

PEDOLOGICAL CHARACTERISATION, SPATIAL VARIABILITY, AND GIS-BASED MAPPING OF SOILS ACROSS CONTRASTING LAND MANAGEMENT AND LANDSCAPE SYSTEMS IN OKITIPUPA, SOUTHWEST NIGERIA

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ABSTRACT

Soil characterization is fundamental to sustainable land management, yet baseline pedological data remain limited for rapidly expanding institutional landscapes in southwestern Nigeria. The Olusegun Agagu University of Science and Technology (OAUSTECH) in Okitipupa covers approximately 400 ha of heterogeneous land uses, producing complex spatial variability in soil properties, with no prior comprehensive soil inventory. This study aimed to morphologically characterize and taxonomically classify soils across three contrasting land management and landscape systems, evaluate the effects of land use and depth on key soil properties, and develop GIS-based spatial maps to improve land management. The study was carried out in 2025. A stratified random sampling approach was applied across river/stream corridors, abandoned farmland, and oil palm plantations. Nine profiles were excavated to a depth of 140-145 cm in (FL 001-003 and OP 001-003), (0-55 cm in RS 1-3), following FAO (2016) guidelines, with samples analyzed for particle-size distribution, pH, organic carbon, total nitrogen, available phosphorus, exchangeable bases, cation exchange capacity, and base saturation. Classification followed USDA Soil Taxonomy and WRB (2022) guidelines. Spatial interpolation using inverse distance weighting in ArcGIS produced 14 thematic maps, while ANOVA with Tukey's HSD test was used to determine statistical differences ($p < 0.05$). Two soil series were identified: Okitipupa series (Typic Paleustalfs / Orthidystic Acrisols) on well-drained uplands and Ode Erinje series (Fluvaqueptic Endoaquepts / Arenic Gleysols) in riverine zones. Soils were moderately to strongly acidic (pH 4.04–6.55) with sandy loam to sandy clay loam textures. Abandoned farmland recorded the highest organic matter, available phosphorus, and CEC. Land use and topography strongly influenced soil variability, providing an essential basis for site-specific management and digital soil mapping.

Keywords: soil characterization; soil classification; GIS mapping; Alfisols; Acrisols; land use; spatial variability

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1. INTRODUCTION

Soil characterisation is a cornerstone of soil science and land resources management, providing critical information on soil genesis, morphology, taxonomy, and agricultural potential. Reliable pedological inventories enable evidence-based decisions on land use planning, fertiliser management, soil conservation, and sustainable intensification-priorities that have gained renewed urgency in sub-Saharan Africa, which confronts simultaneous pressures of population growth, food insecurity, and climate variability (Lal, 2020; Dimkpa et al., 2023; African Fertiliser and Soil Health Summit, 2024). In humid tropical environments such as southwestern Nigeria, pedogenesis is governed by intense weathering, high rainfall, rapid organic matter turnover, and pronounced catenary differentiation, producing deeply weathered soils with low-activity kaolinitic clay mineralogy, acidic pH, and inherently low nutrient reserves (Buol et al., 2011; Brady and Weil, 2016; Akinbola and Adediran, 2021; Jimoh et al., 2025). Land use change further modifies these properties (Juo and Lal, 1977), with studies across the region consistently showing that conversion of secondary forest to arable land reduces SOC by 15--45%, degrades CEC, and accelerates acidification (Aweto, 2023; Akinbode et al., 2024; Falade et al., 2023).

The soils of the Okitipupa Local Government Area in Ondo State derive from coastal plain sands of the Benin Formation and unconsolidated Tertiary-Quaternary sediments, producing coarse-textured, freely draining profiles prone to nutrient leaching (Adesemuyi and Adekayode, 2020; Okunsebor et al., 2024; Nnabuihe et al., 2024). The dominant mapping units, the Okitipupa and Ode Erinje series, occupy contrasting geomorphic positions that impose divergent pedogenic pathways, yet their detailed characterisation under different land use regimes remains inadequately documented. Integration of geographic information systems (GIS), geostatistical interpolation, and multivariate statistics, including PCA, HCA, and regression modelling, now enables high-resolution mapping and decomposition of complex soil data into interpretable management-relevant units (Umeobi et al., 2024; Abdi and Williams, 2010; Kaufman and Rousseeuw, 2009;

Adeniyi et al., 2024; Padarian et al., 2019). The OAUSTECH Teaching and Research Farm presents a unique natural experiment: a confined 400-ha campus supporting three well-defined management and landscape systems, riparian corridors (river/stream floodplains), abandoned farmland, and oil palm plantations on comparable parent material under the same macro-climate. This configuration isolates the independent effects of land use and topographic positions on soil properties, yielding insights generalizable to broader coastal plain sand landscapes. Spatial variability fundamentally affects interpretative modelling and management recommendations in such soil surveys (Wilding et al., 1994), and continental-scale assessments confirm that soil organic carbon stocks in sub-Saharan Africa are controlled by climate, terrain, and land use (von Fromm et al., 2021; Suh and Tsheko, 2024). No systematic pedological characterization had previously been attempted. The objectives of this study were therefore to: (i) characterize morphological, physical, and chemical soil properties across the three management-landscape units; (ii) classify soils according to USDA Soil Taxonomy (2022) and WRB (2022); (iii) assess land

use and depth effects via one-way ANOVA with Tukey's HSD; (iv) apply PCA, HCA, multiple linear regression, and Pearson correlation analysis to identify latent structure; and (v) generate GIS-based spatial distribution maps as a baseline for sustainable land management.

2. MATERIALS AND METHODS

2.1 Study Area

The study was conducted at the OAUSTECH T& RF, Okitipupa, Ondo State, Nigeria (6°30'--6°40'N; 4°45'--4°55'E; ~50--100 m a.s.l.; ~400 ha). The climate is humid tropical with bimodal rainfall (1,500--2,500 mm annually; peaks April--July and September--October), mean annual temperature 27--30°C, and relative humidity 75--85%. Geology is predominantly coastal plain sands of the Benin Formation (Tertiary--Quaternary unconsolidated sands and sandy clay), overlying Precambrian Basement Complex rocks. The gently undulating topography, dissected by seasonal streams, creates distinct upland, slope, and floodplain catenary positions. Secondary forest, fallow land, oil palm plantations, and built-up areas have largely replaced natural tropical rainforest.

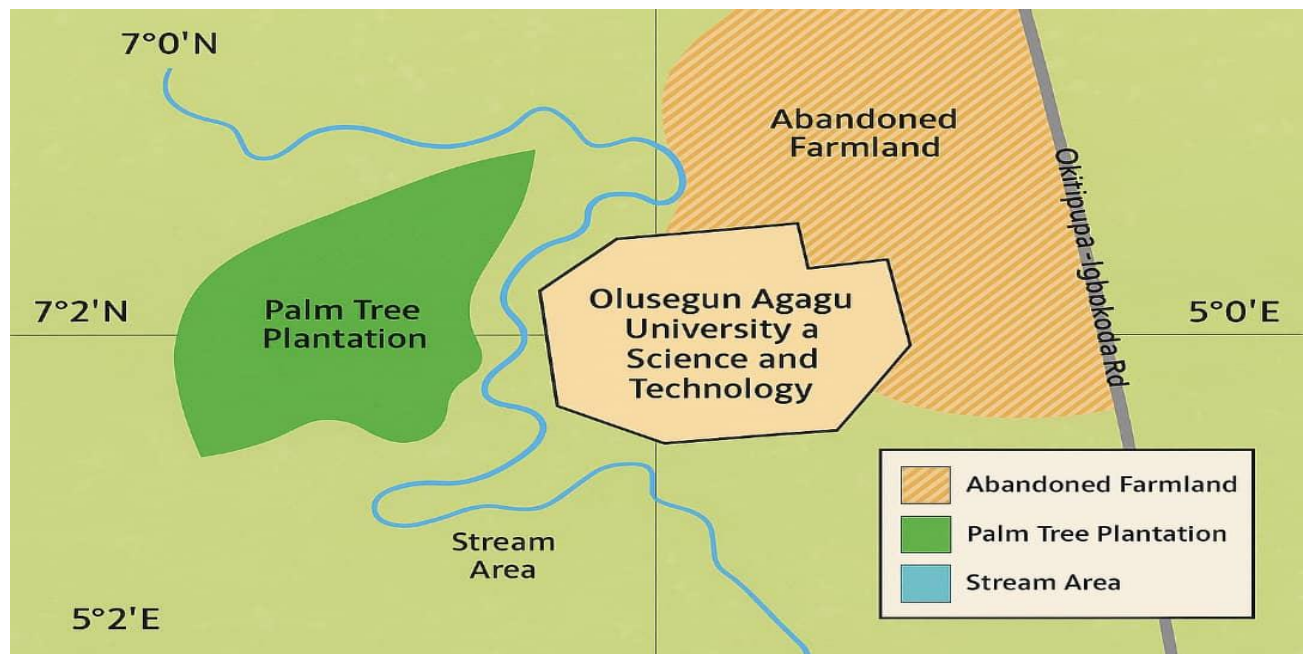


Figure 1: Location map of the study area

2.2 Reconnaissance Survey and Sampling Design

A reconnaissance survey documented land use types, topographic units, vegetation, and drainage patterns. Three management-landscape units, representing distinct land management regimes on contrasting topographic positions, were selected: (1) riparian corridor/river/stream floodplain (RS); (2) abandoned farmland (FL); and (3) oil palm plantation (OP). Three representative sites per unit were selected by stratified random sampling, yielding nine profile pits (RS001--

RS003, FL001--FL003, OP001--OP003), each 1.5 m × 1.0 m × 1.45 m and excavated to 145 cm or to an impermeable horizon. Composite surface samples (0--22 cm) were collected at three sub-sites within a 10 m radius of each pit. Profile descriptions followed FAO (2006) guidelines, recording horizon designations, depth, boundary characteristics, Munsell colour (moist), texture, structure, consistence, drainage, redoximorphic features, root distribution, and biological activity.

