soil colours were predominantly characterised by 7.5YR hues with values and chromas ranging from 4/2 to 8/6, indicating variations in organic matter content, drainage conditions and iron oxide distribution. Darker, moist colours, such as the 7.5YR 4/2 horizon in Pedon 1, may be associated with relatively higher organic carbon accumulation and moisture retention as observed during the field study, whereas the occurrence of pale colours, particularly 7.5YR 7/8 and 8/2 in deeper horizons, suggests low organic matter status and oxidation under well-drained conditions (Schaetzl and Thompson, 2015).

Surface horizons were predominantly sandy loam, while subsurface horizons ranged from sandy loam to loam, suggesting limited profile differentiation and weak horizon development. Particle-size distribution showed variations along the toposequence as influenced by slope position. Sand fractions generally dominated the profiles, particularly in Pedons 1, 5 and 8, where values exceeded 550 g kg^{-1} in most horizons. The silt and clay fractions increased downslope, consistent with the findings of Begna (2020). This trend suggests selective removal of fine particles from upper slope positions through erosion and their subsequent deposition in lower landscape units. Such redistribution of soil materials is characteristic of catena systems, where slope gradient strongly controls sediment transport and depositional processes (Omokaro, 2023).

Bulk density values ranged from 1.12 to 1.39 Mg m^{-3} across the pedons studied. Lower bulk density values observed in some upper-slope and subsurface horizons, particularly in Pedons 1 and 6, may be attributed to greater pore development, relatively higher organic carbon content (Table 2) and increased fine fraction accumulation (Table 1), all of which favour aggregation and structural stability. In comparison, higher bulk density values recorded in the middle-slope positions and in the surface horizons of Pedon 5 likely reflect compaction,

surface crusting and dominance of coarse-textured materials associated with repeated cultivation and reduced organic matter return, conditions commonly reported in semi-arid agricultural soils (Shukla, 2023).

Soil Chemical Characteristics

The soil chemical characteristics exhibited systematic variation along the topographic sequence from the upper slope to the lower slope. Soil pH values ranged from 6.17 to 6.81 (slightly acidic to nearly neutral) across the eight pedons (Table 2).

Table 2: Selected soil chemical characteristics of the study area

Horizon	Depth (cm)	pH (H ₂ O)	OC (g kg ⁻¹)	TN (g kg ⁻¹)	AP (mg kg ⁻¹)	CEC (cmolc kg ⁻¹)
Pedon 1 (TLP1)						
Ap	0–32	6.77	0.98	0.10	8.05	33.64
AB	32–61	6.80	0.55	0.07	5.25	26.48
Bw1	61–119	6.79	0.49	0.04	9.45	23.52
Bw2	119–200	6.81	0.41	0.10	4.82	17.48
Pedon 2 (TLP2)						
Ap	0–40	6.80	0.90	0.03	7.70	20.63
AB	40–134	6.71	0.62	0.06	8.05	20.16
Bw1	134–155	6.62	0.62	0.11	1.05	14.65
Bw2	155–200	6.46	0.43	0.14	2.10	12.30
Pedon 3 (TLP3)						
Ap	0–50	6.64	0.70	0.11	3.15	17.88
Bw1	50–88	6.59	0.41	0.15	1.75	23.25
Bw2	88–131	6.55	0.70	0.10	2.10	17.83
C	131–200	6.51	0.60	0.06	8.40	10.35
Pedon 4 (MPL1)						
Ap	0–34	6.40	0.78	0.06	8.40	25.84
Bw1	34–111	6.50	0.68	0.01	0.35	19.17
Bw2	111–138	6.40	0.68	0.07	3.85	16.68
Bw3	138–200	6.50	0.70	0.14	5.60	10.74
Pedon 5 (MPL2)						
Ap	0–34	6.30	0.82	0.10	4.90	15.15
Bw1	34–75	6.50	0.31	0.06	5.25	12.36
Bw2	75–123	6.50	0.70	0.06	9.45	13.77
Bw3	123–167	6.50	0.60	0.08	8.75	10.84

