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Delineation and Pedological Differentiation of Soil Mapping Units in a Northern Guinea Savanna Agricultural Landscape of Nigeria

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Abstract

Accurate delineation and characterization of soil mapping units are fundamental to resolving soil variability within agricultural landscapes and supporting soil survey and land management. This study delineated and evaluated soil mapping units within the Ahmadu Bello University Farm, Shika, Nigeria, using an integrated field, laboratory and multivariate approach. Fifty-six auger observations were used to delineate mapping units based on landscape position, soil depth, drainage, texture and morphological characteristics, followed by detailed characterization of one representative profile per mapping unit. Morphological, physical and chemical properties were determined, and soils were classified using USDA Soil Taxonomy and the World Reference Base for Soil Resources (WRB). Principal component analysis (PCA) and hierarchical cluster analysis were applied as exploratory approaches to assess multivariate differentiation among the mapping units. Five soil mapping units were delineated within a mapped area of 404.35 ha (including a 26.77 ha farm dam), with ABU1 occupying the largest area (229.96 ha; 56.87%). Profile depth ranged from 23 to 180 cm, while clay content ranged from 100 to 560 g kg^{-1}. Soil pH in water ranged from 5.43 to 7.03, cation exchange capacity from 7.02 to 15.19 cmol(+) kg^{-1}, and organic carbon from 1.48 to 13.11 g kg^{-1}. The soils were classified as Typic Haplustalfs, Typic Plinthustalfs, Aquic Ustifluvents, Typic Plinthaqualfs and Lithic Ustorthents, corresponding to Haplic Luvisols, Haplic Plinthosols, Fluvic Gleysols, Stagnic Plinthosols and Petric Plinthosols under WRB. With five profile-level observations, PCA yielded four components (the maximum possible), of which the first two explained 72.4% of the variance, and cluster analysis separated ABU5 from the other units. The low mean silhouette width (0.15) indicates weak cluster structure, so the multivariate results are exploratory. Overall, the results indicate marked pedological differentiation among the mapping units and provide a useful basis for soil survey, characterization and management in Northern Guinea Savanna agricultural landscapes.

1. Introduction

Soil is a spatially heterogeneous component of terrestrial ecosystems whose properties vary systematically with differences in parent material, relief, climate, organisms, time and their interactions across the landscape (Johnson et al., 2024). This spatial variability is particularly important in agricultural landscapes, where differences in soil depth, texture, drainage, organic matter, reaction, nutrient status and other properties influence land-use potential and management requirements (Adhikari et al., 2025; Chattaraj et al., 2025; De Ros et al., 2025; Subhash et al., 2025). Consequently, the identification and delineation of spatially coherent soil units remain fundamental to soil survey, land evaluation and sustainable agricultural management. Soil mapping provides a framework for organizing this variability by relating observable landscape features and soil characteristics to spatially defined mapping units that can be interpreted for agricultural and environmental applications (Adeniyi et al., 2024; De Caires et al., 2025).

Conventional soil survey relies substantially on the recognition of landscape patterns, geomorphic position, parent material and observable soil morphology to identify areas that are expected to contain

relatively similar soils (Nenkam et al., 2024; Zhu et al., 2024). Soil morphology is particularly important because features such as horizon sequence, colour, structure, consistence, depth, redoximorphic characteristics and the nature of diagnostic horizons provide field-based evidence of soil-forming processes and spatial differentiation (Awwal et al., 2026). Although landscape position can provide an effective basis for preliminary delineation, soils occurring in apparently similar positions may differ substantially because of variation in parent material, hydrological conditions, erosion and deposition, degree of weathering and other pedogenic processes (Awwal & Maniyunda, 2023; Awwal et al., 2026). Conversely, soils occupying different landscape positions may share important properties where similar formative conditions prevail. The reliability of mapping units therefore depends on the extent to which their delineation is supported by measurable differences in soil properties rather than solely by landscape position or visual interpretation (Zhu et al., 2024).

The Northern Guinea Savanna of Nigeria contains extensive agricultural landscapes in which strong spatial variation in soil conditions occurs over relatively short distances (Aliyu et al., 2024; Peter-Jerome et al., 2022). The region is characterized by a seasonal rainfall regime, predominantly weathered crystalline basement rocks in many areas, and landscapes comprising upland, midslope and lower landscape positions with contrasting drainage and redistribution of soil materials (Awwal et al., 2026). These conditions promote the development of soils with substantial variation in morphology, texture, chemical properties and diagnostic characteristics. Agricultural intensification within the region further increases the need for reliable information on the distribution and characteristics of these soils, particularly where a single agricultural landscape contains several soil environments that differ in their capacity to support crop production and respond to management.

The concept of a soil mapping unit provides an important link between field-based pedological observations and the spatial representation of soil variability (Zhu et al., 2024). Mapping units are not necessarily equivalent to individual taxonomic classes; rather, they represent spatial entities delineated at a particular survey scale and according to the criteria used in the survey. Their pedological meaning is strengthened when differences among units can be demonstrated through systematic characterization of their morphological, physical and chemical properties (Subhash et al., 2025). Such characterization also provides an opportunity to determine whether the boundaries established from landscape and field evidence correspond to measurable changes in soil properties. This is especially relevant in detailed investigations of agricultural landscapes, where relatively short distances may encompass substantial changes in soil-forming conditions.

Soil classification provides a complementary framework for interpreting these differences. The USDA Soil Taxonomy and the World Reference Base for Soil Resources (WRB) organize soils according to diagnostic properties and horizons that reflect their degree and nature of pedological development (IUSS Working Group WRB, 2022; Soil Survey Staff, 2022b). Applying both systems to the same set of delineated mapping units can provide a broader understanding of the taxonomic relationships among soils and reveal how locally identified landscape units correspond to internationally recognized soil classes (Awwal et al., 2026). However, taxonomic classification alone does not necessarily explain the

magnitude or pattern of differentiation among mapping units. Soils assigned to different classes may differ in only a limited number of properties, whereas soils within the same broad taxonomic group may exhibit considerable variation in properties relevant to agricultural use. There is therefore value in examining the measured properties of mapping units alongside their taxonomic classification.

Quantitative assessment of pedological differentiation can help address this issue by identifying the properties that most clearly distinguish one mapping unit from another (Peter-Jerome et al., 2022; Wadoux & McBratney, 2024). Properties related to soil texture, organic matter, reaction, exchange characteristics, base status and other morphological or chemical attributes may contribute differently to the separation of landscape units depending on the prevailing soil-forming environment (Zhu et al., 2024). Multivariate approaches, including principal component analysis, can be particularly useful for examining relationships among correlated soil properties and identifying combinations of variables that account for major patterns of variation. When applied as an exploratory tool alongside conventional soil characterization, such analyses can provide additional evidence for interpreting the degree and nature of differentiation among mapping units without replacing field-based pedological judgement (Peter-Jerome et al., 2022; Wadoux & McBratney, 2024).

Despite the growing body of research on soil variability, characterization and classification in the Northern Guinea Savanna of Nigeria, to our knowledge, relatively few studies have combined landscape-based mapping-unit delineation, comprehensive soil characterization, dual-system classification and quantitative assessment of pedological differentiation within a single agricultural landscape (Peter-Jerome et al., 2022; Obasi et al., 2023; Aliyu et al., 2024).

This study therefore investigated the delineation and pedological differentiation of soil mapping units within the Ahmadu Bello University Farm, a representative agricultural landscape in the Northern Guinea Savanna of Nigeria. The study delineated mapping units using landscape position, field observations and soil morphological characteristics; characterized their morphological, physical and chemical properties; classified the soils according to USDA Soil Taxonomy and WRB; and evaluated the degree of pedological differentiation among the mapping units using measured soil properties. Particular attention was given to identifying the major soil properties associated with the separation of the mapping units. By integrating field-based delineation, soil characterization, taxonomic classification and quantitative assessment of property variation, the study provides a coherent basis for understanding the internal differentiation of soils within a managed savanna landscape and the relationship between landscape-based mapping units and their pedological properties.

2. Materials and methods

2.1 Study area

The study was conducted at the Ahmadu Bello University (ABU) Farm, Shika, Zaria, Kaduna State, Nigeria. The farm covers approximately 404.35 ha and lies across the administrative boundary between

Sabon Gari and Giwa Local Government Areas, at approximately 11°11'–11°13' N and 7°35'–7°37' E (Fig. 1). The area forms part of the Northern Guinea Savanna ecological zone of Nigeria and constitutes an intensively used agricultural and research landscape. Previous investigations have also identified the ABU Farm and its surroundings as an important agricultural research environment within the Zaria area (Institute for Agricultural Research [IAR], 2024; Omeke et al., 2022).

The landscape around Zaria is characterized by gently undulating terrain with variations in elevation, slope and drainage that influence soil formation and redistribution of soil materials. The area is underlain predominantly by the Precambrian Basement Complex, with granitic and related rocks and associated weathered materials occurring within the broader Zaria landscape (Awwal et al., 2022; Ifeanyi et al., 2021). Studies of the ABU Farm have reported weathered and lateritic materials within the shallow subsurface, while regional geomorphology includes pediments, plains and locally more elevated or resistant landforms (Alao et al., 2024; Jimoh et al., 2020; Osumejeh et al., 2023). The climate is characterized by a distinct wet and dry season, typical of the Northern Guinea Savanna, with most rainfall concentrated during the growing season. Such seasonal rainfall and associated differences in runoff, infiltration, drainage and soil-water redistribution provide important environmental controls on soil differentiation (IAR, 2024). The farm is predominantly used for agricultural research and production, making it an appropriate setting for examining the relationship between landscape position, soil morphology and measurable pedological variation.

2.2 Delineation of soil mapping units

A reconnaissance soil survey was first undertaken to establish the spatial variability of soils across the farm. Systematic auger observations were made at fixed intervals across the study area, resulting in 56 observation points (Fig. 1). At each observation point, the soil was examined with an auger and relevant site and soil characteristics were recorded. The observations included soil depth, horizonation where discernible, colour, drainage condition, consistency and texture, together with other readily observable morphological characteristics considered useful for distinguishing soils across the landscape. Field texture was estimated by the feel method, in which a moistened soil sample is manipulated between the fingers and formed into a ribbon to estimate the relative proportions of sand, silt and clay (Richer-de-Forges et al., 2025). This procedure follows established USDA soil-survey practice, in which field texture by feel is a standard approach when calibrated against laboratory particle-size analysis (Soil Survey Division Staff, 2017).