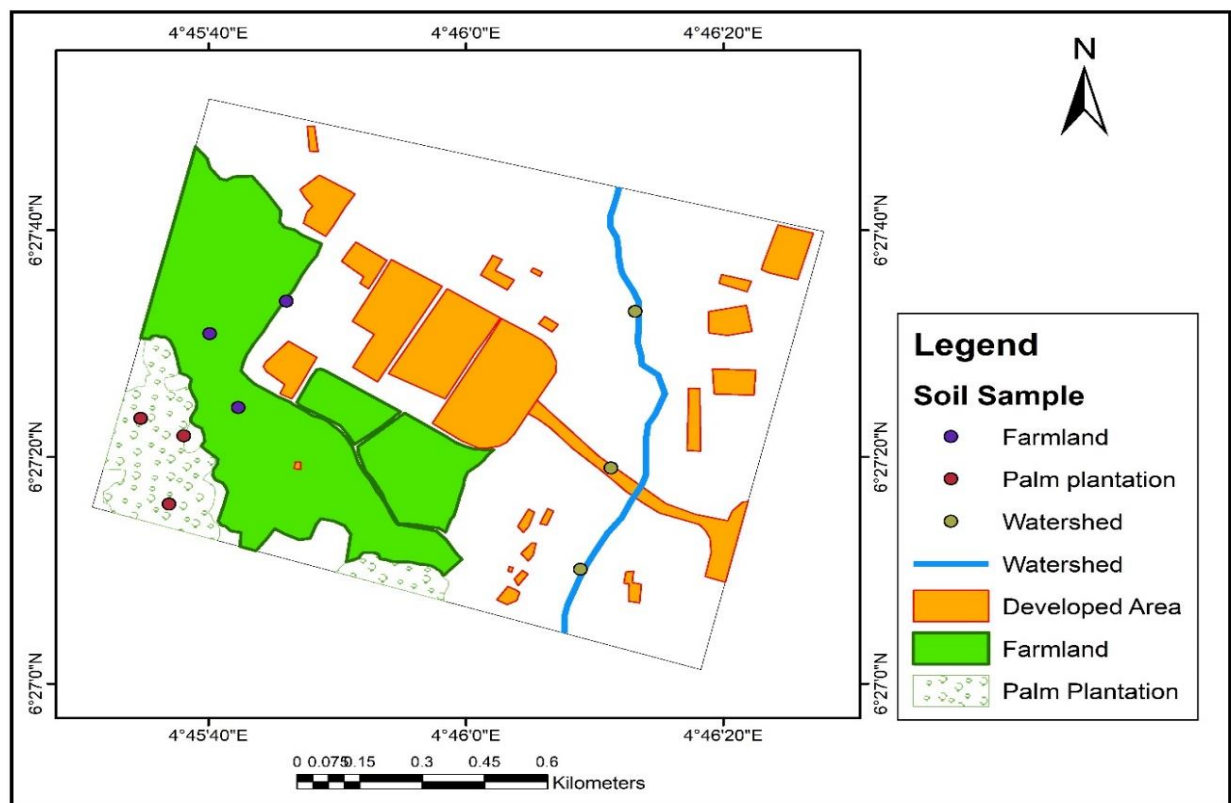


Figure 2: Map Sampling point

Figure 2: Sampling point map showing the three management-landscape units (river/stream floodplain, abandoned farmland, and oil palm plantation) within the broader watershed context; built-up areas and watershed boundaries are shown for geographic reference but were not included in the sampling design.

2.3 Morphological Description

Detailed profile descriptions followed FAO (2016) guidelines, recording horizon designations, depth and boundary characteristics, Munsell colour (moist), texture (field assessment), structure, consistence, drainage class, redoximorphic features, root distribution, and biological activity. Standardized field forms were completed, and all profiles photographed.

2.4 Laboratory Methods

Soil samples were air-dried, crushed, and sieved at 2 mm; subsamples for Organic Carbon (OC) and total nitrogen were ground to <0.5 mm. All analyses were performed in duplicate with blanks and certified reference standards. Particle size distribution was determined by the hydrometer method (Gee and Or, 2002); pH in distilled water and 1 M KCl (1:2.5) following standard potentiometric methods (Thomas, 1996); organic carbon by Walkley--Black oxidation (Nelson and Sommers, 1996); total N by Kjeldahl digestion (Bremner, 1996); available phosphorous by the Bray-1 method (Olsen and Sommers, 1982);

exchangeable Ca^{2+} and Mg^{2+} by atomic absorption spectrophotometry, K^{+} and Na^{+} by flame photometry after 1 M NH_4OAc (pH 7.0) extraction; exchangeable acidity by 1 M KCl titration. Cation exchange capacity (CEC) was calculated as the sum of exchangeable bases plus exchangeable acidity; base saturation (BS) (%) = $[\sum \text{exchangeable bases} / \text{CEC}] \times 100$ (Sumner and Miller, 1996).

2.5 Soil Classification

Local soil series were named according to dominant geographic features in the study area following conventional soil survey nomenclature (Soil Survey Staff, 2022). Soils were classified to the subgroup level using the USDA Soil Taxonomy (Soil Survey Staff, 2022) and correlated with the World Reference Base for Soil Resources 4th edition (IUSS Working Group WRB, 2022). Diagnostic horizons (argillic, cambic, ochric), moisture regimes (ustic, aquic), base saturation, clay distribution patterns, and redoximorphic features were evaluated at each hierarchical level.

2.6 Spatial and Statistical Analysis

The GPS coordinates and soil property values were imported into ArcGIS 10.8. Fifteen continuous surface maps were generated using Inverse Distance Weighting (IDW) interpolation (power = 2; 12 nearest points). Data normality was verified with the Shapiro-Wilk test. One-way ANOVA and Tukey's HSD identified significant differences among land-use

types and depth intervals ($p < 0.05$); $CV < 15\%$ = low variability, $15\text{--}35\%$ = moderate variability, $> 35\%$ = high variability. Principal component analysis (PCA) was performed on the standardized thirteen-variable dataset ($n = 36$) using `prcomp()` in R v4.3.2, retaining components by Kaiser criterion (eigenvalue ≥ 1.0) and cumulative variance $\geq 70\%$. Hierarchical component analysis (HCA) was applied to the first three PCA scores using Ward's minimum variance linkage with Euclidean distance; the optimal cluster number was determined by Calinski-Harabasz index and silhouette width coefficient. Stepwise multi linear regression (MLR) (backward elimination: removal $p > 0.10$, entry $p \leq 0.05$) was used to model CEC, available P, pH, and total N; multicollinearity was assessed by variance inflation factor (VIF) (threshold: 5). Pearson correlation matrices were computed separately by land use type and for the pooled dataset; $|r| \geq 0.70$ and $p < 0.05$ (Bonferroni-corrected) were considered significant.

3. RESULTS

3.1 Soil Morphological Characteristics and Classification

Morphological examination of all nine profiles identified two soil series with contrasting pedogenic pathways, reflecting the strong influence of topographic position and drainage on soil development within the study area. For brevity, representative profiles from six pits are summarized below; full FAO (2006) morphological descriptions for all nine profiles are available in supplementary material. All profiles within each series were consistently classified to the same subgroup (USDA) and qualifier (WRB) level, confirming robust correlation between local series and international taxonomic categories.