Horizon	Depth (cm)	pH (H ₂ O)	OC (g kg ⁻¹)	TN (g kg ⁻¹)	AP (mg kg ⁻¹)	CEC (cmolc kg ⁻¹)
Bw4	167–200	6.40	0.74	0.11	8.05	11.22
Pedon 6 (LLP1)						
Ap	0–30	6.33	0.84	0.13	10.85	16.58
Bw1	30–60	6.40	0.70	0.21	1.05	15.76
Bw2	60–119	6.38	0.70	0.17	6.30	15.05
Bw3	119–200	6.32	0.72	0.24	3.85	13.90
Pedon 7 (LLP2)						
Ap	0–65	6.31	0.86	0.32	3.50	24.22
Bw1	65–160	6.20	0.55	0.25	1.75	19.63
Bw2	160–200	6.41	0.72	0.15	1.05	14.78
Pedon 8 (LLP3)						
Ap	0–70	6.43	0.84	0.25	8.05	13.07
Bw1	70–110	6.17	0.77	0.32	0.70	19.30
Bw2	110–140	6.39	0.92	0.31	1.40	16.69
Bw3	140–200	6.37	0.92	0.27	2.10	17.94

This pH range is generally considered favourable for most agricultural crops because nutrient availability is typically optimal under moderately acidic to neutral soil conditions, where essential plant nutrients remain readily available for uptake (Guo *et al.*, 2024a). Surface horizons (Ap) generally recorded slightly higher pH values than the underlying subsurface horizons, although no pronounced soil acidity constraint was observed throughout the profiles.

Organic carbon (OC) contents were generally low in all pedons, ranging from 0.31 to 0.98g kg⁻¹. Relatively higher OC contents were predominantly recorded in the surface horizons, notably in Pedon 1 (0.98g kg⁻¹), Pedon 2 (0.90g kg⁻¹), and Pedon 8, where elevated values (0.92g kg⁻¹) also occurred within subsurface horizons. The observed decline in OC with increasing depth in most profiles may be attributed to a decrease in organic matter input, limited incorporation of plant residues, and diminished biological activity in subsurface layers. Studies have been reported for agricultural soils, where surface accumulation of soil organic carbon is strongly influenced by biological activity and residue deposition (Wells *et al.*, 2022). The generally low OC status suggests poor accumulation of organic matter, which may negatively affect soil aggregation, nutrient retention, and water-holding capacity.

Total nitrogen (TN) contents followed a distribution pattern alike to that of organic carbon, with values ranging from 0.01 to 0.32g kg⁻¹ across the pedons. The upper and middle slope

positions were characterized by very low TN contents ($0.01\text{--}0.11\text{ g kg}^{-1}$), whereas relatively higher values ($0.15\text{--}0.32\text{ g kg}^{-1}$) were recorded in the lower slope pedons (LLP). The increase in TN content downslope may be attributed to the translocation and subsequent accumulation of nitrogenous materials and organic matter along the slope gradient. The close correspondence between TN and organic carbon distributions further highlights the strong dependence of soil nitrogen reserves on soil organic matter dynamics. Comparable relationships between soil organic matter accumulation and nitrogen distribution in soils have been reported by Ferraz-Almeida (2024). Despite the relatively higher TN contents in the lower slope pedons, the overall nitrogen status of the soils remained low, indicating limited native nitrogen reserves that may constrain crop growth and productivity. Rapid mineralisation and decomposition of organic matter under high temperature conditions often contribute to nitrogen depletion. Such conditions are characteristic of many Sahelian agroecosystems, where maintaining adequate soil fertility remains a major challenge (Masso *et al.*, 2017; Nord *et al.*, 2022).

Available phosphorus (AP) contents exhibited considerable variability across the pedons, ranging from 0.35 to 10.85 mg kg^{-1} . In general, AP levels were low throughout the profiles (Esu, 1991). Higher AP concentrations were commonly observed in the Ap horizons of Pedons 1, 2, 4, 6, and 8, which may be associated with surface accumulation of organic residues and possible fertilizer additions. Conversely, extremely low AP values recorded in several Bw horizons, including Pedon 4 Bw1 (0.35 mg kg^{-1}), Pedon 6 Bw1 (1.05 mg kg^{-1}), and Pedon 8 Bw1 (0.70 mg kg^{-1}), suggest substantial phosphorus fixation and reduced phosphorus bioavailability. This observation is consistent with the findings of Mabagala and Mng'ong'o (2022) and Zhao *et al.* (2023). These findings therefore indicate that phosphorus may constitute a major limiting nutrient within several subsurface horizons.

