



Profile Distribution of Forms of Iron and Aluminium Oxides in Wetland Soils Formed Over Recent Alluvium

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Abstract

Iron (Fe) and aluminium (Al) forms are important properties for understanding soil-forming processes and serve as helpful markers in identifying the horizon where secondary oxides accumulate. This study evaluated the physical, chemical, and extractable forms of Fe and Al in Eriti wetlands, Ogun State, Nigeria. The wetlands were mapped, and three soil pedons were dug and sampled across genetic horizons for laboratory analyses. The data were subjected to descriptive statistics, correlation analysis, and principal component analysis (PCA). Results showed that the soils were predominantly sandy, with sand (478-698 g kg⁻¹) and clay (192-352 g kg⁻¹) in this range. Soil reaction was strongly to moderately acidic (4.58 to 5.80). The organic carbon (1.22-6.69 g kg⁻¹), total nitrogen (0.06-0.64 g kg⁻¹), and available phosphorus (1.47-24.73 mg kg⁻¹) were generally higher in the surface horizons and decreased with depth. Dithionite-extractable Fe (Fe_d) and oxalate-extractable Fe (Fe_o) ranged from 11.33–18.78 mg kg⁻¹ and 5.92–11.19 mg kg⁻¹, respectively. Similar trends were observed for extractable Al fractions. Correlation analysis revealed significant positive relationships among pH, OC, TN, and Fe and Al fractions. The PCA identified four components explaining 96.16% of the total variance, with the first component accounting for 62.70%. The study revealed that the wetland soils are moderately weathered and characterised by appreciable accumulation of Fe and Al oxides, which significantly influence nutrient dynamics and soil development.

Keywords: Dithionite; Oxalate; Pedogenesis; Sesquioxides; Wetlands

Introduction

Wetlands are high-yielding ecosystems that provide vital ecological functions such as groundwater recharge, streamflow maintenance, climate change mitigation, aquatic habitat, water purification, and conservation (Balwan and Kour, 2021; Yusuf *et al.*, 2022). They are transitional areas between the upland and aquatic habitats and can be found anywhere the water table is at or near the soil surface, but

are frequently found in low areas of the landscape and close to water bodies (Butt *et al.*, 2021; Chakraborty *et al.*, 2023). The Ramsar Convention defines wetlands as "Areas of marsh, fen, peat land or water, whether natural or artificial, permanent or temporary, with water that is static or flowing, fresh, brackish, or salt, including areas of marine water, the depth of which at low tide does not exceed six meters" (Ramsar Convention Secretariat, 2016). The majority of the soils are hydromorphic in

nature and can be found in freshwater swamps, floodplains, marshes, rivers, lakes, and catchments (Davidson, 2018; Finlayson, 2018; Junk, 2024).

Sesquioxides are the oxides, hydroxides, and oxy-hydroxides of manganese (Mn), titanium (Ti), iron (Fe), and aluminium (Al), which are critical components of the soil matrix (Ojetade *et al.*, 2022). These compounds often exist as crystalline and amorphous inorganic substances in soils, although they can also be found in small amounts in organic complexes (Olatunji *et al.*, 2015; Sufardi *et al.*, 2019). The characteristics of a soil profile that can be observed depend on the activities that have taken place there and how long ago they occurred. However, it is reasonable to state that the properties of the soil shown in a profile at a specific period are influenced by a range of factors and soil formation processes (Heidari *et al.*, 2022; Gao *et al.*, 2026). The two most significant elements for comprehending various soil formation processes are iron and aluminium (Rennert, 2019). Understanding the distribution of these elements in different forms in the soil is essential for understanding soil chemistry and physicochemical properties (Sufardi *et al.*, 2019).