3.1.1 Ode Erinje Series (RS001-RS003) Fluvaquentic Endoaquepts / Arenic Gleysols

Profiles in the river/stream floodplains exhibited sandy surface horizons (0--15 cm) with dull yellowish-brown colours (10YR 5/4, moist), indicative of gleying and fluctuating redox conditions. A sand-dominated texture (single-grain structure) persisted to depth, with transitional horizons showing yellow-orange (10YR 6/5) and bright yellow (10YR 7/8) colours characteristic of oxidized iron in the zone of water-table fluctuation. Mottles of reddish yellow were observed in all three profiles at 30--60 cm. Consistent moisture throughout the profile during the dry season confirmed an aquic moisture regime. Minimal horizon differentiation and the absence of an argillaceous horizon distinguished these profiles from the upland series. Under USDA Soil Taxonomy (2022), these soils are classified as Fluvaquentic Endoaquepts (Order: Inceptisols; Suborder: Aquepts; Great Group: Endoaquepts) based on aquic conditions within 50 cm of the surface and fluvial influence on soil genesis. The WRB (2022) equivalent is Arenic

Gleysols, reflecting both the sandy texture and pronounced gleyic colour pattern.

3.1.2 Okitipupa Series (FL001--FL003; OP001--OP003) --- Typic Paleustalfs / Orthi-dystric Acrisols

Upland profiles in both abandoned farmland and oil palm plantation positions share a common pedogenic pathway. Surface horizons (0--22 cm) displayed brown (2.5YR 4/4) to brownish-grey (10YR 4/1) colours, with sandy loam texture and sub-angular blocky structure. Subsurface horizons showed a systematic colour progression from yellowish-grey (2.5YR 5/6) at 22--85 cm through yellowish-red (2.5YR 7/5) at 60--90 cm to red (2.5YR 6/5) at 90--120 cm, consistent with progressive iron oxide enrichment with depth. Clay content increased from 17% at the surface to 24% at 85--140 cm, and clay skins (argillans) on ped faces provided definitive evidence of an argillaceous horizon. No redoximorphic features were observed, confirming a ustic moisture regime. Under USDA Soil Taxonomy (2022), these soils are classified as Typic Paleustalfs due to the geologically stable landscape, common with upland soil (Alfisols > Ustalfs > Paleustalfs), based on the presence of an argillic horizon, base saturation $>35\%$, and ustic moisture regime. The WRB equivalent is Orthi-dystric Acrisols, encoding the presence of an argic horizon with a moderate base status and low-activity clay mineralogy (IUSS Working Group WRB, 2022; Nachtergaele and Deckers, 2024).

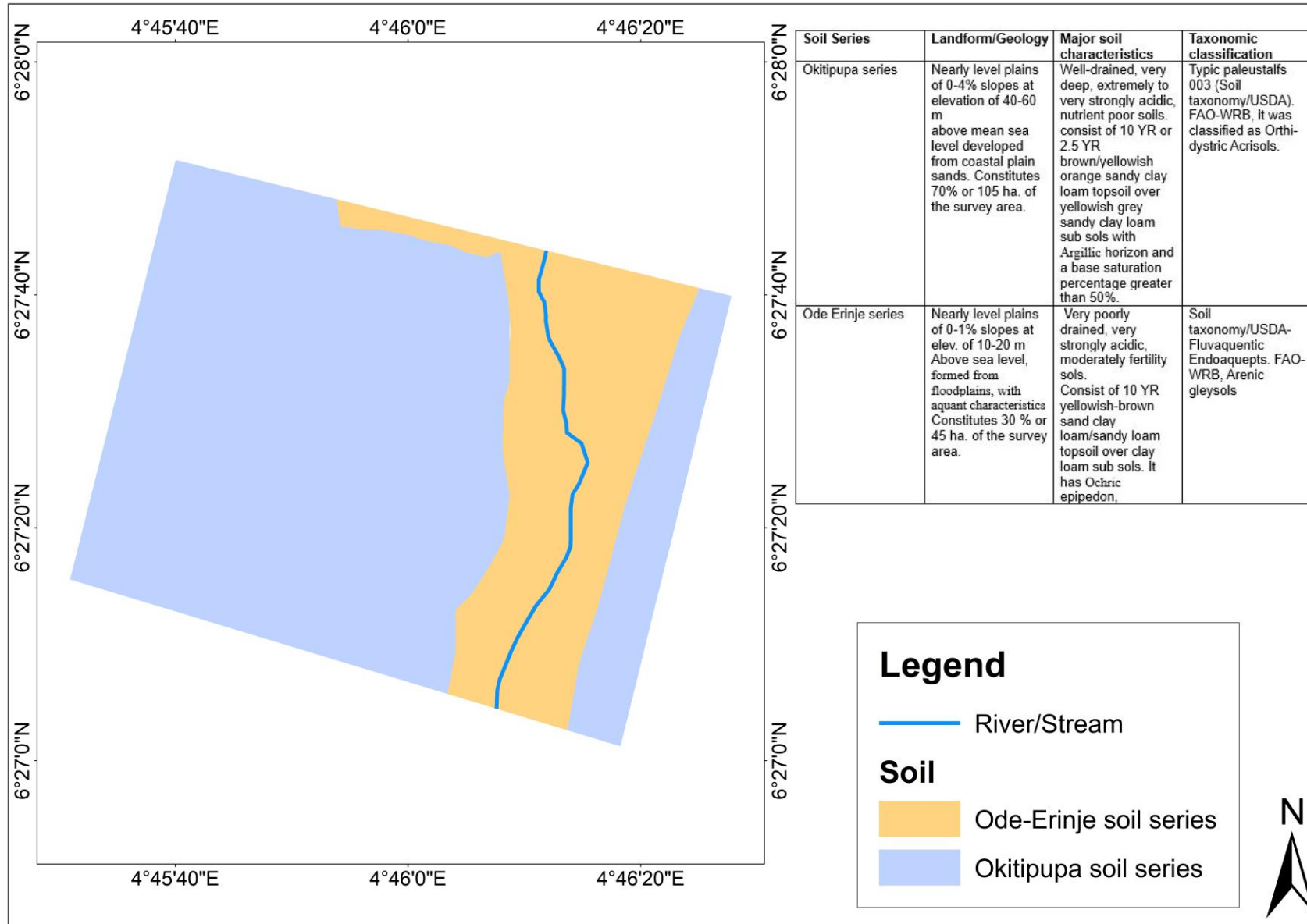


Figure 3. Soil Map of the Study Area

Table 1. Morphological properties of the soil in the Study area

Horizon	Depth (cm)	Munsell colour (moist)	Structure	Texture	Consistence	Boundary	Other Characteristics
USDA: Typic paleustalfs, FAO/WRB: Orthi-dystric Acrisols, Local: Okitipupa series							
Profile Number: FL 001							
Ap	0-22 cm	Brown (2.5YR 4/4)	Weak, fine medium, grave	Loamy sand	Wet, non-sticky, friable	Clear smooth	Fine roots, earthworm cast, plant roots
Bt1	22-55 cm	Yellowish grey (2.5 YR 5/6)	Weak, fine, sub-angular	Sand clay	Wet, sticky, moderate, firm,	Gradual smooth	Medium, fine pore spaces, common medium roots
Bt2	55-85 cm	Yellowish red (2.5 YR 7/5),	Weak, moderate, coarse, sand, sub-angular moderate,	Sand clay	Wet, non-sticky, moderate, firm	Clear smooth	Medium, fine pores, fine and medium roots
Bt3	85-145 cm	Red (2.5 YR 6/5)	coarse, sand, sub-angular	Sand clay	Wet, non-sticky, moderate, firm	-	Fine roots, fine pores
Profile Number: FL 002							
Ap	0-17 cm	Brown (2.5YR 4/4)	Weak, fine medium, granular	Loamy sand	Wet, non-stick, friable	Clear smooth	Fine roots, earthworm cast, plant roots
Bt1	10-60 cm	Yellowish grey (2.5 YR 5/6)	Weak, fine, sub-angular	Sandy clay	Wet, sticky, moderate, fine, loose	Gradual smooth	Medium, fine pore spaces, common medium roots
Bs2	60-95 cm	Yellowish red (2.5 YR 7/5)	Weak, medium, coarse	Sand clay loam	Wet, non-sticky,	Diffuse smooth	Medium, fine pores, fine and medium roots