The auger observations were interpreted in relation to landscape position and the observed continuity or changes in soil characteristics. Areas exhibiting relatively similar combinations of landscape position, depth, drainage, field texture and morphological characteristics were grouped and delineated as individual soil mapping units. Thus, the mapping units represented field-based spatial units defined from the combined evidence of landscape and soil observations rather than from soil classification alone. The resulting delineation provided the sampling framework for subsequent detailed profile characterization.

2.3 Profile description and soil sampling

Following delineation, one representative profile pit was excavated in each of the five mapping units (ABU1–ABU5). Each pit was positioned to represent the central and characteristic conditions of its mapping unit while avoiding unusual local features that could distort its representation. Each profile was exposed, described and sampled following standard procedures including characterization of horizon boundaries, colour, structure, consistence, texture, drainage-related features and other morphological properties relevant to pedological interpretation (Soil Survey Division Staff, 2017).

Soil samples were collected separately from the genetic horizons identified in each profile and subjected to laboratory analysis. Each mapping unit is therefore represented by a single profile, and the values presented for a unit are horizon-level measurements from that profile. This approach allowed the mapping units to be compared on the basis of both their characteristic profile morphology and their measured soil properties, but it does not capture within-unit variability.

2.4 Laboratory analyses

Soil samples were air-dried, gently disaggregated and passed through a 2-mm sieve before laboratory analysis. The analytical procedures followed established soil survey and soil-analysis protocols, particularly the USDA soil survey laboratory methods and standard methods compiled by the Soil Science Society of America (Gee & Or, 2002; Soil Survey Staff, 2022a). The measured properties comprised soil depth, particle-size distribution (sand, silt and clay), textural class, bulk density (BD), particle density (PD), total porosity (TP), saturated hydraulic conductivity (Ks), field capacity (FC), permanent wilting point (PWP), available water capacity (AWC), pH measured in water (pHwater) and $CaCl_2$ ($pHCaCl_2$), ΔpH, electrical conductivity (EC), exchangeable Ca, Mg, K and Na, total exchangeable bases (TEB), exchangeable acidity (EA), cation exchange capacity (CEC), base saturation percentage (BSP), exchangeable sodium percentage (ESP), sodium adsorption ratio (SAR), organic carbon (OC), total nitrogen (TN), and available phosphorus (av. P).

Particle-size distribution was determined using Bouyoucos Hydrometer method with Calgon as the dispersant (Gee and Or, 2002). Textural classes were assigned from the measured particle-size fractions using the USDA soil-textural triangle. Bulk density was determined using the core method, while particle density was determined following pycnometer method (Gee and Or, 2002). Total porosity was calculated from bulk and particle densities as:

$$\mathrm{TP} = \left(1 - \frac{\mathrm{BD}}{\mathrm{PD}}\right) \times 100$$

1

where BD is the bulk density and PD is the particle density (both in Mg m^{-3}). Saturated hydraulic conductivity (Ks) was measured on core samples using constant-head permeameter method described by Klute & Dirksen (1986), while FC and PWP were determined from soil-water retention measurements (Klute, 1986) at 15 bars and − 33 bars respectively. The values were expressed on a mass basis (g g^{-1}).

Available Water Capacity (AWC, cm per horizon) was calculated from the water retained between field capacity and the permanent wilting point, the bulk density and the horizon thickness:

$$\mathrm{AWC} = (\mathrm{FC} - \mathrm{PWP}) \times \mathrm{BD} \times D$$

2

where D is the horizon thickness (cm). Soil reaction was determined potentiometrically in water and calcium chloride suspensions, while EC was measured from the soil extract using a conductivity meter. The use of water and $CaCl_2$ suspensions follows established soil-survey procedures for determining soil reaction and allows the difference between the two measurements to be evaluated. The difference in pH between the two suspensions was expressed as:

$$\Delta pH = pH(H\square O) - pH(CaCl\square)$$

3

Exchangeable Ca and Mg were determined using an atomic absorption spectrophotometer (AAS), while exchangeable K and Na were quantified using a flame photometer following extraction with neutral 1 M ammonium acetate (NH_4OAc, pH 7.0). TEB was calculated as the sum of exchangeable Ca, Mg, K and Na. Exchangeable acidity (EA) was determined by titration following extraction with 1 M potassium chloride (KCl), while cation exchange capacity (CEC) was determined using the ammonium acetate saturation method at pH 7.0 (Soil Survey Staff, 2022a). Base saturation was calculated as:

$$\mathrm{BSP} = \frac{\mathrm{TEB}}{\mathrm{CEC}} \times 100$$

4

Exchangeable Sodium Potential (ESP) was calculated from exchangeable Na relative to CEC, as:

$$\mathrm{ESP} = \frac{\mathrm{Na}}{\mathrm{CEC}} \times 100$$

5

and Sodium Absorption Ratio was calculated from the concentrations of Na, Ca and Mg using the conventional relationship (concentrations in cmol(+) kg^{-1}):

$$\mathrm{SAR} = \frac{\mathrm{Na}}{\sqrt{\frac{\mathrm{Ca} + \mathrm{Mg}}{2}}}$$

6

Organic carbon was determined by a wet oxidation procedure based on the Walkley–Black method (Walkley & Black, 1934), total nitrogen by the Kjeldahl procedure (Bremner & Mulvaney, 1982), and available phosphorus by the Bray-1 extraction procedure (Bray & Kurtz, 1945).

2.5 Soil classification

The soils were classified independently using the USDA Soil Taxonomy and the World Reference Base for Soil Resources (WRB) (IUSS Working Group WRB, 2022; Soil Survey Staff, 2022b). Classification was based on the observed morphological characteristics and measured diagnostic properties of the representative pedons. Classification was carried out systematically from the highest applicable category to the lower taxonomic levels, using diagnostic horizons, diagnostic properties and other criteria required by each system.

2.6 Statistical analysis and assessment of pedological differentiation

The measured soil properties were first subjected to descriptive statistical analysis to summarize the central tendency and variability of the properties within each mapping unit. Means and other appropriate summary statistics were used to characterize the magnitude and direction of differences among units. Principal component analysis (PCA) was applied as an exploratory multivariate approach to characterize patterns of pedological differentiation among the mapping units based on their measured soil properties. Because the observations comprised multiple horizons within each profile, horizon-level measurements were first aggregated to obtain profile-level soil-property signatures for the five mapping units, using thickness-weighted means where valid depth intervals were available and equal horizon weighting otherwise. The resulting profile-level variables were standardized to z-scores prior to PCA so that differences in measurement scale did not disproportionately influence the multivariate structure. PCA was then used to summarize the principal patterns of variation among the mapping units and to identify soil properties with strong contributions to the major principal components. Because the 27 variables greatly outnumbered the five observations, and five observations can define at most four components (n − 1), the PCA was used only descriptively.

Hierarchical cluster analysis was subsequently applied to the same standardized profile-level dataset to examine the similarity structure among the mapping units. Euclidean distances were calculated among profiles and hierarchical clustering was performed using Ward's minimum-variance criterion (Ward.D2). Candidate cluster solutions (k = 2–4) were evaluated using silhouette widths, while pairwise Euclidean distances were used to further describe the degree of similarity or separation among mapping units. Together, PCA, hierarchical clustering, and pairwise distance analysis provided complementary exploratory measures of pedological differentiation and helped identify the soil properties most strongly associated with the observed multivariate separation. Given the small number of independent mapping-unit profiles, the results were interpreted as exploratory evidence of pedological differentiation and were not treated as independent evidence of causal soil-forming processes.

2.7 Soil profile visualization

Soil-profile depth and colour patterns were visualized in R using profile-plotting routines based on the recorded horizon depths and Munsell colour information. Profile depth was represented according to the measured upper and lower boundaries of the genetic horizons, while horizon colours were assigned from the recorded field colour descriptions. The graphical outputs were used to present the vertical organization and colour differentiation of the representative profiles and to facilitate visual comparison among mapping units (Beaudette et al., 2013). All statistical analyses and profile visualizations were performed in the R statistical computing environment (R Core Team, 2026)

3. Results

3.1 Delineation of soil mapping units

Field observations from the 56 auger points showed clear spatial variation in soil depth, drainage, field texture and morphological characteristics across the ABU Farm. Based on the integration of these observations with landscape position and the spatial continuity of similar soil characteristics, five major soil mapping units were delineated: ABU1, ABU2, ABU3, ABU4 and ABU5 (Fig. 2). The farm dam was retained as a separate non-soil unit. The resulting map (Table 1) covered 404.35 ha, with ABU1 constituting the largest mapping unit (229.96 ha; 56.87%), followed by ABU2 (60.85 ha; 15.05%), ABU5 (39.12 ha; 9.67%), ABU3 (34.03 ha; 8.42%) and ABU4 (13.62 ha; 3.37%). The dam occupied 26.77 ha (6.62%) of the mapped area.

Table 1
Area and proportional extent of the soil mapping units delineated at the Ahmadu Bello University Farm, Shika.

Soil mapping unit	Area (ha)	Proportion of area (%)
ABU1	229.96	56.87
ABU2	60.85	15.05
ABU3	34.03	8.42
ABU4	13.62	3.37
ABU5	39.12	9.67
Dam	26.77	6.62
Total	404.35	100.00

The delineated units differed in their field-observed combinations of landscape position, profile depth, drainage, texture and morphological expression. These differences provided the basis for selecting a representative profile pit within each unit for detailed characterization.

3.2 Soil morphological properties

The morphological characteristics showed clear differentiation among the five soil mapping units (Table 2; Fig. 3). ABU1 was a deep profile, extending to 166 cm, with a sequence of Ap–Bt–Btv1–Btv2–BCv horizons. Its texture changed from silt loam in the Ap horizon to silty clay loam throughout the subsoil. The profile was dominated by medium to fine subangular blocky structures in the upper and middle horizons, while the BCv horizon was massive. ABU2 extended to 165 cm and comprised Ap–BAt–Bt–Btv–BCv horizons. Its surface horizon was loam, changing to clay loam in the BAt, Bt and Btv horizons and clay in the BCv. The upper horizons had fine subangular blocky structure, whereas the Bt and BCv horizons were massive. ABU3 was the deepest profile, extending to 180 cm, and was characterized by Apg–ACg–2ACg–2Cg–3Cg horizons. Unlike ABU1 and ABU2, all horizons showed gley-related morphological features, with matrix colours of 2.5Y 5/1 to 6/3 and distinct mottles recorded throughout the profile (Fig. 3). Its texture varied from silty clay loam and clay loam to clay, and the horizons generally had fine to medium angular blocky structure.