In wetland soils, fluctuating water tables and alternating redox conditions strongly influence the transformation, mobility, and distribution of Fe and Al oxides. Under reducing conditions, iron is mobilised and subsequently reprecipitated upon oxidation, resulting in the formation of both crystalline and amorphous forms (Sufardi *et al.*, 2019; Oyebiyi, 2024). The active ratios, such as the ratio of oxalate-extractable iron to dithionite-extractable iron (Fe_o/Fe_d), are widely used to assess the degree of crystallinity and reactivity of these oxides. Higher active ratios generally indicate poorly drained conditions and the dominance of short-range-order minerals, whereas lower values suggest well-drained environments and more crystalline forms (Sufardi *et al.*, 2019).

Despite numerous studies on the forms and distribution of sesquioxides and their role in

understanding pedogenic processes and soil characteristics in tropical soils (Maniyunda *et al.* 2015; Olatunji *et al.* 2015; Osayande *et al.*, 2016; Ojetade *et al.*, 2022; Yusuf *et al.* 2022; Oyebiyi, 2024), there remains limited information on their distribution and pedogenic behaviour in many wetland soils, particularly in Nigeria. This knowledge gap restricts a comprehensive understanding of soil development processes and poses challenges for sustainable land management and agricultural productivity. Information on the distribution patterns of Fe and Al oxides and their relationships with key soil physicochemical properties is essential for assessing soil development stages, maintaining soil fertility and environmental quality, and guiding effective land-use planning in wetland ecosystems. Therefore, this study aims to investigate the distribution and forms of Fe and Al in the wetlands using various extractants, and to evaluate the relationship between Fe and Al oxides and other soil properties to understand the pedogenic processes controlling soil development in the study area.

Materials and Methods

Study Area

The study was conducted in the Eriti wetlands, located in Obafemi-Owode Local Government Area (LGA) of Ogun State, Nigeria. The wetlands are located at latitude 7.734°N and longitude 5.792°E (Figure 1). The average temperature in the area during the rainy season is 24°C, while it increases to 30°C during the dry season (Olawajun *et al.* 2014). Eriti is primarily a farm community, known for cultivating leafy and fruit vegetables. The geology of the region is mainly composed of alluvial materials, which are part of the sedimentary rocks found in Southwestern Nigeria (Obaje 2009).

Field Survey and Soil Sampling

The wetlands were mapped using the rigid grid method of soil survey, and transverse were cut at 100-meter intervals. Soil profile pits were dug to represent each of the identified delineated mapping units, and the coordinates of each pit were recorded using

GPS (Global Positioning Systems). Soil samples were collected from the different

horizons in the profile pits and labelled accordingly.