Bt3	95-140 cm	Red (2.5 Y/R 6/5), Profile Number: OP 001	Weak, medium, coarse	Sand clay loam	moderate, fine loose Wet, non- sticky, moderate, fine loose	Clear smooth	Fine few roots, fine pores
Ap	0-23 cm	Brownish grey (10YR 4/1)	Weak, fine, granular	Loamy sand	Variable, non-sticky, moderate, friable	Clear smooth	Fine roots, earthworm cast, plant roots
Bt1	23-55cm	Greyish yellow (10 YR 6/2),	Weak, fine, sub- angular	Sand clay	Wet, sticky, moderate, fine loose	Gradual smooth	Medium, fine pore spaces, common medium roots
Bt2	55-95 cm	Dull Yellowish red (10 YR 6/4),	Weak, fine, sub- angular	Sand clay loam	Wet, sticky, moderate, fine, loose	Clear smooth	Medium, fine pores, fine and medium roots
Bt3	95-140 cm	Red (10 YR 6/5) Profile Number: OP 002	Weak, fine, sub- angular	Sand clay loam	Wet, sticky, moderate, fine, loose	Clear smooth	Fine few roots, fine pores
Ap	0-13 cm	Brownish grey (10YR 4/1)	Weak, fine medium, granular	Loamy sand	Wet, non- sticky,	Clear smooth	Fine roots, earthworm cast, plant roots
Bt1	13-45 cm	Dull Yellowish red (10 YR 6/4)	Weak, fine, sub- angular	Sandy clay	Wet, sticky, moderate, fine, loose,	Gradual smooth	Medium, fine pore spaces, common medium roots
Bt2	45-90 cm	Dull Yellowish red (10 YR 6/4),	Weak, fine, sub- angular	Sandy clay loamy	Wet, sticky, moderate, fine, loose	Diffuse smooth	Medium, fine pores, fine and medium roots
Bt3	90-140 cm	Red (10 YR 6/5)	Weak, fine, sub- angular	Sandy clay loamy	Wet, sticky, moderate, fine, loose	Clear smooth	Fine few roots, fine pores
USDA: Fluvaquentic Endoaquepts, FAO/WRB: Arenic Gleysol, Local: Ode-Erinje Soil series							
Profile Number: RS 001							

Apg	0-12 cm	Dull yellowish brown (10YR 5/4)	Single grain	sandy	Wet, non-sticky, moderately loose	Clear smooth	Fine roots, earthworm cast, plant roots
Cg1	12-40 cm	Yellow (10 YR6/5)	Single grain	Loamy sand	Wet, non-sticky, moderately loose	Clear smooth	Medium, fine pore spaces, common medium roots
Cg2	40-60 cm	Yellow (10 YR 7/8)	Single grain	Sandy loam	Wet, non-sticky, moderately loose	Clear smooth	Medium, fine pores, fine and medium roots
Profile Number: RS 002							
Apg	0-10 cm	Dull yellowish brown (10YR 5/4),	Single grain	sandy	Wet, non-sticky, moderately loose	Clear smooth	Many fine medium pores and roots, many ants and worm holes
Cg1	10-35 cm	Yellow (10 YR6/5)	Single grain	Loamy sand	Wet, non-sticky, moderately loose	Clear smooth	Common and medium pores, common fine roots, common fine, distinct reddish yellow mottles
Cg2	35-60 cm	Yellow (10 YR 7/8)	Single grain	Sandy loam	Wet, non-sticky, moderately loose	-	Common fine and medium pores and roots, depth of water table 90cm, common fine medium distinct yellow mottles
Profile Number: RS 002							
Apg	0-15 cm	Dull yellowish brown (10Y/R 5/4),	Single grain	sandy	Wet, non-sticky, moderately loose	Clear smooth	Many fine medium pores and roots, many ants and worm holes
Cg1	15-45 cm	Yellow (10 Y/R6/5)	Single grain	loamysand	Wet, non-sticky, moderately loose	Clear smooth	Common and medium pores, common fine roots, common fine, distinct reddish yellow mottles
Cg2	45-55 cm	Yellow (10 Y/R 7/8)	Single grain	Sandy loam	Wet, non-sticky, moderately loose		Common fine and medium pores and roots, depth of water table 90cm, common fine medium distinct yellow mottles

3.2 Physical and Chemical Properties by Land Use

Mean physical and chemical data by land use type and depth interval are presented in Tables 1--3. ANOVA results are summarized in Table 4.

Table 2. Selected soil physical and chemical properties - River/Stream Floodplain (Ode Erinje Series).

Depth (cm)	Sand (%)	Clay (%)	Silt (%)	pH	Total N (%)	TOC (%)	Avail. P (mg/kg)	Ca ²⁺ (mg/kg)	Mg ²⁺ (mg/kg)	K ⁺ (mg/kg)	Na ⁺ (mg/kg)	CEC (mg/kg)	BS (%)
0-15	64.6	22.8	12.7	5.80	0.13	1.09	6.08	3.03	4.13	0.92	0.35	9.88	84.1
15-45	60.9	24.7	14.9	6.10	0.15	0.92	5.86	2.13	2.16	1.00	0.43	7.27	77.1
45-55	58.2	29.6	11.9	6.20	0.12	1.14	5.32	2.71	3.11	1.24	0.71	8.22	81.2

TOC = Total Organic Carbon; Avail. P = Available Phosphorus; CEC = Cation Exchange Capacity; BS = Base Saturation.

Table 3. Selected soil physicochemical properties - Abandoned Farmland (Okitipupa Series).

Depth (cm)	Sand (%)	Clay (%)	Silt (%)	pH	Total N (%)	TOC (%)	Avail. P (mg/kg)	Ca ²⁺ (mg/kg)	Mg ²⁺ (mg/kg)	K ⁺ (mg/kg)	Na ⁺ (mg/kg)	CEC (mg/kg)	BS (%)
0-22	57.9	17.1	25.0	4.90	0.22	1.81	12.80	5.25	3.99	0.83	0.51	11.0	84.6
22-55	54.1	22.1	23.8	5.00	0.18	1.76	15.10	5.86	5.25	1.13	0.60	12.0	86.0
55-85	63.1	22.9	14.0	5.30	0.20	1.56	11.00	3.86	5.83	1.26	0.50	10.9	83.0
85-145	51.5	24.2	24.3	5.30	0.18	1.42	14.10	4.13	4.36	1.26	0.55	12.1	84.7

Table 4. Selected soil physicochemical properties -Oil Palm Plantation (Okitipupa Series).

Depth (cm)	Sand (%)	Clay (%)	Silt (%)	pH	Total N (%)	TOC (%)	Avail. P (mg/kg)	Ca ²⁺ (mg/kg)	Mg ²⁺ (mg/kg)	K (mg/kg)	Na (mg/kg)	CEC (mg/kg)	BS (%)
0-23	64.7	19.2	12.8	5.20	0.17	1.20	6.40	0.61	2.68	0.89	0.33	8.70	82.5
23-55	60.6	26.0	10.1	5.60	0.07	0.98	7.70	0.69	2.58	0.99	0.48	8.60	80.5
55-95	53.7	23.4	19.6	5.50	0.12	0.54	5.90	0.55	2.13	1.05	0.57	8.00	82.0
95-140	57.3	19.6	19.8	5.90	0.08	0.59	5.80	0.55	1.58	1.24	0.72	7.40	81.6

Table 5. One-way ANOVA summary of land use effects on mean soil properties (pooled depths).

Property	Farmland (FL)	Palm (OP)	River/Stream (RS)	F-stat (p)
pH (H ₂ O)	5.13 a	5.55 b	5.30 ab	4.82 (0.021)
Organic carbon (%)	1.64 a	0.83 b	1.06 b	9.13 (<0.001)
Total N (%)	0.20 a	0.11 b	0.16 ab	5.34 (0.008)
Avail. P (mg/kg)	13.25 a	6.45 b	5.01 b	11.2 (<0.001)
CEC (mg/kg)	11.50 a	8.18 b	8.26 b	7.14 (0.002)
Base saturation (%)	84.6 a	81.7 a	80.6 a	1.22 (0.308)
Clay (%)	21.6 a	22.1 a	26.4 b	3.91 (0.031)

Values followed by different letters within each row differ significantly at $p < 0.05$ (Tukey's HSD). FL = Abandoned farmland; OP = Oil palm plantation; RS = River/stream

3.2.1 Particle size distribution and texture

Sand content across all profiles ranged from 50.7 to 68.1%, confirming the dominantly coarse-textured nature of coastal plain sand-derived soils. Clay content ranged from 16.5 to 29.9%, increasing systematically with depth in upland profiles (17% at 0-22 cm to 24% at 55-140 cm), consistent with argillic horizon development. Textural classes were predominantly sandy loam at the surface and sandy clay loam at depth. River/stream soils had slightly higher subsurface clay content, reflecting alluvial deposition; ANOVA indicated no significant textural differences between farmland and oil palm soils, whereas river/stream soils differed significantly ($p < 0.05$) for clay.

3.2.2 Soil reaction, organic carbon, nitrogen, and phosphorus

All soils were acidic (pH 4.04--6.55), consistent with intensely leached coastal plain sands. The acidity gradient across land uses, oil palm (mean pH 5.55) > river/stream (5.30) > abandoned farmland (5.13), reflects interacting influences of organic matter quality, hydrological regime, and management history. A low pH of 3.10 at 55-140 cm in RS profiles is attributed to oxidation of sulphidic material in the water-table fluctuation zone (Esu et al., 2014). Total organic carbon exhibited a clear hierarchy: abandoned farmland (mean TOM 4.34%) > oil palm (2.47%) > river/stream (2.16%) (Table 4, $p < 0.001$). The elevated farmland values reflect organic matter recovery under fallow, when all phytomass is returned to the soil and fungal communities produce more stable humic compounds (Guo et al., 2007). Total nitrogen was generally low (0.01-0.34%): abandoned farmland had the highest mean (0.20%), river/stream intermediate (0.16%), and palm plantations had the lowest (0.11%); high spatial variability in palm soils (CV 57.5%) reflects localized accumulation of palm fruit bunch refuse. Available phosphorus ranged from

0.11 to 15.38 mg kg⁻¹, with farmland achieving the highest mean (12.71 mg kg⁻¹), followed by palm (6.44 mg kg⁻¹) and river/stream (3.92 mg kg⁻¹).