Table 2
Morphological properties of the representative profiles of the five soil mapping units.

Horizon	Depth (cm)	Matrix colour (moist)	Mottle colour	Texture	Structure	Consistence			Boundary
						Wet	Moist	Dry	
ABU1									
Ap	0–35	10YR 6/4	–	SiL	2msbk	ss	fr	s	Cw
Bt	35–80	10YR 5/8	–	SiCL	3msbk	s	fr	vh	Gs
Btv1	80–130	5YR 5/8	–	SiCL	2fsbk	vs	fr	vh	Gs
Btv2	130–150	5YR 5/8	–	SiCL	3fsbk	vs	fr	vh	Dw
BCv	150–166	7YR 5/8	–	SiCL	0m	vs	fr	vh	–
ABU2									
Ap	0–30	7.5YR 5/6	–	L	2fsbk	ss	fr	sh	Gw
BAt	30–55	5YR 4/6	–	CL	2fsbk	ss	fr	sh	Gs
Bt	55–90	5YR 5/6	–	CL	0m	vs	fr	h	Gw
Btv	90–132	5YR 5/6	–	CL	3fsbk	vs	fr	s	Gw
BCv	132–165	7.5YR 5/8	–	C	0m	vs	vfr	s	Gs
ABU3									
Apg	0–28	2.5Y 5/2	7.5YR 5/8	SiCL	3mabk	vs	fr	–	Cw
ACg	28–60	2.5Y 6/3	7.5YR 4/6	CL	2mabk	vs	fr	–	Gw
2ACg	60–97	2.5Y 5/2	7.5YR 4/6	SiCL	3fabk	vs	vfr	–	Dw

Note: Texture - SiL, silt loam; L, loam; SL, sandy loam; CL, clay loam; SiCL, silty clay loam; C, clay. Structure: grade (0, structureless; 2, moderate; 3, strong), size (f, fine; m, medium) and type (sbk, subangular blocky; abk, angular blocky; m, massive). Consistence: wet (ss, slightly sticky; s, sticky; vs, very sticky), moist (vfr, very friable; fr, friable) and dry (s, soft; sh, slightly hard; h, hard; vh, very hard). Boundary: distinctness (a, abrupt; c, clear; g, gradual; d, diffuse) and topography (s, smooth; w, wavy).

Horizon	Depth (cm)	Matrix colour (moist)	Mottle colour	Texture	Structure	Consistence			Boundary
						Wet	Moist	Dry	
2Cg	97–130	2.5Y 5/2	7.5YR 4/6	CL	3fabk	vs	vfr	–	Gw
3Cg	130–180	2.5Y 5/1	10YR 6/8	C	3fabk	vs	vfr	–	–
ABU4									
Apg	0–14	10YR 3/2	7.5YR 5/8	SiL	2msbk	ss	fr	s	Cw
ABg	14–30	10YR 3/1	7.5YR 5/8	SiL	2msbk	ss	fr	s	As
Btgv1	30–60	2.5Y 5/4	7.5YR 5/8	CL	0m	vs	vfr	s	Ds
Btgv2	60–85	2.5YR 6/1	10YR 5/8	SiL	0m	vs	vfr	s	–
ABU5									
Apv	0–12	10YR 4/2	–	SL	0m	s	vfr	h	–
Cv	12–23	10YR 4/4	–	SiL	–	–	–	–	–

Note: Texture - SiL, silt loam; L, loam; SL, sandy loam; CL, clay loam; SiCL, silty clay loam; C, clay. Structure: grade (0, structureless; 2, moderate; 3, strong), size (f, fine; m, medium) and type (sbk, subangular blocky; abk, angular blocky; m, massive). Consistence: wet (ss, slightly sticky; s, sticky; vs, very sticky), moist (vfr, very friable; fr, friable) and dry (s, soft; sh, slightly hard; h, hard; vh, very hard). Boundary: distinctness (a, abrupt; c, clear; g, gradual; d, diffuse) and topography (s, smooth; w, wavy).

ABU4 was shallower, extending to 85 cm, with Apg–ABg–Btgv1–Btgv2 horizons. The two surface horizons were silt loam, followed by clay loam and silt loam in the deeper horizons. Medium subangular blocky structure occurred in the surface horizons, while the Btgv horizons were massive. Mottling was recorded throughout the profile, with matrix colours changing from very dark greyish brown and very dark grey in the surface horizons to lighter greyish colours at depth. ABU5 was the shallowest profile, extending only to 23 cm, with Apv and Cv horizons. The Apv and Cv were described in the field as sandy loam and silt loam, respectively, although laboratory particle-size analysis indicated clay and silty clay (Section 3.3). Overall, the profiles therefore differed in depth, horizon sequence, matrix colour, mottling, texture, structural grade and type, consistency and boundary characteristics, with the most pronounced morphological differentiation occurring between the deeper, relatively well-developed profiles of ABU1 and ABU2 and the shallower or more strongly gleyed profiles of ABU3–ABU5.

3.3 Soil physical properties

The physical properties showed clear variation among the soil mapping units and across the soil profiles (Table 3). Sand content ranged from 60 to 400 g kg^{-1}, silt from 280 to 600 g kg^{-1}, and clay from 100 to 560 g kg^{-1}. Field-estimated textural classes (Table 2) ranged from silt loam, loam and sandy loam in some horizons to clay loam, silty clay loam and clay in others. In ABU1, clay increased from 100 g kg^{-1} in the Ap horizon to 460 g kg^{-1} in Btv2, accompanied by a change in field texture from silt loam to silty clay loam. ABU2 similarly showed an increase in clay from 140 g kg^{-1} in the Ap horizon to 440 g kg^{-1} in the BCv horizon. ABU3 displayed clay contents of 300–480 g kg^{-1}, with the maximum occurring in the deepest 3Cg horizon. In ABU4, clay increased from 120–140 g kg^{-1} in the surface horizons to 280 g kg^{-1} in Btgv1, while ABU5 had a clay-rich Apv horizon containing 560 g kg^{-1} clay.

Table 3
Particle-size distribution and physical properties of the horizons of the five soil mapping units.

Horizon	Depth	Sand	Silt	Clay	BD	PD	TP	Ks	FC	PWP	AWC
	(cm)	(g kg^{-1})			(Mg m^{-3})		(%)	(cm h^{-1})	(g g^{-1})		(cm)
ABU1											
Ap	0–35	300	600	100	1.54	2.37	34.91	1.82	0.27	0.13	7.55
Bt	35–80	140	580	280	1.34	2.39	43.93	0.98	0.34	0.20	10.32
Btv1	80–130	120	520	360	1.51	2.37	36.18	0.83	0.30	0.19	8.31
Btv2	130–150	60	480	460	1.39	2.39	41.84	0.83	0.29	0.19	2.78
BCv	150–166	180	460	360	1.89	2.36	19.81	2.36	0.20	0.16	1.21
ABU2											
Ap	0–30	400	460	140	1.71	2.62	34.94	0.52	0.25	0.13	6.16
BAt	30–55	340	280	380	1.51	2.30	34.58	0.65	0.32	0.15	6.42
Bt	55–90	320	300	380	1.83	2.30	20.33	0.51	0.26	0.15	7.05
Btv	90–132	280	320	400	1.78	2.53	29.53	0.91	0.27	0.15	8.97
BCv	132–165	200	360	440	1.29	2.26	42.77	0.98	0.33	0.09	10.21
ABU3											
Apg	0–28	180	460	360	1.21	2.31	47.71	1.50	0.35	0.24	3.72
ACg	28–60	240	460	300	1.32	2.39	44.73	2.48	0.36	0.19	7.18
2ACg	60–97	160	500	340	1.36	2.28	40.15	2.24	0.38	0.18	10.06
2Cg	97–130	200	500	300	1.74	2.39	27.11	1.31	0.25	0.13	6.89

Note: BD, bulk density; PD, particle density; TP, total porosity; Ks, saturated hydraulic conductivity; FC, field capacity; PWP, permanent wilting point; AWC, available water capacity (per horizon). n.d., not determined.

Horizon	Depth	Sand	Silt	Clay	BD	PD	TP	Ks	FC	PWP	AWC
	(cm)	(g kg^{-1})			(Mg m^{-3})		(%)	(cm h^{-1})	(g g^{-1})		(cm)
3Cg	130–180	200	320	480	1.98	2.29	13.43	0.98	0.18	0.13	4.95
ABU4											
Apg	0–14	320	560	120	1.45	2.43	40.29	1.49	0.26	0.21	1.02
ABg	14–30	340	520	140	1.62	2.55	36.74	2.01	0.57	0.37	5.18
Btgv1	30–60	220	500	280	1.43	2.36	39.16	2.36	0.25	0.18	3.03
Btgv2	60–85	240	500	260	1.72	2.53	31.95	0.79	0.21	0.17	1.72
ABU5											
Apv	0–12	80	360	560	1.98	2.51	21.18	0.98	0.14	0.12	0.48
Cv	12–23	80	500	420	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.

Note: BD, bulk density; PD, particle density; TP, total porosity; Ks, saturated hydraulic conductivity; FC, field capacity; PWP, permanent wilting point; AWC, available water capacity (per horizon). n.d., not determined.

Bulk density ranged from 1.21 to 1.98 Mg m^{-3}, particle density from 2.26 to 2.62 Mg m^{-3}, and total porosity from 13.43 to 47.71%. The lowest bulk density and highest total porosity occurred in the Apg horizon of ABU3, whereas the lowest total porosity was recorded in the 3Cg horizon of the same unit, which, together with the Apv horizon of ABU5, had the highest bulk density (1.98 Mg m^{-3}). Saturated hydraulic conductivity ranged from 0.51 to 2.48 cm h^{-1}, with variation both within and between profiles. Field capacity ranged from 0.14 to 0.57 g g^{-1}, permanent wilting point from 0.09 to 0.37 g g^{-1}, and available water capacity from 0.48 to 10.32 cm per horizon. In several profiles, the changes in water-related properties appeared to follow the observed differences in texture and bulk density. The final Cv horizon of ABU5 (12–23 cm) was not sampled with cores; consequently, bulk density, total porosity, saturated hydraulic conductivity, field capacity, permanent wilting point and available water capacity were not determined for this horizon.