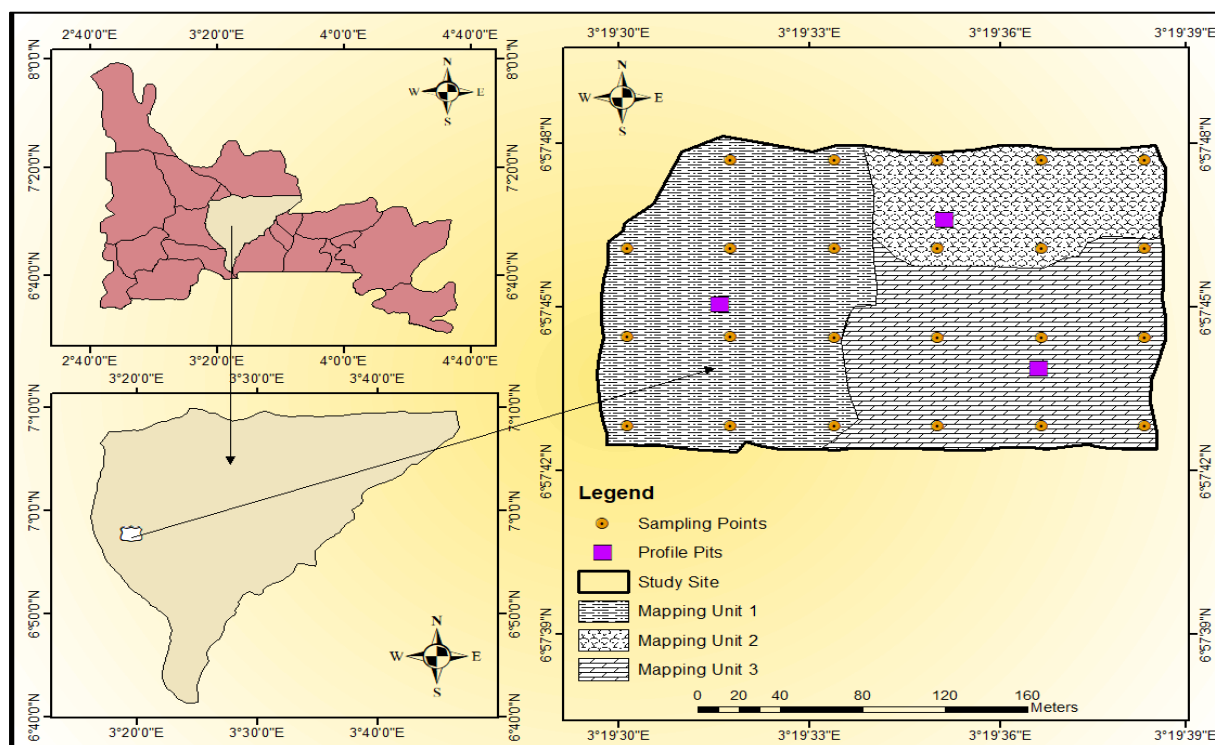


Figure 1: Map of the Sampling and Profile Pits Points at the Study Area

Laboratory Analysis

The collected samples were air-dried before being crushed to pass through a 2 mm sieve. The particle size distribution was determined using the Hydrometer method (Gee and Or 2002). The pH was measured using a 1:2 soil-to-water and soil-to-KCl ratios. Organic carbon (OC) was determined using the method of Nelson and Sommers (1996). Organic matter was derived by multiplying the value of OC by a Bemmelen's factor of 1.724. Total Nitrogen was determined by the micro Kjeldahl digestion method (Bremner and Mulvaney 1982). The available P was extracted with Bray-1 extractant at a soil: extractant ratio of 1:5 (Bray and Kurtz 1945), and the P concentration in the extract was determined by the vanadomolybdate blue method (Murphy and Riley 1962). The total free Fe and Al oxides (Fe_d and Al_d) were extracted with sodium dithionite citrate-bicarbonate (DCB), standing for the non-crystalline plus crystalline fraction. The amorphous Fe and Al oxides (Fe_o and Al_o) were extracted with acid ammonium oxalate

(AAO) in the dark (Jackson *et al.* 1986), representing the non-crystalline fraction. The crystalline fractions were estimated by difference as follows: $Fe_d - Fe_o$ and $Al_d - Al_o$ (Agbenin 2003). The active Fe was obtained as a ratio of Fe_o to Fe_d , and active Al as a ratio of Al_o to Al_d . The percentage of soil ferrihydrite content was calculated from the Fe_o content multiplied by 1.7 (Mizota and van Reeuwijk 1989).

Data Analysis

Data generated were analysed using IBM SPSS version 27.0 for descriptive statistics, correlation, and principal component analysis to identify elements with comparable reactive behaviour.

Results

Physical and Chemical Characteristics

The physical and chemical characteristics results showed that the soil particle size distribution had a moderate to high amount of sand, a low amount of silt, and a low to moderate amount of clay (Table 1). Total sand fractions ranged between 478 g kg^{-1} and 698 g kg^{-1} , while silt and clay ranged

between 110 - 170 g kg⁻¹ and 192 - 352 g kg⁻¹, respectively. The soil pH values indicated strong acid and moderate acid, with pH (H₂O) ranging from 4.58 to 5.80, and KCl ranged between 3.17 and 4.30, with a mean value of 5.21 and . Organic carbon (OC) values ranged from 1.22 to 11.02 g kg⁻¹, with a mean value of 3.419. Generally, OC values were highest at the surface horizons and decreased down the profile. Similarly, organic matter (OM) values ranged from 2.10 to 11.02 g kg⁻¹, with a mean value of 5.69 g kg⁻¹. The highest OM content was recorded in the surface horizon (A horizon) of Pedon 3 (11.02 g kg⁻¹), while the lowest value occurred in the subsurface Bt horizon of Pedon 1 (2.10 g kg⁻¹). The total nitrogen (TN) was low, ranging from 0.06 to 0.64 g kg⁻¹. The values revealed a high level of significance (p<0.05) across the pedons. The available P content of the soils showed a significant (p<0.05) decrease with depth, and the values ranged from low to moderate (1.47 - 24.73 mg kg⁻¹).