3.2.3 Exchangeable bases, CEC, and base saturation

Calcium (0.54-6.04 mg kg⁻¹), magnesium (1.01-8.47 mg kg⁻¹), K⁺ (<0.01-1.66 mg kg⁻¹) and Na⁺ (0.21-0.77 mg kg⁻¹) exhibited a consistent hierarchy with farmland > river/stream > palm plantation for Ca and Mg. Several soil horizons showed near-zero K, indicating severe depletion from continuous harvest without adequate K-fertilizer replacement (Goh and Hårdter, 2003). CEC ranged from 6.09 to 15.75 mg kg⁻¹ with the strong CEC organic carbon correlation ($r = 0.48-0.80$) demonstrating the dominant contribution of organic carbon to effective CEC in these kaolinitic systems. Base saturation was uniformly elevated (75-88%) across all land uses, meeting the >50% threshold for Alfisol classification despite the acidic pH.

3.3 Pearson Correlation Analysis

Correlation matrices revealed land-use-specific patterns (Tables 5-7). In river/stream soils, K⁺ showed strong positive correlations with pH ($r = 0.83$) and Mg²⁺ ($r = 0.82$), suggesting co-control by base saturation status under fluctuating redox conditions. In abandoned farmland, pH correlated strongly with total phosphorus ($r = 0.98$) and TOM ($r = 0.87$), while total N was negatively correlated with pH ($r = -0.79$), reflecting a competitive relationship between nitrification, acidification and organic matter buffering. In palm soils, Na⁺ was strongly correlated with TOM ($r = 0.76$) and K⁺ ($r = 0.83$), suggesting co-accumulation under frond litter inputs. CEC correlated positively with TOM across all land uses ($r = 0.48--0.80$), underscoring organic matter management as central to maintaining CEC in kaolinite-dominated soils

Table 5. Pearson correlation matrix — River/Stream soils.

	pH	Total-N	TOC	Total-P	Na	K	Ca ²⁺	Mg ²⁺	EA	CEC	BS
pH	1.00	0.58	0.11	0.32	0.78	0.83	0.28	0.46	0.47	0.25	0.01
Total-N	0.58	1.00	0.43	0.23	0.26	0.79	0.17	0.86	0.71	0.63	0.52
TOC	0.11	0.43	1.00	0.68	0.35	0.55	0.38	0.64	0.38	0.80	0.26
Total-P	0.32	0.23	0.68	1.00	0.48	0.60	0.34	0.55	0.44	0.76	0.04
Na	0.78	0.26	0.35	0.48	1.00	0.67	0.22	0.30	0.26	0.20	-0.17
K	0.83	0.79	0.55	0.60	0.67	1.00	0.47	0.82	0.61	0.68	0.23
Ca ²⁺	0.28	0.17	0.38	0.34	0.22	0.47	1.00				
Mg ²⁺	0.46	0.86	0.64	0.55	0.30	0.82	0.24	1.00	0.72	0.83	0.55
EA	0.47	0.71	0.38	0.44	0.26	0.61	-0.22	0.72	1.00	0.62	0.41
CEC	0.25	0.63	0.80	0.76	0.20	0.68	0.35	0.83	0.62	1.00	0.39
BS	0.01	0.52	0.26	0.04	-0.17	0.23	-0.12	0.55	0.41	0.39	1.00

Table 6. Pearson correlation matrix — Abandoned Farmland soils.

	pH	Total-N	TOM	Total-P	Na	K	Ca ²⁺	Mg ²⁺	EA	CEC	BS
pH	1.00	-0.79	0.87	0.98	-0.61	-0.33	0.20	0.68	-0.68	-0.01	0.06
Total-N	-0.79	1.00	-0.51	-0.78	0.86	0.81	0.09	-0.43	0.77	0.12	-0.06
TOM	0.87	-0.51	1.00	0.85	-0.42	-0.08	0.47	0.87	-0.45	0.12	0.33
Total-P	0.98	-0.78	0.85	1.00	-0.56	-0.28	0.21	0.71	-0.63	-0.05	0.13
Na	-0.61	0.86	-0.42	-0.56	1.00	0.78	0.11	-0.39	0.71	0.11	-0.22
K	-0.33	0.81	-0.08	-0.28	0.78	1.00	0.26	-0.05	0.56	0.11	-0.01
Ca ²⁺	0.20	0.09	0.47	0.21	0.11	0.26	1.00	0.50	0.13	0.64	0.26
Mg ²⁺	0.68	-0.43	0.87	0.71	-0.39	-0.05	0.50	1.00	-0.49	0.29	0.61
EA	-0.68	0.77	-0.45	-0.63	0.71	0.56	0.13	-0.49	1.00	-0.24	0.04
CEC	-0.01	0.12	0.12	-0.05	0.11	0.11	0.64	0.29	-0.24	1.00	-0.06
BS	0.06	-0.06	0.33	0.13	-0.22	-0.01	0.26	0.61	0.04	-0.06	1.00

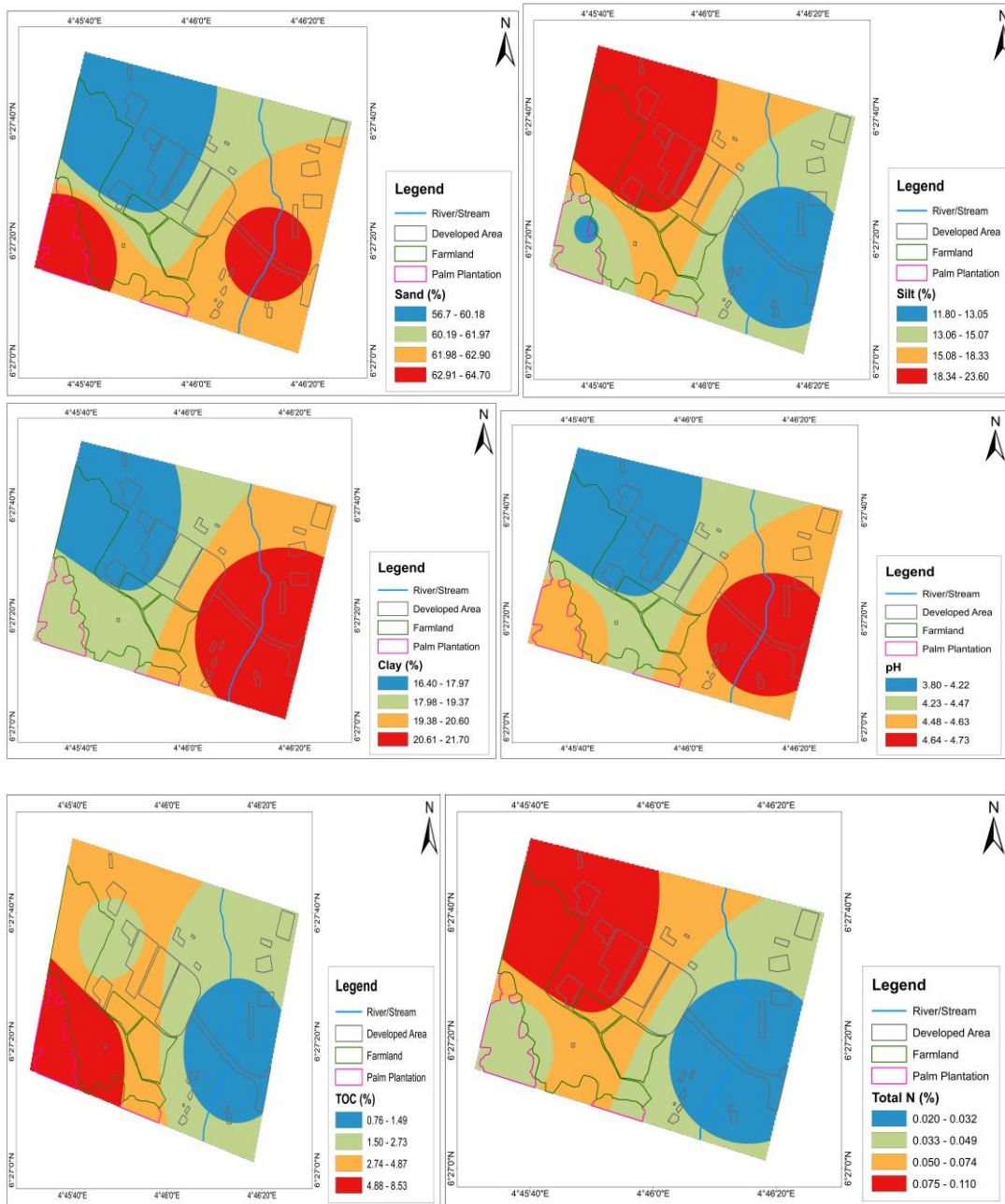
Table 7. Pearson correlation matrix — Oil Palm Plantation soils.