Cation exchange capacity (CEC) values ranged from 10.35 to $33.64\text{ cmolc kg}^{-1}$, indicating medium to high nutrient retention capacity across the pedons as per the Esu rating scale. The highest CEC value was recorded in the Ap horizon of Pedon 1 ($33.64\text{ cmolc kg}^{-1}$), whereas the lowest occurred in the C horizon of Pedon 3 ($10.35\text{ cmolc kg}^{-1}$). In most profiles, CEC decreased with depth, corresponding with reductions in organic matter content and possibly clay distribution. Decreases in CEC with declining soil organic matter and clay fractions have been reported by Costa *et al.* (2020) and Antonangelo *et al.* (2024). Despite the generally low OC contents, the moderate-to-high CEC values suggest that the soils possess an appreciable capacity to retain exchangeable bases and plant nutrients.

Principal Component Analysis of Soil Characteristics (PCA)

The PCA biplot illustrates the distribution of soil characteristics and sampling positions across the study area. Principal component analysis (PCA) identified two primary components that together explained 72% of the variance in soil properties along the toposequence (Table 3 and Fig. 2).

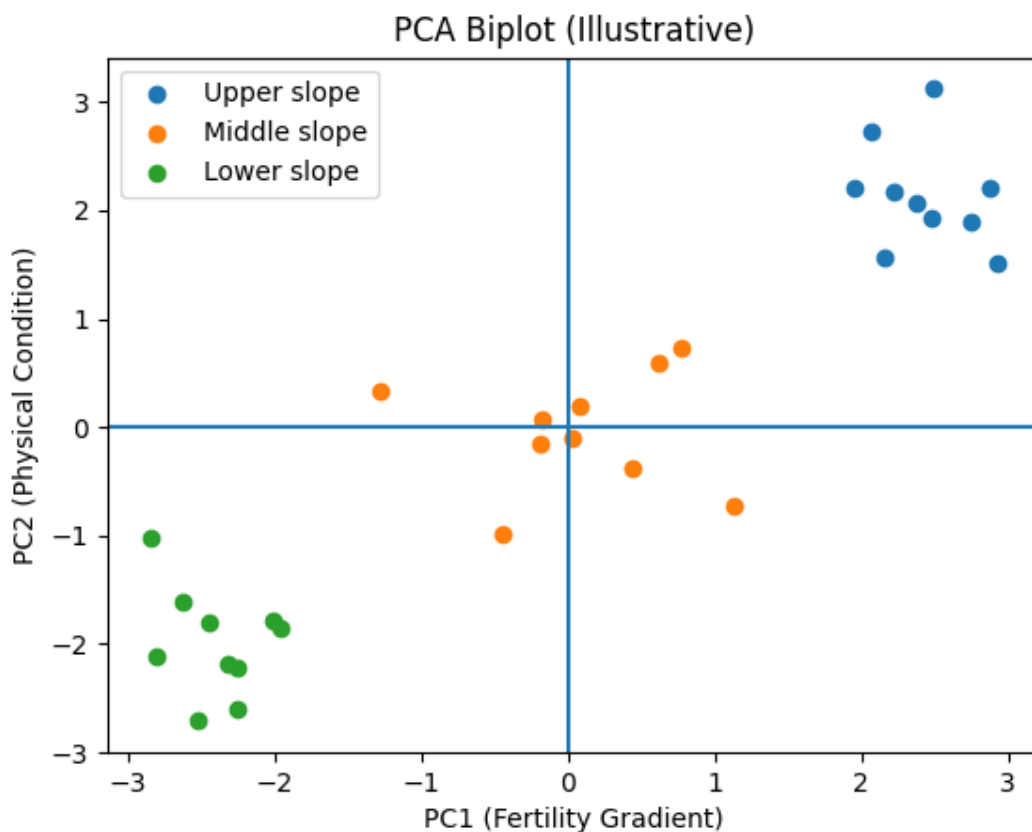


Fig. 2: Principal component analysis (PCA) biplot showing the distribution of soil samples along fertility (PC1) and physical (PC2) gradients. Upper-slope soils cluster with sand and bulk density, while lower-slope soils align with clay content and cation exchange capacity, indicating enhanced fertility in depositional zones.

PC1 explains 46% of the changes in the soil. It is linked to clay, organic carbon, total nitrogen, and cation exchange capacity (CEC). Sand shows the opposite pattern. In simple terms, PC1 shows soil fertility. As you move down the slope, more fine particles and organic matter collect. This helps the soil hold more nutrients and improves fertility in lower areas (Schaetzl and Thompson, 2015).