Table 1: Physical and Chemical Characteristics of Wetland Soils of Eriti

Horizon Designation	Depth (cm)	Sand g kg⁻¹.....	Silt g kg⁻¹.....	Clay	pH (H₂O)	pH (KCl)	OCg kg⁻¹.....	OMg kg⁻¹.....	TN	Avail-P mg kg⁻¹
Pedon 1										
Ap	0-16	678	120	202	5.80	4.17	5.98	10.32	0.64	24.73
B _t	16-109	568	160	272	5.12	3.83	1.22	2.10	0.12	3.73
Pedon 2										
Ap	0-12	668	130	202	5.41	3.90	5.84	10.07	0.57	10.92
B _t	12-94	588	120	292	4.74	3.33	1.29	2.22	0.06	2.05
Pedon 3										
A	0-9	698	110	192	5.73	4.30	6.69	11.02	0.59	9.32
AB	9-26	618	150	232	5.20	3.32	1.69	2.92	0.12	1.55
B _t	26-98	478	170	352	4.58	3.17	1.52	2.62	0.07	1.47
	Mean	613.71	137.14	249.14	5.205	3.714	3.419	5.694	0.312	7.681
	SD	73.251	23.053	56.493	0.471	0.434	2.354	4.076	0.261	8.010

OC = Organic Carbon; **OM** = Organic matter; **TN** = Total Nitrogen; **Avail-P** = Available Phosphorus, **SD** = Standard Deviation.

Profile Distribution and Forms of Fe and Al

Table 2 shows the distribution of Fe and Al oxide forms. The values of DCB extractable iron (Fe_d) and aluminium (Al_d) were higher compared to AAO extractable iron (Fe_o) and aluminium (Al_o) in all the horizons and profiles. The value of DCB extractable Fe and Al ranges between 11.33-18.78 $mg\ kg^{-1}$ and 13.25-18.61 $mg\ kg^{-1}$, with a mean value of 15.102 $mg\ kg^{-1}$ and 15.840 $mg\ kg^{-1}$ (Table 1). The value of AAO extractable Fe and Al ranges between 5.92-11.19 $mg\ kg^{-1}$ and 5.01-10.85 $mg\ kg^{-1}$, with a mean value of 8.639 $mg\ kg^{-1}$ and 8.526 $mg\ kg^{-1}$ (Tables 2 and 3). The concentrations of the crystalline iron oxide (Fe_d-Fe_o) and aluminium (Al_d-Al_o) were estimated by the difference between Fe_d and Fe_o and Al_d and Al_o . The values recorded ranged from 4.68 - 8.04 $mg\ kg^{-1}$ to 5.45 - 8.76 $mg\ kg^{-1}$, with the mean values 6.467 $mg\ kg^{-1}$ and 7.311 $mg\ kg^{-1}$, respectively, and decreased with increasing depth.

The Fe_o/Fe_d ranged between 0.49 and 0.64 with a mean of 0.570 (Tables 2 and 3) and increased with depth in all the profiles, with the highest values occurring in the subsoil compared to the surface horizon. The Al_o/Al_d ranged from 0.38 – 0.66 with a mean of 0.534, and its distribution pattern was similar to that of the active Fe, with the highest value also found in the subsoil. The DCB Fe (Fe_d) to DCB Al (Al_d) ratio of the soils ranged between 0.77 and 1.14, with a mean of 0.955, and values were also the same in profiles 2 and 3, but differed in profile 1. The $Fe_d/clay$ ratios ranged between 0.05 and 0.08, with a mean of 0.062, and decreased with depth. The $Al_d/clay$ ratios ranged between 0.05 and 0.09, with a mean of 0.066, and decreased with depth. The ferrihydrite values ranged from 10.06% to 19.02%, with an average of 14.69%, and increased with depth.