3.4 Soil chemical properties

Soil reaction varied among horizons (Table 4), with pH measured in water ranging from 5.43 to 7.03, while pH measured in $CaCl_2$ ranged from 4.49 to 5.71. The corresponding ΔpH values ranged from 0.58 to 1.80. Within ABU1, pHwater increased from 5.43 in the Ap horizon to 6.22 in the Btv1 horizon before declining to 5.68 in the BCv horizon. ABU2 showed values of 6.06–6.39, whereas ABU3 recorded a

progressive increase from 5.80 in the Apg horizon to 7.03 in the 3Cg horizon. In ABU4, pHwater increased from 5.62 to 6.44 down the profile, while ABU5 recorded 5.99 and 6.10 in the Apv and Cv horizons, respectively. Electrical conductivity ranged from 0.013 to 0.055 dS m^{-1} across the sampled horizons, with the lowest value occurring in the Btv2 horizon of ABU1 and the highest in the Ap horizon of the same unit.

Organic carbon ranged from 1.48 to 13.11 g kg^{-1}, total nitrogen from 0.03 to 1.23 g kg^{-1}, and available phosphorus from 3.43 to 17.64 mg kg^{-1}. The highest organic carbon concentration occurred in the Apg horizon of ABU4 (13.11 g kg^{-1}) and the highest total nitrogen concentration in the Apg horizon of ABU3 (1.23 g kg^{-1}). Available phosphorus was highest in the Apg horizon of ABU4 and lowest in the BCv horizon of ABU1. Across the profiles, OC and TN generally varied substantially between adjacent horizons and did not decline regularly with depth in ABU3, while av. P also showed distinct differences among horizons within and between pedons.

Table 4

Soil reaction, electrical conductivity, organic carbon, total nitrogen, available phosphorus, exchangeable sodium percentage and sodium adsorption ratio of the horizons of the five soil mapping units.

Horizon	pH	pH	ΔpH	OC	TN	Av. P	EC	ESP	SAR
	(H_2O)	($CaCl_2$)		(g kg^{-1})		(mg kg^{-1})	(dS m^{-1})	(%)	
ABU1									
Ap	5.43	4.79	0.64	5.29	0.50	11.76	0.055	2.52	0.12
Bt	6.16	5.13	1.03	5.71	0.42	5.39	0.022	1.93	0.09
Btv1	6.22	5.20	1.02	5.08	0.34	4.90	0.019	1.47	0.07
Btv2	6.00	5.16	0.84	4.02	0.22	3.92	0.013	2.85	0.15
BCv	5.68	5.04	0.64	4.86	0.28	3.43	0.040	3.57	0.17
ABU2									
Ap	6.12	5.16	0.96	4.02	0.42	8.33	0.018	3.31	0.17
BAt	6.06	4.80	1.26	4.86	0.28	7.35	0.016	3.09	0.15
Bt	6.39	4.89	1.50	2.75	0.25	5.39	0.017	2.78	0.15
Btv	6.27	5.17	1.10	3.38	0.11	4.41	0.015	3.09	0.17
BCv	6.36	5.26	1.10	2.75	0.14	5.88	0.014	3.10	0.18
ABU3									
Apg	5.80	4.71	1.09	2.96	1.23	7.84	0.023	3.63	0.19
ACg	6.44	5.02	1.42	12.90	0.67	5.88	0.018	3.41	0.20
2ACg	6.73	5.54	1.19	2.33	0.42	7.84	0.020	3.17	0.17
2Cg	6.85	5.59	1.26	3.81	0.17	6.37	0.023	5.31	0.30
3Cg	7.03	5.71	1.32	3.84	0.03	4.90	0.022	4.39	0.26
ABU4									
Apg	5.62	5.03	0.59	13.11	0.98	17.64	0.050	3.28	0.17
ABg	6.04	4.73	1.31	5.49	0.20	14.70	0.045	4.48	0.23
Btgv1	6.29	4.49	1.80	2.11	0.11	8.33	0.040	1.78	0.10

Note: OC = organic carbon; TN = total nitrogen; Av. P = available phosphorus; EC = electrical conductivity; ESP = exchangeable sodium percentage; SAR = sodium adsorption ratio (dimensionless); ΔpH = pH(H_2O) − pH($CaCl_2$).

Horizon	pH	pH	ΔpH	OC	TN	Av. P	EC	ESP	SAR
	(H_2O)	($CaCl_2$)		(g kg^{-1})		(mg kg^{-1})	(dS m^{-1})	(%)	
Btgv2	6.44	5.26	1.18	1.48	0.08	7.84	0.045	4.27	0.19
ABU5									
Apv	5.99	5.41	0.58	4.23	0.14	11.27	0.050	2.38	0.12
Cv	6.10	4.71	1.39	9.09	0.03	8.33	0.045	1.17	0.13

Note: OC = organic carbon; TN = total nitrogen; Av. P = available phosphorus; EC = electrical conductivity; ESP = exchangeable sodium percentage; SAR = sodium adsorption ratio (dimensionless); ΔpH = pH(H_2O) − pH($CaCl_2$).

Exchangeable Ca, Mg, K and Na (Table 5) ranged from 3.80–10.20, 1.14–3.06, 0.08–0.49 and 0.15–0.72 cmol(+) kg^{-1}, respectively. Total exchangeable bases ranged from 5.32 to 13.89 cmol(+) kg^{-1}, while exchangeable acidity ranged from 0.20 to 0.80 cmol(+) kg^{-1}. Cation exchange capacity varied from 7.02 to 15.19 cmol(+) kg^{-1}, with the highest value recorded in the Btgv1 horizon of ABU4. Base saturation ranged from 75.78 to 92.21%, with the lowest value occurring in the Btgv2 horizon of ABU4. Exchangeable sodium percentage ranged from 1.17 to 5.31%, while sodium adsorption ratio ranged from 0.07 to 0.30. Within the individual profiles, the exchangeable bases, total exchangeable bases and CEC varied among horizons, with particularly pronounced differences in ABU3 and ABU4.

Table 5
Exchangeable cations, cation exchange capacity and base saturation of the horizons of the five soil mapping units.

Horizon	Ca	Mg	K	Na	TEB	EA	CEC	BSP
	(cmol(+) kg^{-1})							(%)
ABU1								
Ap	7.00	1.89	0.24	0.26	9.39	0.60	10.29	91.25
Bt	5.80	1.74	0.20	0.17	7.91	0.60	8.81	89.78
Btv1	7.00	1.92	0.20	0.15	9.27	0.80	10.17	91.15
Btv2	8.00	2.16	0.17	0.33	10.66	0.80	11.56	92.21
BCv	5.80	1.74	0.20	0.32	8.06	0.60	8.96	89.96
ABU2								
Ap	7.20	2.16	0.15	0.37	9.88	0.40	11.18	88.37
BAt	6.40	1.95	0.16	0.32	8.83	0.60	10.33	85.47
Bt	8.40	2.52	0.16	0.36	11.44	0.60	12.94	88.41
Btv	7.80	2.34	0.25	0.38	10.77	0.60	12.27	87.78
BCv	9.40	2.82	0.22	0.44	12.88	0.40	14.18	90.83
ABU3								
Apg	7.40	2.22	0.21	0.42	10.25	0.40	11.55	88.74
ACg	9.20	2.76	0.19	0.49	12.64	0.80	14.34	88.15
2ACg	8.40	2.52	0.18	0.42	11.52	0.80	13.22	87.14
2Cg	8.40	2.60	0.13	0.72	11.85	0.80	13.55	87.45
3Cg	8.60	2.58	0.26	0.63	12.07	0.60	13.57	88.94
ABU4								
Apg	7.40	2.80	0.49	0.40	11.09	0.20	12.19	90.98
ABg	6.80	2.07	0.28	0.49	9.64	0.40	10.94	88.12
Btgv1	10.20	3.06	0.36	0.27	13.89	0.40	15.19	91.44
Btgv2	3.80	1.14	0.08	0.30	5.32	0.80	7.02	75.78
ABU5								

Note: TEB = total exchangeable bases; EA = exchangeable acidity; CEC = cation exchange capacity; BSP = base saturation percentage.

Horizon	Ca	Mg	K	Na	TEB	EA	CEC	BSP
	(cmol(+) kg⁻¹)							(%)
Apv	5.60	1.68	0.22	0.23	7.73	0.60	9.23	83.75
Cv	7.50	2.25	0.14	0.29	10.18	0.80	11.88	85.69

Note: TEB = total exchangeable bases; EA = exchangeable acidity; CEC = cation exchange capacity; BSP = base saturation percentage.

3.5 Soil taxonomic classification

The soils of the ABU Farm were classified using USDA Soil Taxonomy and the World Reference Base for Soil Resources (WRB). ABU1 had clay-enriched Bt/Btv horizons, high-activity clay and base saturation above 50%, giving an argillic horizon and placement as Typic Haplustalfs, corresponding to Haplic Luvisols (Loamic) in WRB. ABU2 had clay-enriched Bt/Btv horizons, high base saturation and plinthic material within 100 cm, resulting in Typic Plinthustalfs and Haplic Plinthosols (Loamic), respectively. ABU3 had gleyed horizons from the surface, prominent redoximorphic features and irregular horizon development, resulting in Aquic Ustifluvents and Fluvic Gleysols (Loamic). ABU4 had redoximorphic features from the surface, a clay-enriched Btgv horizon and plinthic material within the subsoil, resulting in Typic Plinthaqualfs and Stagnic Plinthosols (Loamic). ABU5 was very shallow, with limited horizon development and a petroplinthic condition near the surface, resulting in Lithic Ustorthents and Petric Plinthosols (Loamic), subject to confirmation of the lithic contact required for the USDA subgroup.

The resulting classification showed correspondence between the major diagnostic properties of the mapping units and their respective taxonomic classes. ABU1 was separated by argillic horizon development without the additional features required for plinthic or aquic classes, ABU2 by the combination of argillic and plinthic features, ABU3 by gleying and fluvic characteristics, ABU4 by the combination of aquic, argillic and plinthic features, and ABU5 by shallow profile development and petroplinthic conditions. The USDA Soil Taxonomy and WRB classifications for the five mapping units are presented in Table 6.