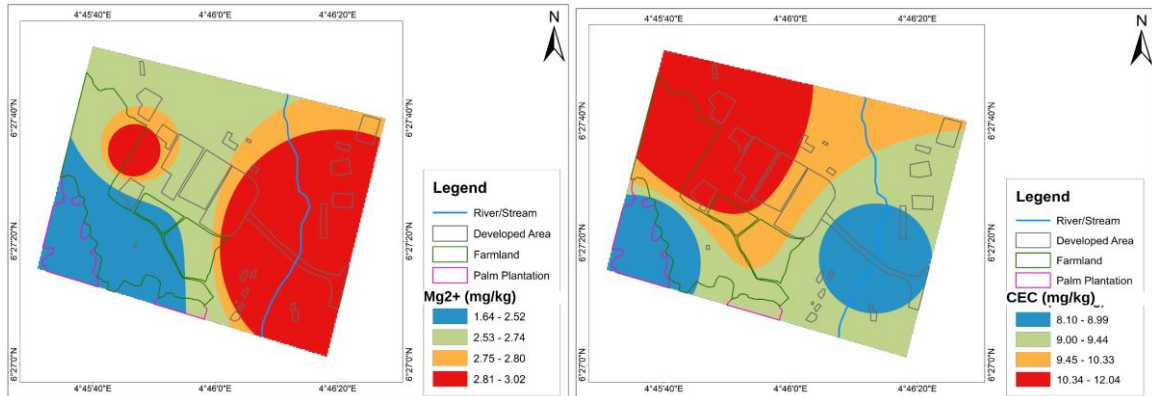
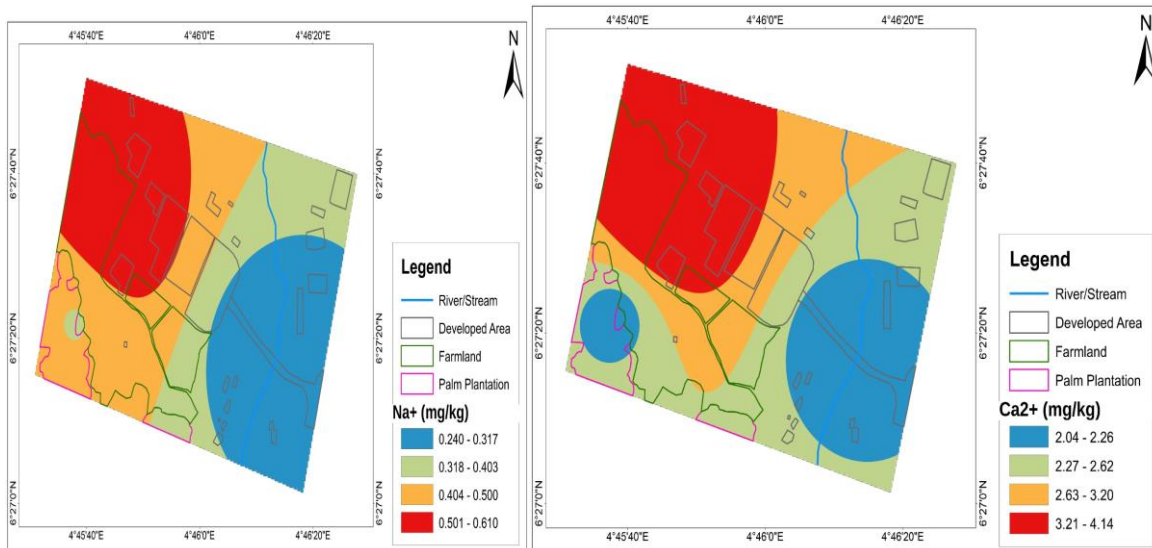
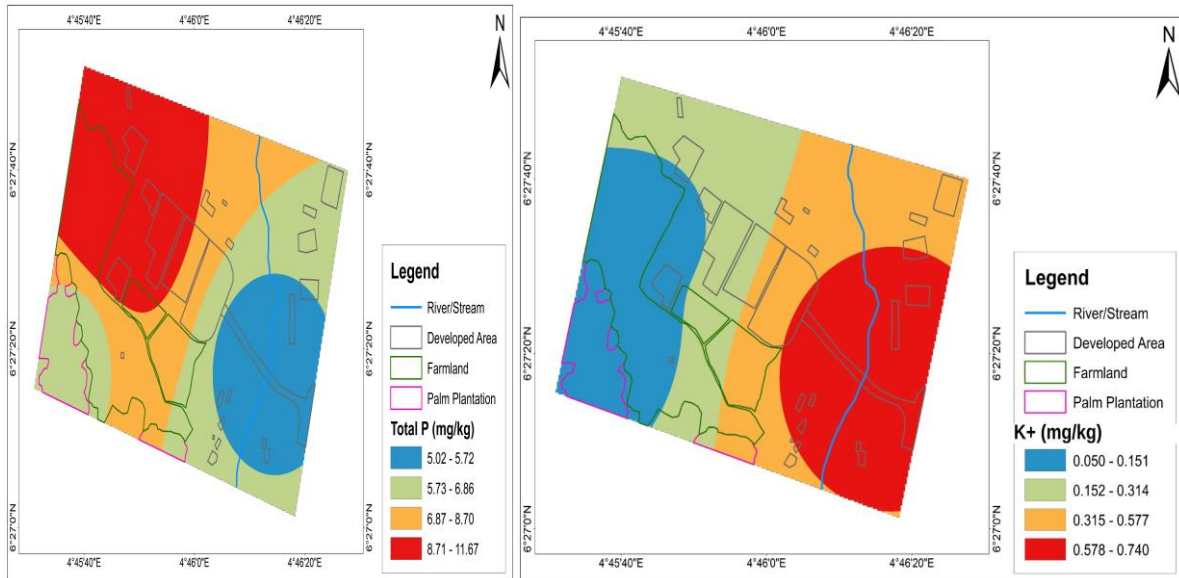
	pH	Total-N	TOM	Total-P	Na	K	Ca ²⁺	Mg ²⁺	EA	CEC	BS
pH	1.00	-0.11	-0.29	-0.55	-0.43	-0.22	-0.03	0.09	-0.26	-0.07	-0.21
Total-N	-0.11	1.00	0.75	0.02	0.62	0.86	0.20	0.21	0.27	0.19	0.31
TOM	-0.29	0.75	1.00	0.32	0.76	0.66	0.36	0.39	0.19	0.63	0.22
Total-P	-0.55	0.02	0.32	1.00	0.74	0.40	0.32	0.26	0.00	0.36	0.16
Na	-0.43	0.62	0.76	0.74	1.00	0.83	0.34	0.46	0.20	0.53	0.27
K	-0.22	0.86	0.66	0.40	0.83	1.00	0.27	0.37	0.28	0.35	0.35
Ca ²⁺	-0.03	0.20	0.36	0.32	0.34	0.27	1.00	-0.17	-0.73	0.29	0.18
Mg ²⁺	0.09	0.21	0.39	0.26	0.46	0.37	-0.17	1.00	0.33	0.64	-0.10
EA	-0.26	0.27	0.19	0.00	0.20	0.28	-0.73	0.33	1.00	0.19	0.05
CEC	-0.07	0.19	0.63	0.36	0.53	0.35	0.29	0.64	0.19	1.00	0.05
BS	-0.21	0.31	0.22	0.16	0.27	0.35	0.18	-0.10	0.05	0.05	1.00

3.4 GIS-based spatial distribution maps

Fourteen continuous surface maps were generated using IDW interpolation. Representative maps illustrating the spatial distribution of key soil properties are presented in Figure 4. Thematic maps captured soil variability at three scales: (i) between land use types--the dominant source of variance for pH, OC, N, P, and CEC; (ii) within land use types--moderate to high CV (15--35%) for exchangeable

acidity and N in river/stream and palm soils; and (iii) with depth-systematic clay translocation and OC decline patterns. The current sampling density (~1 profile per 44 ha) provides adequate general characterization; future densification guided by the OC gradient between land uses and the catenary clay gradient would substantially improve the utility of digital maps for precision soil management.