PC2 explains 26% of the changes. It is mainly controlled by sand and bulk density. These affect how water and air move in the soil. Sandy soils drain water quickly but do not hold much water or nutrients. Soils with high bulk density adversely affect moisture retention and plant growth (Shukla, 2023).

Table 3: Principal component loadings of selected soil properties, eigenvalues, and percentage variance explained

Variable	PC1	PC2
Clay	0.82	-0.21
CEC	0.78	-0.12
Organic C	0.75	0.10
Sand	-0.81	0.28
Bulk density	-0.30	0.71

Land Capability Assessment

Land capability classification was conducted using selected topographic, morphological, physical, and chemical soil attributes considered critical for sustained agricultural productivity. The assessment followed the principles of the FAO Framework for Land Evaluation and the USDA Land Capability Classification system. Diagnostic criteria included slope gradient, effective soil depth, surface texture, bulk density, drainage condition, erosion susceptibility, soil reaction, organic carbon, total nitrogen, available phosphorus, and cation exchange capacity (CEC). These parameters are widely recognized as key indicators of soil quality, nutrient retention, rooting conditions, and long-term agricultural sustainability (FAO, 2022; Guo *et al.*, 2024b).

Table 4. Criteria used for land capability assessment of the study area

Land characteristic	Unit	Slight limitation	Moderate limitation	Severe limitation	Major agricultural implication
Slope gradient	%	0–2	3–5	>5	Increased runoff, erosion hazard, and cultivation difficulty
Effective depth	soil cm	>150	100–150	<100	Restriction to rooting depth and water storage capacity
Surface texture	—	loam–sandy loam	sandy loam	sand	Reduced nutrient and moisture retention
Bulk density	Mg m ⁻³	<1.30	1.30–1.40	>1.40	Root restriction, compaction, and reduced infiltration
Organic carbon	g kg ⁻¹	>1.0	0.5–1.0	<0.5	Decline in aggregation, nutrient reserve, and moisture retention
Total nitrogen	g kg ⁻¹	>0.15	0.08–0.15	<0.08	Nitrogen deficiency and reduced crop productivity
Available phosphorus	mg kg ⁻¹	>10	5–10	<5	Phosphorus limitation and impaired root development
Cation exchange capacity	cmolc kg ⁻¹	>25	15–25	<15	Reduced nutrient retention capacity
Drainage condition	—	well drained	moderately drained	poorly/excessively drained	Aeration or moisture stress limitations
Erosion susceptibility	—	low	moderate	high	Increased soil loss and land degradation risk

Source: Adapted from the FAO Framework for Land Evaluation and USDA Land Capability Classification guidelines

Table 5. Interpretation of land capability classes used in the study

Capability class	Interpretation	Dominant limitations	Recommended use and management
Class I	Very good arable land with minimal limitations for sustained cultivation	None or very slight limitations	Suitable for a wide range of crops under conventional management
Class II	Moderately good arable land with moderate limitations	Moderate erosion risk, slight fertility decline, or moderate textural constraints	Suitable for regular cultivation with moderate conservation practices
Class III	Arable land with severe limitations restricting crop choice	Erosion hazard, coarse texture, low fertility, shallow rooting depth, or compaction	Requires intensive fertility and erosion management
Class IV	Marginal arable land with very severe limitations	Severe erosion susceptibility, poor nutrient status, shallow profile development, or excessive sandiness	Suitable only for occasional or carefully managed cultivation
Class V	Non-arable land with limited erosion risk	Wetness, stoniness, flooding, or other non-erosive limitations	Suitable mainly for grazing or forestry
Class VI	Non-arable land with severe limitations	Steep slopes, severe erosion risk, or shallow soils	Restricted to grazing, forestry, or wildlife use
Class VII	Land with very severe limitations	Extreme erosion hazard or severe degradation	Restricted to conservation and watershed protection
Class VIII	Land unsuitable for commercial plant production	Extremely severe environmental limitations	Suitable only for recreation or wildlife conservation

Table 6. Interpretation of land capability subclasses

Subclass	Interpretation
e	Erosion limitation associated with slope gradient, runoff, and soil loss risk
s	Soil limitation including shallow depth, coarse texture, low fertility, compaction, or poor rooting conditions
w	Wetness or drainage limitation resulting from poor aeration or periodic saturation
c	Climatic limitation related to moisture deficit, temperature, or growing season constraints

Land Capability Evaluation of the study area

The land capability evaluation revealed marked spatial variability in soil quality and agricultural potential across the studied toposequence, emphasizing the strong influence of topography on pedogenic processes, sediment redistribution, and nutrient dynamics within the semi-arid landscape. Variations in morphological, physical, and chemical properties across the slope continuum significantly influenced the nature and severity of land-use limitations observed among the different landscape positions. These findings are consistent with established pedological principles indicating that topographic position exerts substantial control over soil formation, hydrological behaviour, and long-term fertility evolution in catena systems (Schaetzl and Thompson, 2015; FAO, 2022).