Table 6
USDA Soil Taxonomy (Soil Survey Staff, 2022b) and World Reference Base (IUSS Working Group WRB, 2022) classification of the five soil mapping units.

Soil mapping unit	USDA Soil Taxonomy	WRB (2022)
ABU1	Typic Haplustalfs	Haplic Luvisols (Loamic)
ABU2	Typic Plinthustalfs	Haplic Plinthosols (Loamic)
ABU3	Aquic Ustifluvents	Fluvic Gleysols (Loamic)
ABU4	Typic Plinthaqualfs	Stagnic Plinthosols (Loamic)
ABU5	Lithic Ustorthents	Petric Plinthosols (Loamic)

3.6 Multivariate differentiation of soil mapping units

Principal component analysis (PCA) of the standardized profile-level soil properties yielded four principal components (Fig. 4a), the maximum possible with five observations, which by construction account for 100% of the total variance. PC1 had the highest eigenvalue (13.11) and explained 48.54% of the variance, while PC2 had an eigenvalue of 6.44 and accounted for 23.86%, giving a cumulative contribution of 72.41%. PC3 and PC4 accounted for 16.29% (eigenvalue = 4.40) and 11.30% (eigenvalue = 3.05), respectively. The variable loadings (Table 7) showed that PC1 was associated mainly with exchangeable sodium percentage (0.266), total exchangeable bases (0.255), calcium (0.250), magnesium (0.243), sodium (0.242) and sodium adsorption ratio (0.242). PC2 had positive loadings for potassium (0.376), permanent wilting point (0.350), silt (0.292) and available phosphorus (0.260), and negative loadings for clay (− 0.325) and pH($CaCl_2$) (− 0.289). Potassium, permanent wilting point, clay, exchangeable sodium percentage and calcium were among the variables contributing most to PC1 and PC2 (Fig. 4d).

Table 7
Variable loadings, eigenvalues and variance explained for the four principal components extracted from the standardized profile-level soil properties of the five mapping units (n = 5).

Variable	PC1	PC2	PC3	PC4
Sand	0.190	0.128	0.010	-0.373
Silt	-0.036	0.292	-0.134	0.340
Clay	-0.142	-0.325	0.088	0.084
BD	-0.225	-0.146	0.212	-0.034
PD	-0.214	0.111	0.239	-0.151
TP	0.207	0.213	-0.183	-0.004
Ks	0.116	0.218	0.036	0.410
FC	0.234	0.181	-0.119	-0.055
PWP	0.113	0.350	0.006	0.120
AWC	0.207	-0.119	-0.259	-0.135
pH(H_2O)	0.213	-0.163	0.213	0.110
pH($CaCl_2$)	0.118	-0.289	-0.020	0.301
ΔpH	0.199	0.019	0.319	-0.105
EC	-0.197	0.206	0.191	0.137
Ca	0.250	-0.150	0.087	-0.005
Mg	0.243	-0.057	0.214	-0.047
K	0.048	0.376	0.112	-0.040
Na	0.242	-0.072	0.187	0.118
TEB	0.255	-0.107	0.133	-0.004
EA	-0.090	-0.242	-0.116	0.387
CEC	0.230	-0.129	0.211	-0.003
BSP	0.112	0.011	-0.435	0.035
ESP	0.266	0.075	0.084	0.054
SAR	0.242	-0.031	0.205	0.120
OC	-0.174	0.070	0.208	0.354
TN	0.233	0.079	-0.106	0.257

Variable	PC1	PC2	PC3	PC4
Avail. P	-0.091	0.260	0.321	-0.012
Eigenvalue	13.11	6.44	4.40	3.05
Variance explained (%)	48.54	23.86	16.29	11.30
Cumulative variance (%)	48.54	72.41	88.70	100.00

Sand, silt and clay are particle-size fractions; BD, bulk density; PD, particle density; TP, total porosity; Ks, saturated hydraulic conductivity; FC, field capacity; PWP, permanent wilting point; AWC, available water capacity; OC, organic carbon; TN, total nitrogen; Avail. P, available phosphorus; EC, electrical conductivity; TEB, total exchangeable bases; EA, exchangeable acidity; CEC, cation exchange capacity; BSP, base saturation percentage; ESP, exchangeable sodium percentage; SAR, sodium adsorption ratio.

Hierarchical cluster analysis based on standardized soil properties, Euclidean distance and Ward's method separated the five profile pits into two clusters at a tree height of approximately 8.5 (Fig. 5a). Cluster 1 comprised ABU1, ABU2, ABU3 and ABU4, whereas ABU5 formed a separate cluster. Silhouette assessment gave the highest mean silhouette width for the two-cluster solution (0.15), compared with 0.11 for three clusters and 0.07 for four clusters (Fig. 5c); even the highest value was low, indicating weak cluster structure. The standardized heatmap (Fig. 5b) showed that ABU5 had comparatively high positive z-scores for clay, organic carbon, electrical conductivity, bulk density and particle density, and negative z-scores for exchangeable bases and field capacity. Pairwise Euclidean distances among the five profiles (Fig. 5d) ranged from 5.49 between ABU2 and ABU3 to 9.81 between ABU5 and ABU3, indicating greater multivariate separation of ABU5 from the other profile observations.

4. Discussion

4.1 Landscape differentiation and delineation of soil mapping units

The delineation of five soil mapping units within the relatively small area of the Ahmadu Bello University Farm indicates that appreciable pedological variability can occur even within a managed agricultural landscape. The units were separated using a combination of landscape position, profile depth, drainage, field texture, colour, horizon development and other morphological attributes rather than relying on a single diagnostic property. This approach is consistent with conventional soil survey practice in which mapping units represent spatially associated populations of soils distinguished by observable differences in morphology and site characteristics (Jimoh et al., 2016b; Sadiq et al., 2021b). Similar studies in the Northern Guinea Savanna of Nigeria have reported that soil depth, texture, drainage, landscape position, subsoil clay accumulation and the presence or absence of hardened plinthic materials are effective criteria for separating soil mapping units (Awwal & Maniyunda, 2023; Sadiq et al., 2021b). For example, studies around Zaria and other parts of the Guinea Savanna have delineated

mapping units using combinations of colour, texture, drainage and depth, subsequently showing substantial differences in their classification and agricultural characteristics (Awwal & Maniyunda, 2023). The relatively large extent of ABU1 compared with the smaller ABU3, ABU4 and ABU5 units is consistent with spatial differences in the distribution of soil-forming conditions rather than an arbitrary subdivision of the farm.

The spatial pattern of the units also suggests that relief and hydrological position may have influenced the expression of soil development. The occurrence of deep, relatively well-developed profiles in some parts of the landscape contrasts with the shallow and poorly drained profiles represented by other units. Such variation is expected where differences in surface position, water movement, erosion and deposition modify the balance between soil formation and material removal or accumulation (Sadiq et al., 2021b). In Northern Guinea Savanna landscapes, differences in soil depth and horizon development have similarly been related to landscape position, parent material and erosion, while lower landscape positions may experience greater water accumulation and contrasting pedogenic conditions (Awwal & Maniyunda, 2023; Jimoh et al., 2020). Thus, the mapping units may be interpreted as a spatial expression of differences in the local soil-forming environment.

4.2 Morphological differentiation and profile development

The morphological characteristics provide the strongest evidence that the five mapping units represent distinct pedological environments. ABU1 and ABU2 were deep profiles with well-expressed subsurface horizons and progressive clay enrichment, indicating more advanced profile differentiation than the shallow ABU5 profile. The increase in clay from the surface into the Bt and Btv horizons of ABU1 and ABU2 corresponds with the field recognition of argillic horizons and indicates substantial differentiation between surface and subsurface materials. Comparable increases in subsoil clay have been reported for Northern Guinea Savanna soils and are commonly associated with clay translocation and accumulation within the profile (Awwal & Maniyunda, 2023; Sharu et al., 2026). Such differentiation is important because it may reflect cumulative pedogenic change, although lithological discontinuities cannot be excluded without micromorphological or mineralogical evidence.

The contrast between ABU1 and ABU2 also indicates that similar degrees of profile development can occur under different hydrological and pedogenic conditions. Both units contain clay-enriched horizons, but ABU2 additionally exhibits plinthic features, suggesting a stronger expression of processes associated with periodic wetting, drying and iron concentration. Plinthic materials are widespread in savanna soils of Nigeria and may occur at different depths depending on landscape position and hydrological conditions (Oluwatosin et al., 2020; Yaro et al., 2006). Their presence within ABU2 therefore adds an important dimension to the differentiation that would not be captured by texture alone.

ABU3 represents a markedly different pedogenic environment. The profile is deep but dominated by gley-related horizons from the surface, with grey matrix colours and mottling throughout the profile. Rather than indicating limited soil development, these features suggest prolonged or recurrent influence of water saturation and restricted drainage. Similar gleying features have been documented in seasonally

saturated soils of Nigerian savanna landscapes, particularly where geomorphic position promotes water accumulation (Jimoh et al., 2020; Sharu et al., 2026). The association of gleying with fluvic characteristics in ABU3 is therefore consistent with a landscape position where deposition and periodic saturation have influenced profile development.

ABU4 combines shallow-to-moderate depth with strong mottling, greyish colours and a clay-enriched subsurface horizon. This combination is particularly informative because it suggests that profile differentiation has occurred under conditions where water movement and periodic saturation have strongly influenced the soil environment. The presence of plinthic material further suggests repeated redox conditions capable of concentrating and reorganizing iron within the subsoil. Similar combinations of argillic, aquic and plinthic characteristics have been reported in Nigerian savanna soils and have been used to distinguish closely associated mapping units and taxonomic classes (Adekiya et al., 2022; Jimoh et al., 2020).

ABU5 represents the most restricted form of profile development, with only 23 cm of described soil above the underlying material. Its shallow depth and very high clay content in the surface horizon distinguish it strongly from the deeper units. Where shallow soils over hardened materials occur in savanna landscapes, effective soil depth becomes a major control on profile development, water storage and root penetration (Oluwatosin et al., 2020; Yaro et al., 2006). The occurrence of petroplinthic material near the surface is therefore pedologically important and provides a stronger basis for distinguishing ABU5 than its textural characteristics alone.