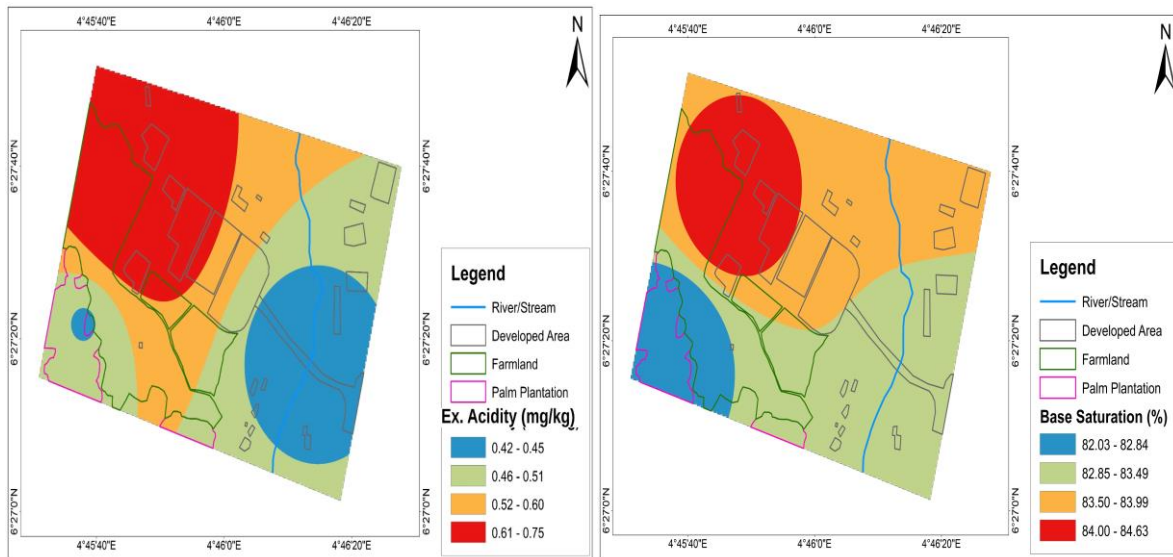


Figure 4. Fourteen continuous surface maps were generated using IDW interpolation. Representative maps illustrating the spatial distribution of key soil properties

3.5 Principal component analysis (PCA)

PCA of the standardized thirteen-variable dataset (n = 36) identified three principal components (eigenvalues > 1.0) accounting for 74.4% of total variance (Table 8). PC1 (eigenvalue = 5.21; 40.1% variance) had strong positive loadings on TOC (0.81), available P (0.83), total N (0.78), CEC (0.76), and pH (0.72), and a moderate negative loading on exchangeable acidity (-0.66) and clay (-0.58)-representing a Soil Fertility Gradient along which abandoned farmland land use scores highest, palm plantation land se intermediate, and river/stream lowest. The PC2 (eigenvalue = 2.84; 21.8%)

contrasted clay (0.74) against sand (-0.79), capturing a Texture--Depth Axis reflecting depth-dependent clay illuviation in the Okitipupa Paleustalfs. The PC3 (eigenvalue = 1.63; 12.5%) was loaded by base saturation (0.73) and Ca²⁺ (0.54), representing a Base Status Axis differentiating profiles with Ca²⁺-dominated exchange complexes from those with greater exchangeable acidity. Biplot visualization showed clear land use separation along PC1 and moderate overlap between oil palm and river/stream soils on PC2; RS subsurface horizons (90-120 cm) separated distinctly on PC1 due to low pH and high total N, likely reflecting sulphidic conditions.

Table 9. PCA Results: Loadings for the Three Retained Principal Components

Soil Property	PC1 (Fertility Gradient)	PC2 (Texture--Depth)	PC3 (Base Status)
pH (H ₂ O)	0.72	-0.18	0.41
Total Organic Carbon (%)	0.81	0.23	-0.14
Total Nitrogen (%)	0.78	0.31	-0.09
Available P (mg/kg)	0.83	0.14	0.28
CEC (cmol/kg)	0.76	0.38	-0.11
Ca ²⁺ (cmol/kg)	0.69	-0.22	0.54
Mg ²⁺ (cmol/kg)	0.62	0.47	0.33
K ⁺ (cmol/kg)	0.55	0.61	-0.37
Na ⁺ (cmol/kg)	0.41	0.68	0.22
Clay (%)	-0.58	0.74	0.18
Sand (%)	0.53	-0.79	-0.11
Base Saturation (%)	0.47	-0.31	0.73
Exchangeable Acidity	-0.66	0.29	-0.49
Eigenvalue	5.21	2.84	1.63
% Variance explained	40.1%	21.8%	12.5%

Strong loadings ($|r| \geq 0.60$) are shown in bold. PC1 = Soil Fertility Gradient; PC2 = Texture--Depth Axis; PC3 = Base Status Axis.

3.6 Hierarchical cluster analysis (HCA)

The HCA using Ward's linkage and Euclidean distance produced a four-cluster solution (Calinski-Harabasz index maximum at $k = 4$, $CHI = 18.7$; silhouette width 0.62), indicating robust cluster cohesion. Cluster 1 (High-Fertility Upland; $n = 8$): all abandoned farmland horizons, with the highest mean TOC (1.64%), available P (13.25 mg kg⁻¹), CEC (11.50 mg kg⁻¹), and Ca²⁺ (4.78 mg kg⁻¹). Cluster 2 (Moderate-Fertility Upland; $n = 8$): all oil palm plantation horizons, with intermediate TOC (0.83%) and available P (6.45 mg/kg), the highest mean pH (5.55), but the lowest Ca²⁺ (0.60 mg kg⁻¹), from continuous K and Ca depletion through harvest.

Cluster 3 (Sandy Hydromorphic; $n = 16$): all RS001-RS003 horizons from 0--145 cm in Okitipupa soil series, while 0-55 cm in Ode-Erinje soil series, characterized by intermediate pH (5.37), elevated clay (26.4%), and gleying features. Cluster 4 (Fluvaquentic Endoaquepts (USDA)/Acid Deep Gleysol (FAO?WRB); $n = 4$): the 90-120 cm horizons of RS002 and RS003, with anomalously low pH (3.10), very high total N (1.22%), and intermediate CEC (7.66 mg kg⁻¹), representing the sulphidic transition zone with strong implications for acidification risk. ANOVA of cluster centroids confirmed significant differences for pH, TOC, available P, CEC, and Ca²⁺ ($p < 0.001$).

Table 9. HCA Cluster Membership and Mean Ward's Linkage Distance

Profile / Horizon	Land Use	Cluster Assignment	Cluster Label
FL001-FL003 (0-22 cm)	Abandoned Farmland	Cluster 1	High-Fertility Upland
FL001-FL003 (22-145 cm)	Abandoned Farmland	Cluster 1	High-Fertility Upland
OP001-OP002 (0-23 cm)	Oil Palm Plantation	Cluster 2	Moderate-Fertility Upland
OP001-OP002 (23-140 cm)	Oil Palm Plantation	Cluster 2	Moderate-Fertility Upland
RS001-RS003 (0-10 cm)	River/Stream Floodplain	Cluster 3	Sandy Hydromorphic
RS001-RS003 (10-45 cm)	River/Stream Floodplain	Cluster 3	Sandy Hydromorphic
RS002-RS003 (45-55 cm)	River/Stream Floodplain	Cluster 4	Acid Deep Fluvaquentic Endoaquepts

Four clusters were identified using Ward's minimum variance linkage with Euclidean distance on standardised PCA scores (first three components retained). Optimal k determined by Calinski-Harabasz index ($k=4$; $CHI = 18.7$) and silhouette width (0.62).

Table 10 (Supplementary). Cluster Centroids --- Mean Soil Properties by HCA Cluster

Soil Property	Cluster 1 High-Fertility Upland	Cluster 2 Moderate-Fertility Upland	Cluster 3 Sandy Hydromorphic	Cluster 4 Acid Deep Gleysol
pH (H ₂ O)	5.13	5.55	5.37	3.10
TOC (%)	1.64	0.83	1.05	1.05
Total N (%)	0.20	0.11	0.15	1.22
Available P (mg/kg)	13.25	6.45	5.01	2.77
CEC (mg kg ⁻¹)	11.50	8.18	8.26	7.66
Ca ²⁺ (mg kg ⁻¹)	4.78	0.60	2.56	2.37
Mg ²⁺ (mg kg ⁻¹)	4.86	2.24	2.78	1.73
Clay (%)	21.6	22.10	26.40	28.60
Sand (%)	56.7	59.10	61.20	56.20
Base Saturation (%)	84.6	81.70	80.60	80.00

Values are means across all observations within each cluster. Cluster labels: 1 = High-Fertility Upland (FL); 2 = Moderate-Fertility Upland (OP); 3 = Sandy Hydromorphic (RS, 0--90 cm); 4 = Acid Deep Gleysol (RS, 90--120 cm).