The slope gradient of 3–8% represents gently undulating terrain with moderate susceptibility to runoff and erosion. Although the slopes are not excessively steep, upper slope positions exhibited evidence of selective removal of fine particles and organic matter, resulting in coarser surface textures and reduced fertility status. Similar topographic influences on soil redistribution and fertility decline have been widely reported in semi-arid environments where erosion preferentially transports fine particles and nutrients downslope (Begna, 2020; Omokaro, 2023).

Effective soil depth across the pedons exceeded 130 cm and extended to approximately 200 cm without major restrictive horizons. Such deep profiles provide favourable rooting environments and enhance soil water storage capacity, thereby improving resilience to short-term moisture stress under semi-arid conditions (Shukla, 2023). Thus, soil depth did not constitute a major limitation to agricultural capability within the study area.

Soil texture varied systematically along the toposequence and exerted a strong influence on moisture retention and nutrient dynamics. Sandy loam textures dominated the upper slope positions, whereas relatively finer-textured loam horizons occurred downslope. Coarse-textured soils are typically associated with rapid drainage, low water-holding capacity, and weak nutrient retention, characteristics that frequently constrain crop productivity in dryland agro ecosystems (Naorem *et al.*, 2023), in contrast to finer-textured at lower slope positions. Principal component analysis strongly supported this interpretation, with clay showing a strong positive loading on PC1 (0.82), while sand exhibited a strong negative loading (-0.81), confirming particle-size distribution as a major determinant of soil fertility variation across the landscape.

Bulk density values ranged from 1.12 to 1.39 Mg m⁻³. Higher values recorded particularly in Pedon 5 suggest with possible surface crusting associated with repeated cultivation and low organic matter return. Lower bulk density values observed within several lower slope horizons likely reflect improved aggregation associated with greater accumulation of clay and organic matter. The strong positive loading of bulk density on PC2 (0.71) further demonstrates its importance in regulating soil physical quality and root development.

Soil reaction was generally favourable throughout the profiles, with pH values ranging from 6.17 to 6.81. These slightly acidic to nearly neutral conditions are considered suitable for nutrient availability and microbial activity in most tropical agricultural systems (Guo *et al.*, 2024b). Consequently, soil pH did not represent a major limitation to crop production within the study area.

Despite the favourable pH conditions, soil fertility was constrained by generally low organic carbon and total nitrogen contents (Nord *et al.*, 2022). Organic carbon exhibited a strong positive loading on PC1 (0.75), emphasizing its central role in controlling nutrient retention, aggregation, and overall soil quality.

Available phosphorus contents were generally low to moderate and highly variable among horizons. Extremely low phosphorus levels recorded within several subsurface horizons suggest phosphorus fixation and reduced bioavailability, conditions commonly reported in tropical and semi-arid soils (Zhao *et al.*, 2023). Phosphorus deficiency therefore represents a significant fertility constraint likely to limit sustained crop productivity without external nutrient supplementation.

Higher CEC values observed within some upper and lower slope horizons likely reflect contributions from clay fractions and residual organic matter. The positive loading of CEC on PC1 (0.78) further highlights its importance in defining fertility variation across the toposequence.

The upper slope pedons (TLP1–TLP3) were characterized by weak horizon differentiation, coarse-textured surface horizons, and generally low inherent fertility. Morphological evidence of active erosion, including limited accumulation of fine particles and organic matter, indicates persistent removal of surface materials through runoff and sediment