4.3 Physical properties and implications for soil differentiation

The physical properties reinforce the morphological distinction among the mapping units. The broad range in clay content may reflect differences in both parent material distribution and pedogenic redistribution within profiles. In ABU1 and ABU2, increasing clay with depth corresponds closely with the Bt and Btv horizons, providing analytical support for the morphological evidence of clay accumulation. Similar vertical clay differentiation has been widely reported in cultivated soils of northern Nigeria and has been associated with eluviation from surface horizons and accumulation in subsurface horizons (Awwal et al., 2022; Jimoh et al., 2020).

Bulk density and total porosity also varied considerably among the units. Bulk density and porosity did not vary systematically with depth. The lowest bulk density and highest porosity occurred in the surface horizon of ABU3, possibly reflecting a more open structure, whereas the high bulk densities of the surface horizons of ABU2 and ABU5 and of the deepest horizons of ABU1 and ABU3 indicate greater packing and fewer transmission pores. These differences may help explain the contrasting saturated hydraulic conductivity observed among the profiles. However, hydraulic conductivity did not follow clay content alone, indicating that pore continuity, aggregation, structure and compaction also contribute to water transmission (Awwal et al., 2022; Sadiq et al., 2021b). This is evident in the contrasting conductivity values among horizons having similar textural classes.

The water-retention properties further distinguish the units. Higher field capacity and available water storage in some clay-enriched horizons are consistent with the greater capacity of fine-textured materials to retain water, although available water capacity was not uniformly controlled by clay content. The contrasting relationship reflects the combined influence of texture, bulk density, pore-size distribution and the degree of structural development (Awwal et al., 2022). Because AWC is expressed per horizon, it also depends on horizon thickness. Consequently, the physical data indicate that the mapping units differ not only in their morphological appearance but also in functional properties related to water storage and movement.

4.4 Chemical differentiation and soil-forming environment

The chemical properties provide additional evidence of pedological differentiation, although their patterns are less spatially systematic than the morphological and physical properties. Soil reaction ranged from strongly acidic to neutral, while base saturation remained relatively high across the profiles. This combination is consistent with the generally base-rich character reported for many soils developed on Basement Complex materials in the Northern Guinea Savanna (Jimoh et al., 2020; Sadiq et al., 2021a). Comparable studies in the Zaria region have reported relatively high exchangeable base contents and base saturation in soils developed on similar geological materials (Jimoh et al., 2020; Sadiq et al., 2021a).

The variation in exchangeable Ca, Mg, K and Na among horizons indicates differences in the distribution and retention of base cations within the profiles. Calcium and magnesium were the dominant exchangeable bases, which is consistent with observations from other savanna soils of northern Nigeria (Jimoh et al., 2020; Sadiq et al., 2021a). Differences among horizons may reflect variation in mineral weathering, redistribution with percolating water, organic matter inputs and clay-associated exchange sites rather than a single controlling process. The relatively high base saturation across the profiles also helps explain the occurrence of Alfisol-related and Luvisol-type classifications among several mapping units.

Organic carbon and total nitrogen showed pronounced vertical and between-profile variation, with the highest concentrations of organic carbon (ABU4) and total nitrogen (ABU3) occurring in surface horizons. This is consistent with the concentration of plant residues and biological activity near the soil surface. However, concentrations did not decline regularly with depth in all profiles (e.g., ABU3 and ABU5), which may reflect the stratified, fluvic character of ABU3 and local differences in drainage, vegetation inputs, cultivation and decomposition (Awwal et al., 2022; Sadiq et al., 2021b); this should be interpreted cautiously because each unit is represented by a single profile. The relatively low electrical conductivity across the profiles indicates that soluble salts were not a major differentiating feature of these soils. Similarly, the variation in available phosphorus may reflect differences in surface inputs and soil retention processes rather than a broad separation of the mapping units by phosphorus status.

4.5 Taxonomic expression of pedological differentiation

The taxonomic classifications provide an integrated expression of the morphological differences identified among the mapping units. ABU1 was classified as Typic Haplustalfs and Haplic Luvisols, reflecting its well-developed clay-enriched subsurface horizons and relatively high base status. ABU2 was distinguished by the additional presence of plinthic characteristics, resulting in Typic Plinthustalfs and Haplic Plinthosols. The progression from ABU1 to ABU2 therefore illustrates how the addition of a specific pedogenic feature can shift taxonomic placement even where the two profiles share broad similarities in depth and clay accumulation.

ABU3 and ABU4 illustrate the importance of hydrological conditions in soil classification. The gleyed and fluvic characteristics of ABU3 resulted in its classification as Aquic Ustifluvents and Fluvic Gleysols, whereas the combination of aquic, argillic and plinthic features in ABU4 resulted in Typic Plinthaqualfs and Stagnic Plinthosols. Comparable taxonomic sequences have been reported from Northern Guinea Savanna landscapes, where closely associated soils may range from Alfisols and Luvisols on better-drained positions to Gleysols and aquic subgroups in lower or seasonally saturated positions (Awwal et al., 2026; Jimoh et al., 2020). This correspondence suggests that the taxonomic differences observed in the present study reflect measurable differences in soil morphology and profile development rather than merely differences in nomenclature.

ABU5 was distinctly separated by its shallow profile and petroplinthic condition and was placed in Lithic Ustorthents and Petric Plinthosols, respectively. The USDA classification should, however, be interpreted subject to confirmation of the lithic contact required for the subgroup designation. The occurrence of shallow soils associated with hardened plinthic materials is well documented in Nigerian savanna environments, where petroferric or petroplinthic layers can strongly constrain effective soil depth and differentiate adjacent soil units (Yaro et al., 2006). The taxonomic results therefore reinforce the usefulness of combining field morphology with laboratory characterization when defining mapping units.

4.6 Multivariate differentiation among mapping units

The PCA and hierarchical cluster analysis provide a quantitative summary of the multidimensional differences observed among the profiles. The first principal component accounted for 48.54% of the total variance and was dominated by exchangeable bases, total exchangeable bases, calcium, magnesium, sodium and sodium-related indices. This indicates that the major axis of variation among the profile observations was associated principally with the distribution of exchangeable cations and overall base status. The second component, which explained 23.86% of the variance, contrasted potassium, water-retention characteristics, silt and available phosphorus with clay and pH measured in $CaCl_2$. Together, the first two components therefore captured more than 70% of the observed multivariate variation.

The strong contribution of exchangeable bases to PC1 is consistent with the chemical differences observed among the profiles. Clay loaded negatively on PC2, opposite to potassium, permanent wilting point, silt and available phosphorus, so this axis partly expresses textural contrast among the profiles. The PCA therefore does not introduce an independent pedological pattern; rather, it summarizes several

measured properties that collectively express the differences already identified through profile description and laboratory analysis.

Ward's cluster analysis further separated ABU5 from ABU1–ABU4. This separation is understandable in light of the distinctive properties of ABU5, particularly its shallow profile and contrasting clay, bulk density, organic carbon and exchange-property characteristics. Similarity among ABU1–ABU4 does not imply that these units are pedologically identical, but rather that their overall multivariate property profiles were more similar than that of ABU5. The low silhouette width of 0.15 indicates weak cluster separation, so the analysis should be regarded as exploratory rather than as independent statistical confirmation of five discrete populations. This limitation is particularly important because the multivariate analysis was based on only five profile-level observations described by 27 variables, so the loadings and cluster structure are likely to be unstable, and a single profile per mapping unit cannot represent within-unit variability. The multivariate results therefore describe the five sampled profiles rather than the mapping units as populations. Its principal value in the present study is therefore to identify broad patterns of multivariate similarity and difference that complement, rather than replace, field-based pedological interpretation.

4.7 Integrated pedological interpretation

The results indicate that the differentiation of the five mapping units reflects the interaction of contrasting landscape and soil-forming conditions. ABU1 and ABU2 represent relatively deep, clay-differentiated profiles, with ABU2 showing additional plinthic expression. ABU3 is distinguished primarily by deep gleyed and fluvic characteristics associated with prolonged hydrological influence, whereas ABU4 combines restricted depth, strong redoximorphic expression, clay enrichment and plinthic features. ABU5 represents a shallow soil environment strongly constrained by hardened material. These differences are consistent with the major pedogenic pathways recognized in Northern Guinea Savanna soils, including clay translocation, wetting and drying, redoximorphic redistribution of iron, accumulation of materials in lower landscape positions and restriction of profile development by hardened subsurface materials (Awwal et al., 2026; Sharu et al., 2026).

The findings also suggest why mapping-unit delineation based only on surface texture or a single laboratory property would be inadequate for this landscape. Several units share broad chemical characteristics, yet differ substantially in depth, horizon development, drainage expression and subsurface morphology. Conversely, some units with similar morphological features differ in their physical and chemical properties. The most meaningful differentiation therefore emerges from the integration of landscape position, morphology, physical properties, chemical characteristics and taxonomic criteria. This integrated interpretation is consistent with conventional soil survey studies in northern Nigeria, where combinations of morphology, depth, texture, drainage and diagnostic horizons have provided the basis for resolving spatial soil variability (Awwal et al., 2026).

The study therefore suggests that even within a relatively small agricultural research landscape, soil variability can reflect distinct pedological pathways. The mapping units are therefore not simply

cartographic subdivisions but spatially coherent soil entities with different combinations of profile development, hydrological expression, physical behaviour and chemical characteristics. Their delineation provides a more detailed soil information framework for subsequent land evaluation, crop suitability assessment and site-specific management, while the exploratory multivariate results provide a complementary quantitative perspective on the degree of similarity among the mapped units. Because each unit was represented by a single profile, within-unit variability was not quantified, and additional pedons per unit would be needed to test the mapping-unit boundaries statistically.

5. Conclusion

The study indicated clear pedological differentiation within the Ahmadu Bello University Farm through the integration of field-based soil survey, profile morphology, laboratory characterization and taxonomic classification. Five major soil mapping units were delineated from landscape position, soil depth, drainage, texture and morphological continuity. The units showed distinct combinations of horizon development, colour, mottling, texture, structure and profile depth, which were further supported by differences in particle-size distribution, bulk density, porosity, hydraulic conductivity, water retention and chemical properties.