Table 2: Extractable Fe and Al of Wetland Soils of Eriti

Horizon Designation	Depth (cm)	Fe _d	Fe _o	Al _d	Al _o	Fe _d -Fe _o	Al _d -Al _o	Fe _o /Fe _d	Al _o /Al _d	Fe _d /Al _d	Fe _d /Clay	Al _d /Clay	Ferrihydrite
	mg kg ⁻¹											
Pedon 1													
Ap	0-16	11.33	5.92	14.71	7.78	5.41	6.93	0.52	0.53	0.77	0.06	0.07	10.06
B _t	16-109	12.26	7.58	15.84	10.39	4.68	5.45	0.62	0.66	0.77	0.05	0.06	12.89
Pedon 2													
Ap	0-12	14.48	8.13	13.25	5.01	6.35	8.24	0.56	0.38	1.09	0.07	0.07	13.82
B _t	12-94	17.43	11.19	15.27	9.08	6.24	6.19	0.64	0.59	1.14	0.06	0.05	19.02
Pedon 3													
A	0-9	14.98	7.38	16.50	7.74	7.60	8.76	0.49	0.47	0.91	0.08	0.09	12.55
AB	9-26	16.48	9.53	16.68	8.83	6.95	7.85	0.58	0.53	0.99	0.07	0.07	16.20
B _t	26-98	18.78	10.74	18.61	10.85	8.04	7.76	0.57	0.58	1.01	0.05	0.05	18.26
	Mean	15.102	8.639	15.840	8.526	6.467	7.311	0.570	0.534	0.955	0.062	0.066	14.686
	SD	2.694	1.918	1.689	1.950	1.181	1.178	0.051	0.091	0.145	0.012	0.012	3.261

SD = Standard Deviation.

Pearson's Correlation Coefficient

Correlations between sesquioxides and some soil properties of the study area are depicted in Table 3. Dithionite Fe (Fe_d) correlated significantly with Fe_o ($r = 0.923$), Fe_d-Fe_o ($r = 0.782$), Fe_d/Al_d ($r = 0.770$), and ferrihydrite ($r = 0.923$), but not with other properties. However, Fe_o correlated with Fe_d/Al_d ($r = 0.778$) and ferrihydrite ($r = 1.000$). There was a significant correlation between Al_d with Al_o ($r = 0.800$) and clay ($r = 0.790$). The relationship between Al_o and Al_o/Al_d ($r = 0.919$), Fe_d ($r = 0.837$), Al_d ($r = 0.862$) and O.C ($r = -0.202$) were significant while those of clay ($r = 0.188$), silt ($r = -0.029$), sand ($r = -0.169$), pH ($r = -0.057$), N ($r = 0.064$) were not significantly correlated. Active Fe was significantly correlated with pH ($r = -0.766$), O.C ($r = -0.853$) and TN ($r = -0.815$).

Al_d , Fe_d-Fe_o , Al_d-Al_o , and $Fe_d/Clay$ with 16.87% of the total variance.

Principal Component Analysis

The principal component analysis (PCA) results, as depicted in Table 4, reveal that only four components have eigenvalues > 1 , accounting for 96% of cumulative variance. The extraction sums of squared loadings ($62.699 + 19.160 + 9.708 + 4.591$) are 96.158% of the total variance of the obtained data. Similarly, the rotation sums of squared loadings ($33.713 + 27.682 + 17.892 + 16.871$) amount to 96.158% of the total variance. The component matrix extracted using PCA (Table 5) showed that PC1 is loaded with sand, pH (H_2O and KCl), OC, OM, TN, Av. P, $Fe_d/Clay$, and $Al_d/Clay$ with 62.70 % of the total variance. The PC2 loaded with Fe_d , Fe_o , Fe_d-Fe_o , Al_d-Al_o , Fe_d/Al_d , $Fe_d/Clay$, and ferrihydrite, representing 19.16% of the variance. PC3 loads only Al_d with 9.71% of the variance, while PC4 loads nothing but accounts for 4.59% of the total variance. The rotated component matrix (Table 6 and Figure 2) revealed that clay, BD, Fe_d , Fe_o , Fe_o/Fe_d , Fe_d/Al_d , and ferrihydrite formed the PC1 with a total variance of 33.71%, while Ksat., porosity, OC, OM, TN, and Av. P formed the PC2 with 27.68% of the total variance. Sand, pH (H_2O), $Fe_d/Clay$, and $Al_d/Clay$ fell in PC3 with a total variance of 17.89%, PC4 loads