Table 7. Summary of land capability limitation levels in the study area

Land quality/characteristic	Diagnostic criteria	observed	Condition in study area	Limitation level
Climate (rainfall)	550–650 mm annual rainfall		Semi-arid rainfall regime suitable mainly for drought-tolerant crops	Moderate
Temperature regime	Mean temperature >30 °C	annual	High evapotranspiration and rapid organic matter decomposition	Moderate
Slope gradient	3–8%		Gentle undulating terrain with moderate erosion susceptibility	Moderate
Erosion hazard	Evidence of upslope particle removal and downslope deposition		Upper slopes vulnerable to erosion	Moderate
Drainage	Well-drained profiles		Good aeration and minimal waterlogging risk	Slight
Effective soil depth	Profiles extend to ~200 cm		Deep rooting zone and high storage capacity	Slight
Texture	Sandy loam to loam		Sandy upper slopes and finer lower slopes	Moderate
Bulk density	1.12–1.39 Mg m ⁻³		Moderate compaction in middle slopes	Moderate
Water-holding capacity	Influenced by sandy texture		Low to moderate moisture retention	Moderate
Soil reaction (pH)	6.17–6.81		Slightly acidic to neutral	Slight
Organic carbon	0.31–0.98g kg ⁻¹		Very low organic matter reserves	Severe
Total nitrogen	0.01–0.32g kg ⁻¹		Generally nitrogen deficient	Severe
Available phosphorus	0.35–10.85mg kg ⁻¹		Low to moderate phosphorus availability	Moderate–Severe
CEC	10.35–33.64cmolc kg ⁻¹		Moderate nutrient retention capacity	Slight–Moderate
Pedogenic development	Weak to moderate horizon differentiation		Better profile development downslope	Moderate
Landscape position	Upper, middle, and lower slopes		Fertility and clay increase downslope	Variable

transport. Organic carbon and total nitrogen contents were uniformly low, while cation exchange capacity declined progressively with depth. Collectively, these characteristics indicate soils with limited nutrient reserves, low moisture-retention capacity, and weak structural stability. Therefore, the upper slope soils were classified predominantly within

Capability Classes IIIe and IVe due to severe erosion hazards, coarse texture, and low fertility status.

The middle slope pedons (MPL1–MPL2) showed intermediate morphological and fertility characteristics. Although the profiles were generally deeper and more developed than those of the upper slope, sandy loam textures remained dominant. Bulk density values were comparatively higher, particularly in Pedon 5, confirming surface crusting associated with repeated cultivation and reduced organic matter incorporation as observed earlier during field work. Available phosphorus remained highly variable and frequently deficient within subsurface horizons. These soils were therefore assigned mainly to Capability Classes IIIs and IIIe, reflecting moderate erosion susceptibility, compaction, and fertility-related limitations.

The lower-slope pedons (LLP1–LLP3) were showed to have comparatively more favourable conditions for agricultural production. These soils were generally deeper, more structurally developed, and characterized by greater accumulation of silt and clay fractions. Depositional enrichment of fine particles likely contributed to improved aggregate stability, enhanced nutrient-retention capacity, and greater moisture storage. Total nitrogen contents were relatively higher within these pedons, while lower bulk density values indicated improved porosity and root penetrability. Despite these advantages, low organic matter reserves and phosphorus deficiency remained important limitations. So, the lower-slope soils were classified mainly within Capability Classes II and III, indicating moderate suitability for sustained arable cultivation with appropriate fertility and conservation management.

The principal component analysis further clarified the dominant factors controlling soil variability and land capability across the landscape. PC1, which explained 46% of the total variance, represented a fertility and pedogenic development gradient strongly associated with clay, organic carbon, total nitrogen, and cation exchange capacity. PC2, which accounted for 26% of the variance, reflected the influence of soil physical properties, particularly sand content and bulk density, on water movement, aeration, and root development. The PCA therefore confirms that both fertility-related and physical limitations jointly regulate land capability across the studied toposequence.

Table 8: Summary of soil characteristics and land capability across topographic positions

Topographic position	Dominant characteristics	Principal limitations	Land Capability Class
Upper (TLP1–TLP3)	Weakly developed, coarse-textured soils with low OC, TN, and CEC; texture, low moisture retention and structural stability; evidence of active erosion	Severe erosion, coarse texture, low fertility	IIIe–IVe
Middle (MPL1–MPL2)	Moderately developed sandy loam soils with relatively high bulk density and variable available P	Moderate surface compaction, P deficiency, moderate fertility constraints	IIIc–IIIe
Lower (LLP1–LLP3)	Deep, well-developed soils with silt and clay; improved aggregate stability, nutrient retention, moisture storage, and lower bulk density	Low organic matter and P deficiency	II–III

Abbreviations: OC = organic carbon; TN = total nitrogen; CEC = cation exchange capacity; P = available phosphorus.