3.7 Multiple linear regression (MLR) analysis

Stepwise MLR models ($n = 36$) passed all diagnostic tests (Shapiro-Wilk, Breusch-Pagan, Durbin-Watson 1.8--2.2; VIF < 1.40 in all models). CEC

Model ($R^2_{adj} = 0.68$): TOC dominated ($\beta = 0.74$, $p < 0.001$), followed by clay ($\beta = 0.31$, $p = 0.006$) and pH ($\beta = 0.19$, $p = 0.054$), confirming the overwhelming dominance of humus-derived charge over permanent kaolinitic clay charge. Available P Model ($R^2_{adj} = 0.72$): TOC ($\beta = 0.71$, $p < 0.001$) and total N ($\beta = 0.44$, $p = 0.001$) were dominant predictors, with pH contributing positively ($\beta = 0.33$, $p = 0.009$), underscoring biological control on P availability. pH

Model ($R^2_{adj} = 0.59$): land use category (FL vs. OP reference) was the strongest predictor ($\beta = -0.63$, $p < 0.001$), confirming structural management-history effects; depth negatively predicted pH ($\beta = -0.28$, $p = 0.022$). Total N Model ($R^2_{adj} = 0.79$): TOC dominated

($\beta = 0.82$, $p < 0.001$), with sand fraction negatively predicting N ($\beta = -0.29$, $p = 0.004$), confirming that total N is essentially a surrogate for organic matter content in these soils.

Table 11. Summary of Stepwise Multiple Linear Regression Results

Response Variable	Predictor(s)	β (Std. Coeff.)	t-value	p-value	R^2_{adj}
CEC (cmol/kg)	TOC	0.74	6.12	<0.001	0.68
	Clay (%)	0.31	2.88	0.006	
	pH	0.19	1.97	0.054	
Available P (mg/kg)	TOC	0.71	5.87	<0.001	0.72
	Total N (%)	0.44	3.61	0.001	
pH (H ₂ O)	pH	0.33	2.71	0.009	0.59
	Land Use (FL vs OP)	-0.63	-5.21	<0.001	
	Depth (cm)	-0.28	-2.34	0.022	
	TOC	0.41	3.40	0.001	
Total N (%)	TOC	0.82	8.44	<0.001	0.79
Response Variable	Predictor(s)	β (Std. Coeff.)	t-value	p-value	R^2_{adj}
CEC (cmol/kg)	TOC	0.74	6.12	<0.001	0.68
	Clay (%)	0.31	2.88	0.006	
	pH	0.19	1.97	0.054	
Available P (mg/kg)	TOC	0.71	5.87	<0.001	0.72
	Total N (%)	0.44	3.61	0.001	
pH (H ₂ O)	pH	0.33	2.71	0.009	0.59
	Land Use (FL vs OP)	-0.63	-5.21	<0.001	
	Depth (cm)	-0.28	-2.34	0.022	
	TOC	0.41	3.40	0.001	
Total N (%)	TOC	0.82	8.44	<0.001	0.79
	Sand (%)	-0.29	-2.97	0.004	
	CEC	0.21	2.17	0.034	

β = standardized regression coefficient; VIF = Variance Inflation Factor; R^2_{adj} = adjusted coefficient of determination. Models tested for normality (Shapiro--Wilk), homoscedasticity (Breusch--Pagan), and independence (Durbin--Watson). All VIF < 5 (no multicollinearity). Land use is encoded as a dummy variable (reference: oil palm).

4. DISCUSSION

4.1 Pedogenic pathways and taxonomic implications

The morphological dichotomy between the Okitipupa and Ode Erinje series reflects fundamentally different pedogenic pathways operating within metres of each other, illustrating how microrelief variations of 5-10 m elevation create divergent soil-forming environments in tropical catenary sequences (Buol et al., 2011). The upland Typic Paleustalfs display progressive argillic horizon development, modest clay enrichment (5-10 percentage points), red hues from haematite-goethite formation, and well-expressed structural peds indicating advanced pedogenesis consistent with Quaternary coastal plain sand geomorphology. The floodplain Fluvaquentic Endoaquepts retain weak horizonation, sandy texture, and gleying features attributable to periodic

waterlogging that inhibits clay illuviation. The dual USDA/WRB classification scheme reflects current best practice for international comparability (Nachtergaele and Deckers, 2024), and the HCA solution corroborated within-series management heterogeneity: Clusters 1 and 2-both taxonomically Typic Paleustalfs are statistically distinct on all major fertility parameters due purely to land use history, a differentiation that conventional taxonomic classification does not resolve.

4.2 Multivariate structure and land use as a driver of variability

The PCA results quantitatively confirm that organic matter accumulation under abandoned farmland is the single most important source of soil property variability, explaining 40.1% of total variance through PC1. The identification of PC2 as a Texture--Depth Axis confirms that clay illuviation, rather than land

use, controls subsurface textural differentiation, consistent with the pedogenic maturity of the Paleustalfs. The HCA four-cluster solution provides a directly actionable management classification system. The isolation of Cluster 4 (Acid Deep Gleysol) as a distinct management unit, despite RS profiles being within the same land use category, demonstrates the added value of multivariate clustering over conventional land-use-based zoning; these potentially sulphidic subsurface horizons represent an agronomic constraint that could be missed by univariate analysis alone. The significant elevation of TOC under abandoned farmland (~4.3-5.5%) relative to actively managed palm plantations (~1.0-4.1%) and river/stream areas (~0.8-3.7%) demonstrates that organic matter degradation from prior cultivation is partially reversible on timescales of 5-10 years (Adekiya et al., 2021; Salako et al., 2001). The regression model for total N ($R^2_{adj} = 0.79$) and PC1 loadings together confirms organic matter as the master variable governing N availability, CEC, and available P in these kaolinitic soils, providing a strong mechanistic rationale for organic matter management as the foundational soil fertility intervention across all three land use systems (Six et al., 2002).

4.3 Management implications

The available P model ($R^2_{adj} = 0.72$) demonstrates that organic matter enhances P availability through dual mechanisms: direct mineralization of organic P and indirect reduction of P fixation by Fe/Al oxides--confirming that liming and organic matter addition are complementary rather than alternative P management strategies. The pH model highlights land use type as the dominant structural predictor of soil acidity, implying that liming recommendations for farmland rehabilitation should be framed as long-term management programs rather than single-application corrections. Critically, near-zero K values in several palm plantation soil horizons, combined with the regression finding that K is not a significant predictor of CEC in the oil palm system, point to potassium as the most acute nutrient deficit in oil palm management at OAUSTECH, requiring targeted annual K fertilization. The pervasive soil acidity (pH 4.04--6.55) with coexisting high base saturation (75--88%) is a characteristic feature of these Alfisols, reflecting the distinction between active acidity (controlled by Al^{3+} hydrolysis and organic acid dissociation) and exchangeable acidity dominated by basic cations---a phenomenon well-documented in tropical soil chemistry (Brady and Weil, 2016). The spatial patterns and PCA structure identified in this study provide an empirically grounded framework for future digital soil mapping: PC1 scores could be predicted from satellite-derived vegetation indices (NDVI, EVI), PC2 scores from digital elevation models, and PC3 scores from legacy exchange base measurements (Umeobi et al., 2024; Chen et al., 2022). The well-drained upland Okitipupa series Alfisols are agronomically suitable for oil palm, cocoa, cassava,

and root crop systems with adequate fertility management; the Ode Erinje series Gleysols are more suitable for flood-tolerant wetland rice and fadama vegetable production.

5. CONCLUSION

This study provides the first comprehensive pedological characterisation of OAUSTECH's Teaching and Research Farm, establishing a robust baseline integrating morphological, physicochemical, taxonomic, spatial, and advanced multivariate statistical dimensions. Two taxonomically distinct series---the well-drained upland Typic Paleustalfs (Orthidystic Acrisols) and the hydromorphic floodplain Fluvaquentic Endoaquepts (Arenic Gleysols) are mapped across contrasting land use systems. The PCA identified three latent components: a Soil Fertility Gradient, a Texture--Depth Axis, and a Base Status Axis, explaining 74.4% of the total dataset variance. The HCA delineated four management-relevant clusters transcending the three-way land use classification, importantly isolating the Acid Deep Gleysol subgroup as a distinct management zone with sulphidic risk. Multiple regression confirmed TOC as the dominant predictor of CEC ($R^2_{adj} = 0.68$), available P ($R^2_{adj} = 0.72$), and total N ($R^2_{adj} = 0.79$), with land use category and soil depth as key predictors of pH variability. Key management-relevant findings: (i) land use type and topographic position jointly control soil physicochemical variability, with abandoned farmland showing the most favorable fertility conditions; (ii) oil palm plantation soils require targeted K-fertilization; (iii) the coexistence of acidic pH and high base saturation confirms the Alfisols classification while highlighting an active acidity constraint; (iv) the four-cluster HCA solution provides a statistically validated, spatially implementable framework for differentiated management zone delineation; and (v) the PCA-derived component structure provides an evidence-based template for environmental covariate selection in future digital soil mapping efforts. The baseline dataset supports digital soil mapping, precision agriculture planning, and land evaluation at OAUSTECH&RF and contributes to the broader pedological documentation of coastal plain sandy soils in southern Nigeria.

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Conflict of Interest

The authors declare no conflict of interest.

Data Availability

The dataset generated in this study is available from the corresponding author upon reasonable request.

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