Table 3: Pearson's Correlation Coefficients among the Soil Properties

	Sand	Silt	Clay	pH	OC	TN	Av. P	Fe _d	Fe _o	Al _d	Al _o	Fe _d -Fe _o	Al _d -Al _o	Fe _o /Fe _d	Al _o /Al _d	Fe _d /Al _d	Fe _d /Clay	Al _d /Clay	
Silt	-0.833*																		
Clay	0.977**	0.696																	
pH	0.912**	-0.638	0.938**																
OC	0.831*	-0.709	-0.806*	0.862*															
TN	0.841*	-0.680	-0.830*	0.898**	0.987**														
Av. P	0.656	-0.549	-0.640	0.792*	0.773*	0.849*													
Fe _d	-0.572	0.287	0.632	-0.747	-0.476	-0.595	-0.731												
Fe _o	-0.687	0.368	0.750*	0.901**	-0.713	-0.793*	-0.811*	0.923**											
Al _d	-0.662	0.567	0.641	-0.496	-0.483	-0.558	-0.534	0.579	0.446										
Al _o	-0.800*	0.645	0.790*	-0.637	-0.777*	-0.779*	-0.528	0.319	0.419	0.800*									
Fe _d -Fe _o	-0.189	0.056	0.223	-0.240	0.072	-0.070	-0.350	0.782*	0.482	0.596	0.047								
Al _d -Al _o	0.375	-0.254	-0.389	0.343	0.594	0.490	0.108	0.302	-0.054	0.110	-0.508	0.777*							
Fe _o /Fe _d	-0.604	0.426	0.619	-0.766*	-0.853*	-0.815*	-0.623	0.292	0.633	-0.008	0.437	-0.362	-0.735						
Al _o /Al _d	-0.671	0.502	0.677	-0.549	-0.780*	-0.737	-0.391	0.063	0.286	0.504	0.919**	-0.321	-0.798*	0.602					
Fe _d /Al _d	-0.180	-0.084	0.267	-0.525	-0.203	-0.293	-0.496	0.770*	0.778*	-0.073	-0.240	0.493	0.292	0.363	-0.325				
Fe _d /Clay	0.652	-0.567	-0.628	0.451	0.574	0.477	0.059	0.198	-0.052	-0.191	-0.670	0.536	0.835*	-0.540	-0.808*	0.402			
Al _d /Clay	0.818*	-0.567	-0.843*	0.875**	0.762*	0.731	0.486	-0.394	-0.657	-0.138	-0.490	0.168	0.613	-0.847*	-0.557	-0.367	0.699		
Ferrihydrite	-0.687	0.368	0.750	0.901**	-0.713	-0.793*	-0.811*	0.923**	1.000**	0.446	0.419	0.482	-0.054	0.633	0.286	0.778*	-0.052	-0.657	

* Significant at the 0.05 level; ** Significant at the 0.01 level.

Table 4: Total Variance of the Principal Component Analysis

Component	Initial Eigenvalues			Extraction Sums of Squared Loadings			Rotation Sums of Squared Loadings		
	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %
1	15.048	62.699	62.699	15.048	62.699	62.699	8.091	33.713	33.713
2	4.599	19.160	81.859	4.599	19.160	81.859	6.644	27.682	61.394
3	2.330	9.708	91.567	2.330	9.708	91.567	4.294	17.892	79.287
4	1.102	4.591	96.158	1.102	4.591	96.158	4.049	16.871	96.158
5	0.651	2.712	98.870						
6	0.271	1.130	100.000						

Extraction Method: Principal Component Analysis.