Hence, the capability assessment established a clear downslope improvement in soil quality and agricultural suitability. This confirmed the dominant influence of topography on erosion intensity, sediment redistribution, nutrient accumulation, and pedogenic development. The principal land-use limitations identified in the study area include erosion susceptibility, coarse texture, low organic matter status, nitrogen deficiency, phosphorus limitation, and moderate compaction.

Conclusions

The study shows that landscape position strongly shapes soil development, fertility distribution and land capability within the study area. Erosion and runoff on upper slopes, combined with deposition in lower areas, create clear differences in soil quality and how the

land can be managed. Principal component analysis confirmed that soil variability was governed mainly by fertility-related properties, particularly clay, organic carbon, total nitrogen, and cation exchange capacity, together with physical characteristics associated with sand content and bulk density. Land capability evaluation showed a progressive improvement in agricultural suitability downslope, although soil reaction was generally favourable, low organic carbon, nitrogen deficiency, and limited phosphorus availability remain major constraints. To use these soils sustainably, integrated management is essential. This includes improving organic matter levels, applying balanced fertilisation, and strengthening soil and water conservation practices.

REFERENCES

- Abuzaid, A.S., Mazrou, Y.S., El Baroudy, A.A., Ding, Z. and Shokr, M.S. (2022). Multi-indicator and geospatial-based approaches for assessing variation of land quality in arid agroecosystems. *Sustainability*, **14**(10): 5840.
- Agegehu, G., Shewangizaw, B., Desta, G., Asefa, S., Legesse, G., Adissie, S. and Stewart, Z. (2024). Influence of landscape position on sorghum yield response to different nutrient sources and soil properties in a semi-arid tropical environment. *Heliyon*, **10**: 1–29.
- Ahmad, N., Virk, A.L., Shoukat, M.R., Zahra, N., Arshad, I., Wang, X. and Hafeez, M.B. (2025). Nutrient management on soil organic carbon storage and crop production under changing environments. In: *Agricultural Crop Improvement*, pp. 258–273. CRC Press.
- Antonangelo, J.A., Culman, S. and Zhang, H. (2024). Comparative analysis and prediction of cation exchange capacity via summation: Influence of biochar type and nutrient ratios. *Frontiers in Soil Science*, **4**: 1371777.
- Bashir, O., Ali, T., Baba, Z. A., Rather, G. H., Bangroo, S. A., Mukhtar, S. D. and Bhat, R. A. (2021). Soil organic matter and its impact on soil properties and nutrient status. In *Microbiota and biofertilizers, Vol 2: Ecofriendly tools for reclamation of degraded soil environs* (pp. 129-159). Cham: Springer International Publishing.
- Begna, M. (2020). Effect of toposequence on soil physicochemical properties. *Ethiopian Journal of Environmental Studies and Management*, **13**(4).
- Bray, R.H. and Kurtz, L.T. (1945). Determination of total, organic, and available forms of phosphorus in soils. *Soil Science*, **59**(1): 39–46.
- Bremner, J.M. and Mulvaney, C.S. (1982). Nitrogen—total. In: *Methods of Soil Analysis, Part 2: Chemical and Microbiological Properties*, **9**: 595–624.
- Costa, A.C.S., Souza Junior, I.G., Canton, L.C., Gil, L.G. and Figueiredo, R. (2020). Contribution of the chemical and mineralogical properties of sandy-loam tropical soils to the cation exchange capacity. *Revista Brasileira de Ciência do Solo*, **44**: e0200019.