The taxonomic assessment showed that the delineated mapping units encompassed soils with contrasting diagnostic characteristics, including argillic, gley-related and plinthic features and differences in profile development. These differences resulted in distinct USDA Soil Taxonomy and WRB classifications, supporting the interpretation that the mapping units represent meaningful pedological subdivisions of the study landscape. The exploratory PCA and hierarchical clustering provided additional quantitative evidence of multivariate differentiation, particularly the distinct position of ABU5, although the small number of profile observations limits the extent to which these multivariate patterns can be generalized. Overall, the integration of landscape-based delineation with detailed pedon characterization and complementary taxonomic systems provided a coherent framework for resolving soil variability within the farm and offers a useful basis for subsequent soil survey, land evaluation and site-specific soil management in similar Northern Guinea Savanna agricultural landscapes.

Declarations

Competing interests:

The authors declare that they have no competing interests.

Clinical trial number

Not applicable.

Consent to publish:

Not applicable.

Ethical approval:

Not applicable.

Consent to participate:

Not applicable. This study did not involve human participants or animals.

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Author Contribution

Wonchiko A. conceptualised and led the research, coordinated the study, and prepared the manuscript. S. L. Yau supervised the research and provided academic guidance. A. Awwal Agono and A. H. Ahmad contributed to fieldwork and assisted with the GIS analysis. S. Gisilanbe, A. B. Shobayo, and A. Jamila participated in the fieldwork. W. O. J. Kadiri reviewed the work and contributed to its improvement. All authors contributed to the research in their respective capacities and provided input toward the manuscript.

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Data Availability Statement:

The datasets generated and analyzed during the current study are available from the corresponding author upon reasonable request.

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Figures

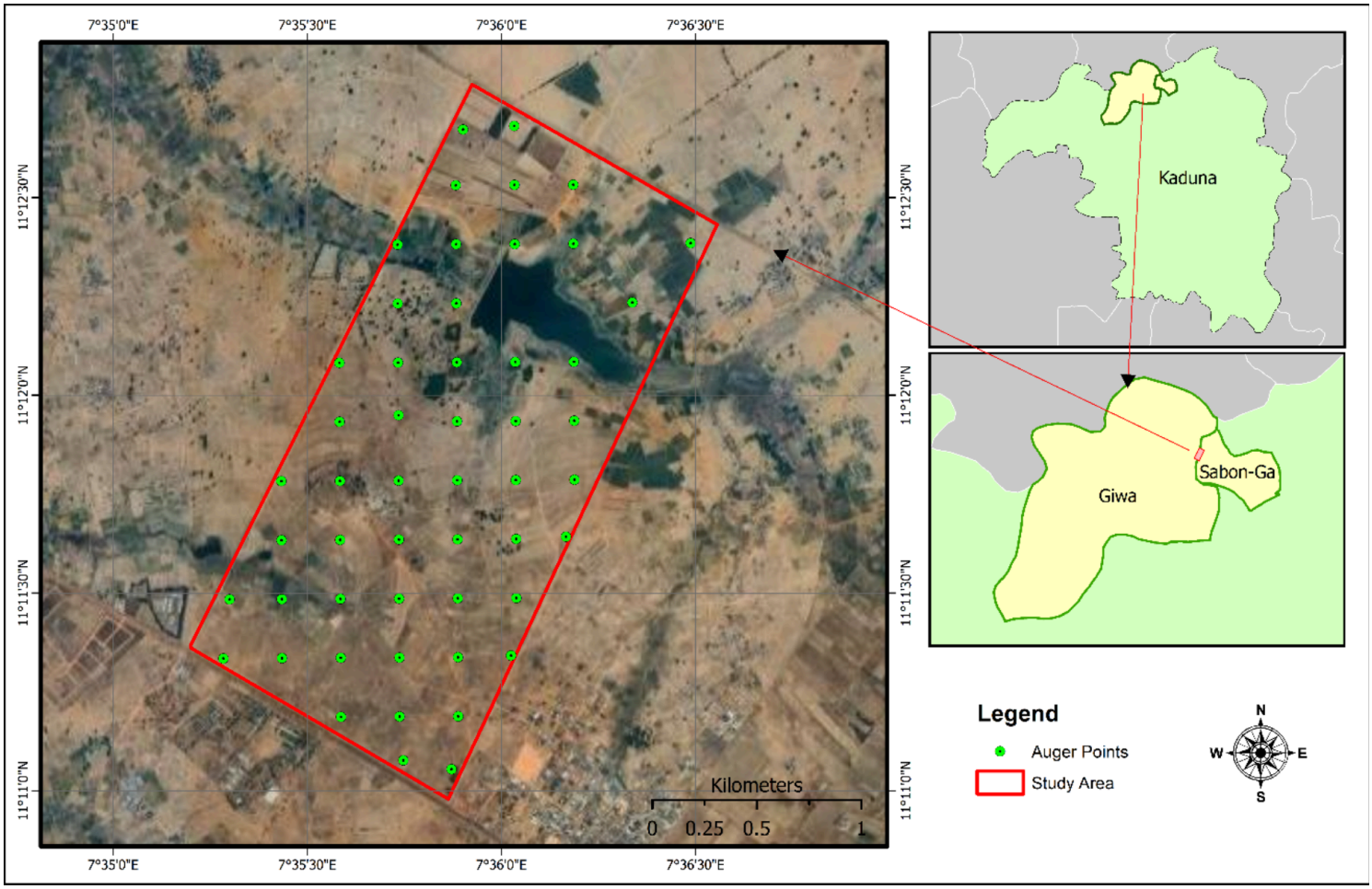


Figure 1

Location of the study area at the Ahmadu Bello University Farm, Shika, Zaria (Giwa and Sabon Gari Local Government Areas, Kaduna State, Nigeria), showing the auger observation points and the study area boundary on satellite imagery.

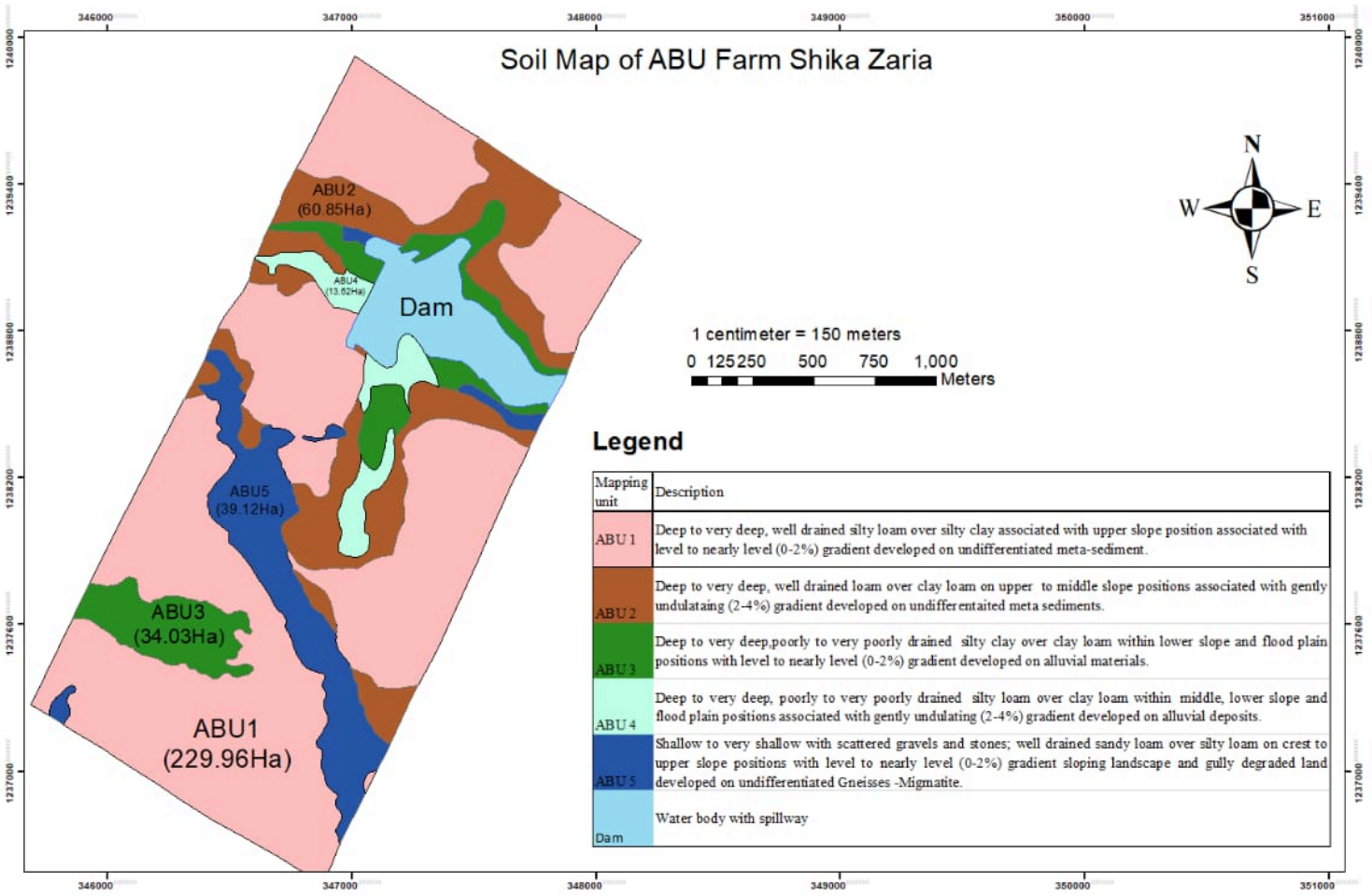


Figure 2

Soil map of the Ahmadu Bello University Farm, Shika, Zaria, showing the five soil mapping units (ABU1–ABU5) and the farm dam. Unit areas are given in hectares (Table 1).