Table 5: Component Matrix

	Component			
	1	2	3	4
Sand	0.916	0.035	-0.161	-0.364
Silt	-0.702	-0.158	0.268	0.362
Clay	-0.918	0.015	0.105	0.332
pH (H ₂ O)	0.952	-0.179	0.141	-0.188
pH (KCl)	0.894	-0.299	0.106	-0.066
OC	0.965	0.158	0.060	0.130
OM	0.968	0.147	0.041	0.150
TN	0.983	0.022	0.018	0.158
Av. P	0.813	-0.334	0.018	0.253
Fe _d	-0.639	0.757	0.053	0.023
Fe _o	-0.821	0.521	-0.194	-0.030
Al _d	-0.592	0.203	0.777	0.003
Al _o	-0.800	-0.308	0.490	-0.057
Fe _d -Fe _o	-0.124	0.882	0.435	0.102
Al _d -Al _o	0.475	0.802	0.304	0.100
Fe _o /Fe _d	-0.792	-0.233	-0.550	-0.117
Al _o /Al _d	-0.736	-0.582	0.227	-0.155
Fe _d /Al _d	-0.317	0.773	-0.543	0.020
Fe _d /Clay	0.539	0.749	-0.023	-0.363
Al _d /Clay	0.806	0.160	0.403	-0.389
Ferrihydrite	-0.821	0.521	-0.194	-0.030

Extraction Method: Principal Component Analysis.

a. 4 components extracted.

Table 6: Rotated Component Matrix

	Component			
	1	2	3	4
Sand	-0.441	0.462	0.766	0.053
Silt	0.182	-0.424	-0.712	-0.032
Clay	0.503	-0.436	-0.720	-0.057
pH (H ₂ O)	-0.754	0.352	0.534	0.123
pH (KCl)	-0.785	0.374	0.385	0.022
OC	-0.544	0.641	0.361	0.374
OM	-0.544	0.662	0.346	0.358
TN	-0.619	0.661	0.324	0.257
Av. P	-0.739	0.531	0.087	-0.022
Fe _d	0.833	-0.237	-0.160	0.458
Fe _o	0.925	-0.281	-0.206	0.084
Al _d	0.117	-0.760	-0.373	0.516
Al _o	0.077	-0.858	-0.478	-0.092
Fe _d -Fe _o	0.397	-0.085	-0.030	0.909
Al _d -Al _o	0.040	0.330	0.256	0.892
Fe _o /Fe _d	0.625	-0.262	-0.219	-0.700
Al _o /Al _d	0.005	-0.775	-0.378	-0.460
Fe _d /Al _d	0.930	0.303	0.103	0.160
Fe _d /Clay	0.163	0.311	0.722	0.583
Al _d /Clay	-0.567	0.083	0.661	0.472
Ferrihydrite	0.925	-0.281	-0.206	0.084

Extraction Method: Principal Component Analysis.

Rotation Method: Varimax with Kaiser Normalization.

a. Rotation converged in 8 iterations.