- Daura, M.M., Dawha, E.D. and Odihi, J.O. (2023). Landforms of the Chad Basin. In: *Landscapes and Landforms of Nigeria*, pp. 125–134. Springer.
- Esu, I.E. (1991). *Detailed Soil Survey of NIHORT Farm at Bunkure, Kano State, Nigeria*. Institute for Agricultural Research, Ahmadu Bello University, Zaria, Nigeria.
- FAO (1976). *A Framework for Land Evaluation*. Food and Agriculture Organization of the United Nations.
- FAO (2006). *Guidelines for Soil Description*. 4th ed. Food and Agriculture Organization of the United Nations.
- FAO (2022). *World Reference Base for Soil Resources*. Food and Agriculture Organization of the United Nations.
- Ferraz-Almeida, R. (2024). Balance of nitrate and ammonium in tropical soil conditions: Soil factors analyzed by machine learning. *Nitrogen*, 5(3): 732–745.
- Gee, G.W. and Or, D. (2002). Particle-size analysis. In: *Methods of Soil Analysis, Part 4: Physical Methods*, 5: 255–293.
- Gerasimova, M. and Lebedeva, M. (2018). Organo-mineral surface horizons. In: *Interpretation of Micromorphological Features of Soils and Regoliths*, pp. 513–538. Elsevier.
- Grossman, R.B. and Reinsch, T.G. (2002). Bulk density and linear extensibility. In: *Methods of Soil Analysis, Part 4: Physical Methods*, pp. 201–228. Soil Science Society of America.
- Guo, B.X., Zhou, J., Zhan, L.Q., Wang, Z.Y., Wu, W. and Liu, H.B. (2024a). Spatial and temporal variability of soil pH, organic matter and available nutrients (N, P and K) in Southwestern China. *Agronomy*, 14(8): 1796.
- Guo, J., Fan, Y., Li, Y., Bi, Y., Wang, S., Hu, Y. and Song, W. (2024b). Topography dominates spatial variability of soil bulk density in arid zones. *Sustainability*, 16(22): 9670.
- Hillel, D. (2004). *Introduction to Environmental Soil Physics*. Elsevier.
- Huggett, R.J. and Shuttleworth, E. (2022). *Fundamentals of Geomorphology*. 5th ed. Routledge.
- Klingebiel, A.A. and Montgomery, P.H. (1961). *Land Capability Classification*. Agriculture Handbook No. 210. USDA Soil Conservation Service.
- Kosma, C., Triantafyllidis, V., Zotos, A., Pittaras, A., Kouneli, V. and Bilalis, D. (2022). Spatial variability of soil properties in Mediterranean farming systems. *Land*, 11(4): 557.
- Mabagala, F.S. (2022). On the tropical soils: The influence of organic matter on phosphate bioavailability. *Saudi Journal of Biological Sciences*, 29(5): 3635–3641.
- Masso, C., Nziguheba, G., Mutegi, J., Galy-Lacaux, C., Wendt, J., Butterbach-Bahl, K. and Datta, A. (2017). Soil fertility management in sub-Saharan Africa. In: *Sustainable Agriculture Reviews*, pp. 205–231. Springer International Publishing, Cham.

Naorem, A., Jayaraman, S., Dang, Y.P., Dalal, R.C., Sinha, N.K., Rao, C.S. and Patra, A.K. (2023). Soil constraints in an arid environment: Challenges, prospects and implications. *Agronomy*, **13**(1): 220.

NIMET (2021). *State of the Climate in Nigeria*. Nigerian Meteorological Agency.

Nord, A., Snapp, S. and Traore, B. (2022). Soil fertility practices in the Sahel. *Agronomy for Sustainable Development*, **42**(4): 79.

Omokaro, G.O. (2023). Impacts of toposequence on soil properties. *American Journal of Environmental Sciences*, **2**(3): 114–120.

Schaetzl, R.J. and Thompson, M.L. (2015). *Soils: Genesis and Geomorphology*. 2nd ed. Cambridge University Press.

Shukla, M.K. (2023). *Soil Physics: An Introduction*. 2nd ed. CRC Press.

Talha, I.Z., Buji, I.B. and Adamu, I. (2025). Soil characterization in Maiduguri, Nigeria. *ADAN Journal of Agriculture*, **6**(1).

Tomaz, A., Martins, I., Catarino, A., Mourinha, C., Dôres, J., Fabião, M. and Palma, P. (2022). Insights into the spatial and temporal variability of soil attributes in irrigated farm fields and correlations with management practices: A multivariate statistical approach. *Water*, **14**(20): 3216.

Wells, J.M., Crow, S.E., Sierra, C.A., Deenik, J.L., Carlson, K.M., Meki, M.N. and Kiniry, J. (2022). Edaphic controls of soil organic carbon in tropical agricultural landscapes. *Scientific Reports*, **12**(1): 21574.

Yuan, Z.Q., Fang, C., Zhang, R., Li, F.M., Javaid, M.M. and Janssens, I.A. (2019). Topographic influences on soil properties and aboveground biomass in lucerne-rich vegetation in a semi-arid environment. *Geoderma*, **344**: 137–143.

Zhao, W. and Huang, L.M. (2023). Changes in soil nutrients and stoichiometric ratios reveal increasing phosphorus deficiency along a tropical soil chronosequence. *Catena*, **222**: 106893.