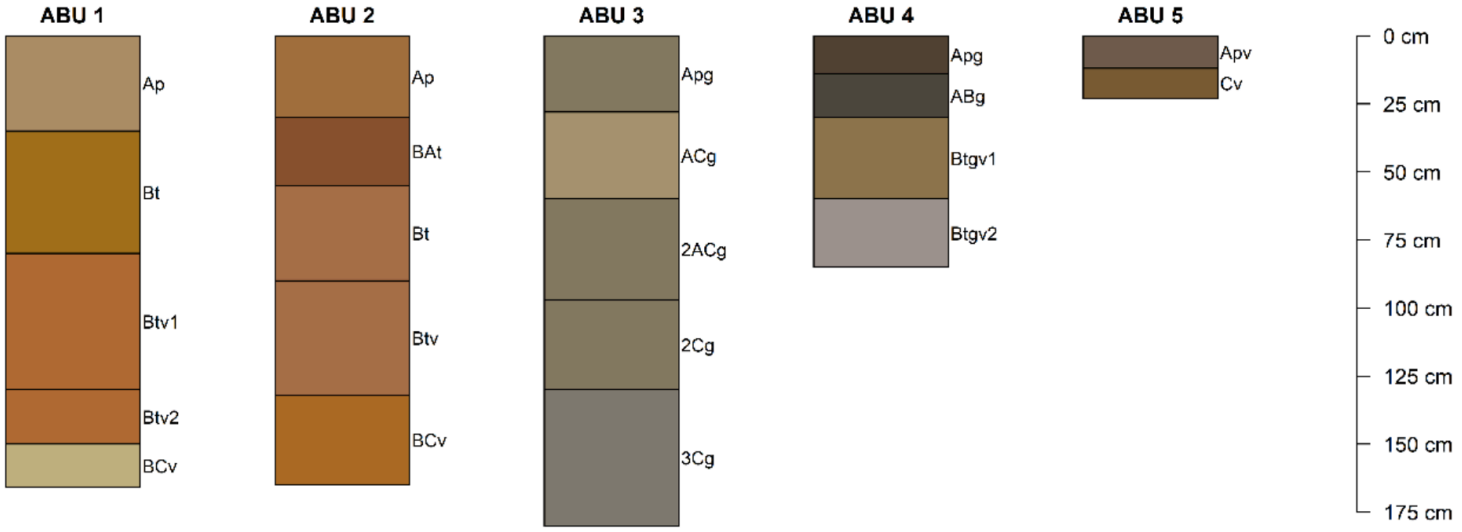


Figure 3

Schematic profile diagrams showing horizon depths and moist matrix colours of the representative profiles of the five soil mapping units (ABU1–ABU5). Colours were assigned from the Munsell notations recorded in the field.

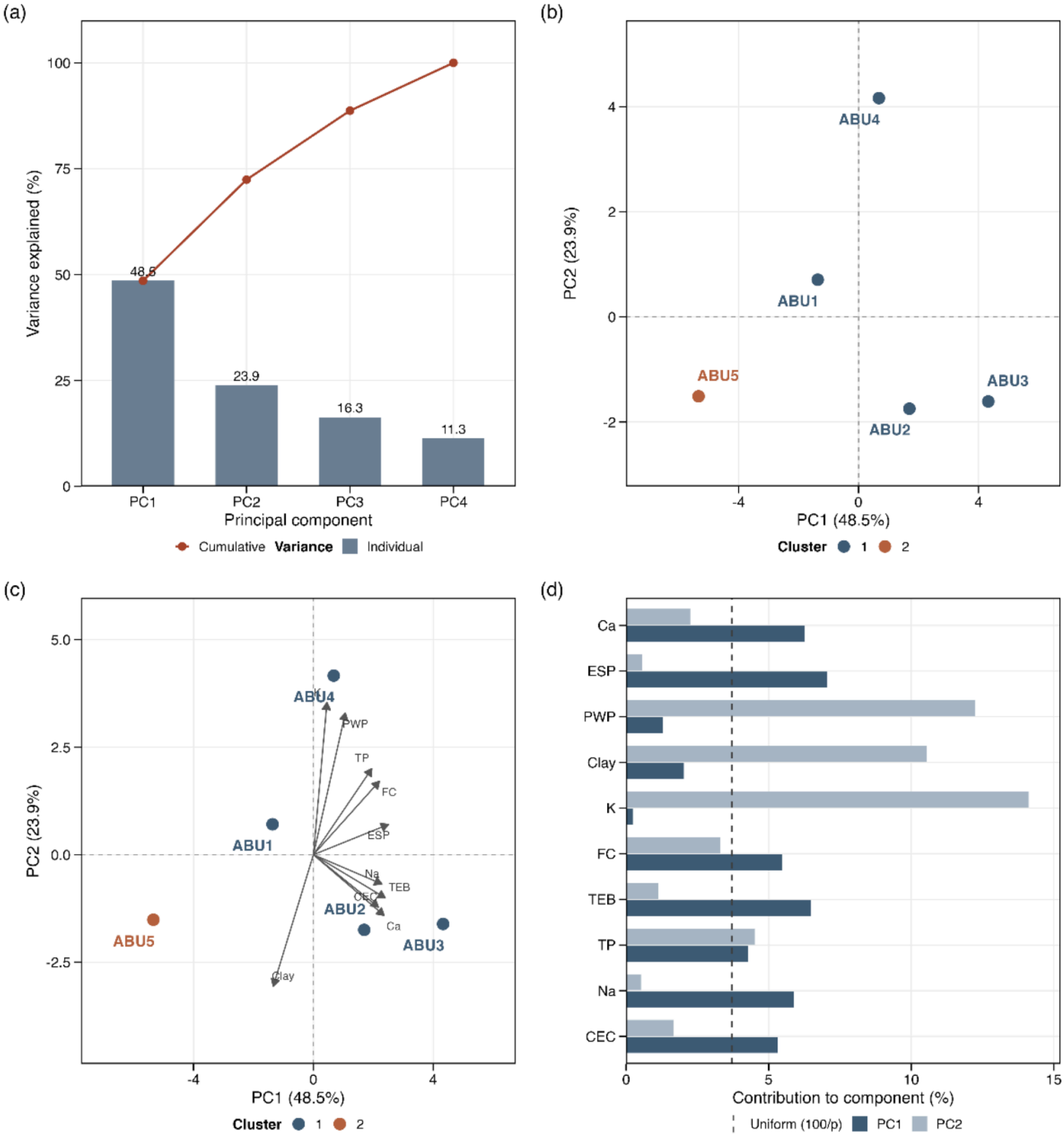


Figure 4

Principal component analysis of the standardized profile-level soil properties of the five mapping units: (a) individual and cumulative variance explained by each component; (b) PC1–PC2 score plot, with units coloured by cluster; (c) PC1–PC2 biplot showing the loadings of selected variables; (d) percentage contributions of the ten variables contributing most to PC1 and PC2 (the dashed line marks the contribution expected if all variables contributed equally, 100/p %).

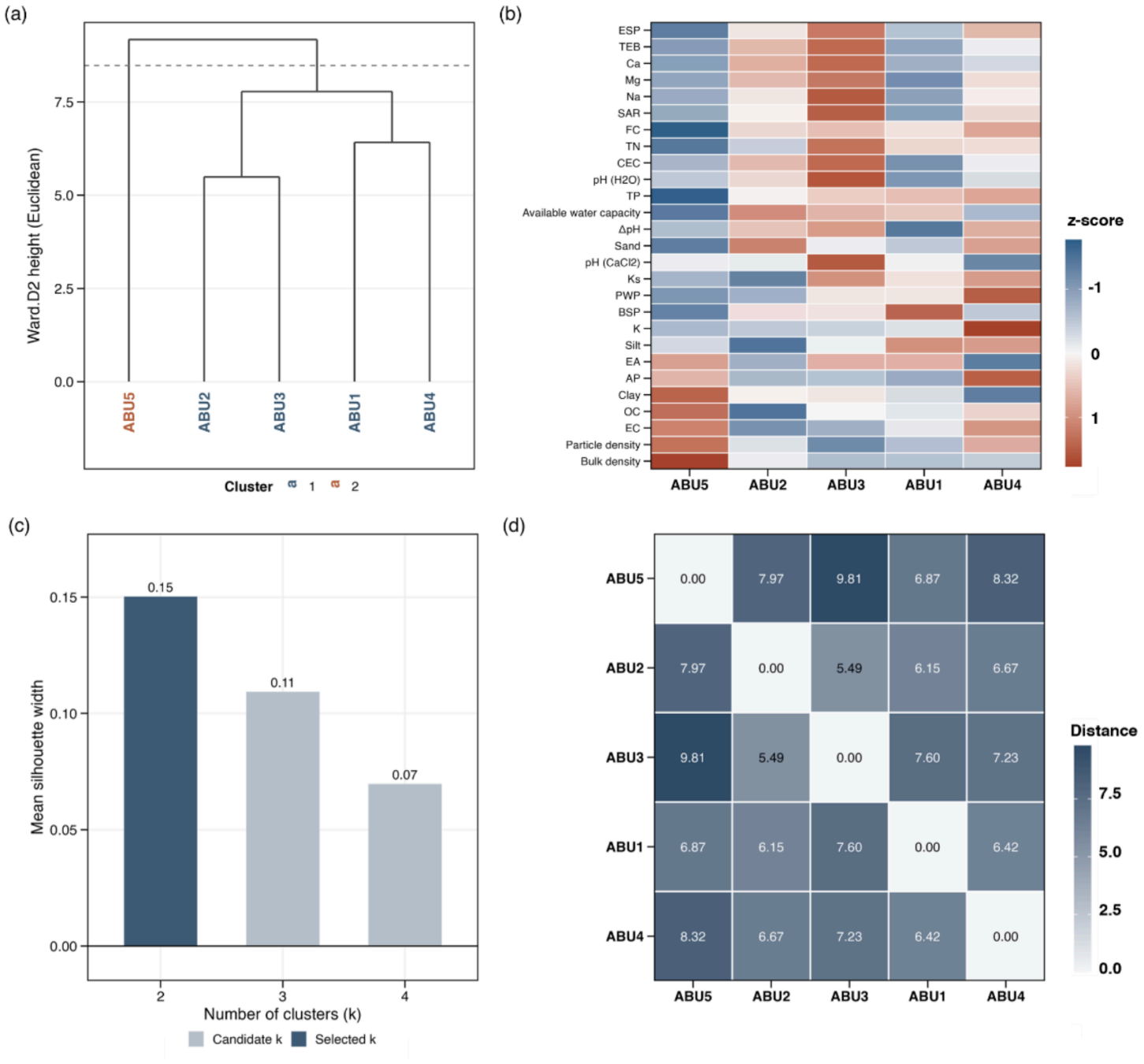


Figure 5

Hierarchical cluster analysis (Euclidean distance, Ward.D2) of the five profile-level observations: (a) dendrogram, with the dashed line marking the cut height (≈ 8.5); (b) heatmap of standardized (z-score)

soil properties; (c) mean silhouette width for two to four clusters; (d) pairwise Euclidean distances among the mapping units.