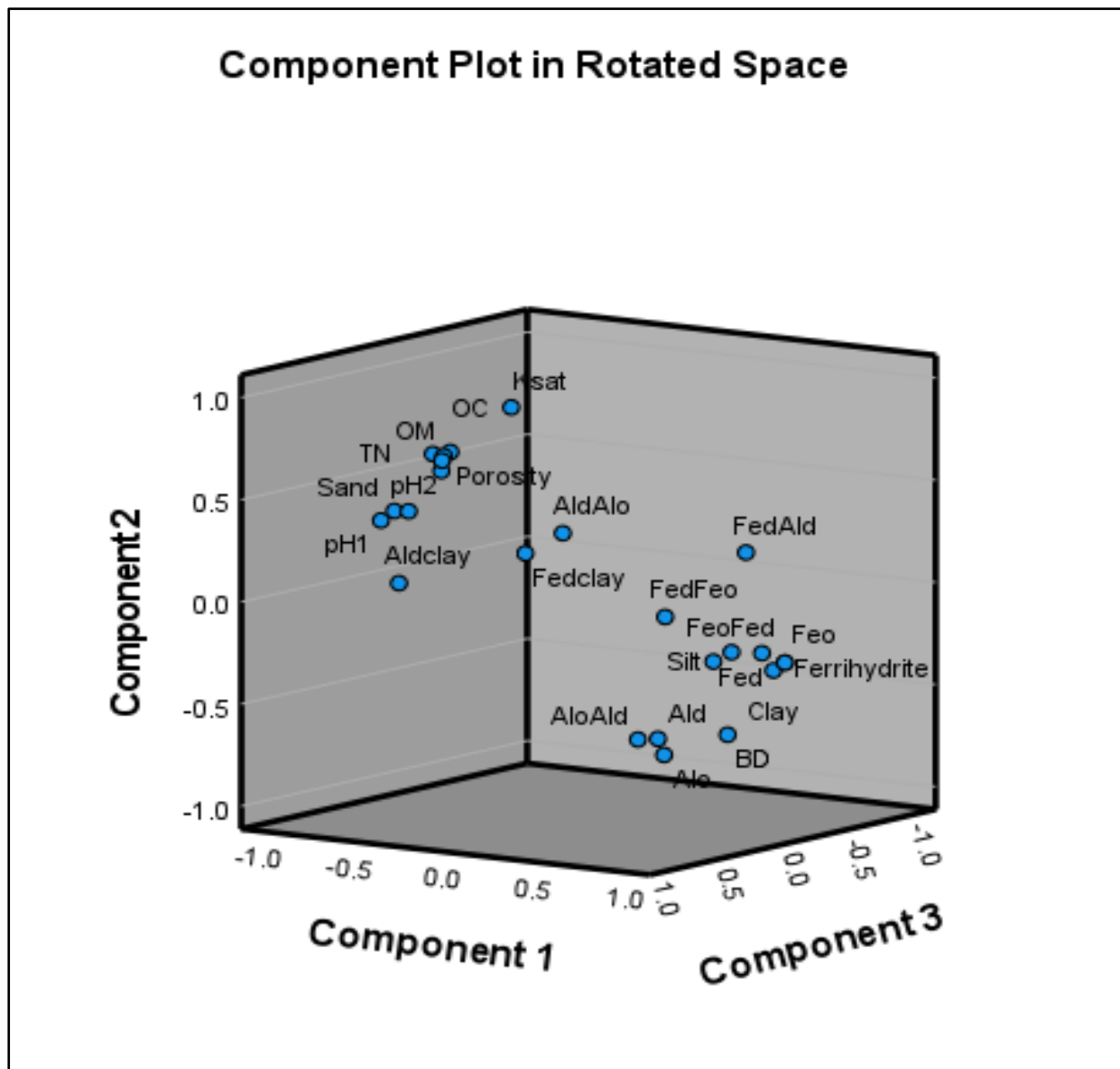


Figure 2: Principal Component Analysis of Loading Plot in Rotated Space

Discussion

Parent materials have a major impact on how soils develop and are distributed globally. One key indicator of the origin of soil-forming materials is the distribution of particle sizes (Heidari *et al.* 2022). Investigations into tropical soil chronosequences have reaffirmed that changes in particle size distribution from the solum towards the parent material often reveal lithological discontinuities and pedogenic transformations (Qui *et al.*, 2024; Wu *et al.*, 2025). Furthermore, contemporary studies have highlighted that clay illuviation, evidenced by increased clay concentrations

in argillic horizons, is often intensified in humid tropical environments due to high precipitation (Weil and Brady, 2017; Osinuga *et al.*, 2024). These findings reinforce earlier pedological interpretations that solum differentiation can be effectively traced through vertical changes in texture and clay accumulation patterns.

The structural stability of these soils is significantly modulated by organic matter (OM). In comparison to the subsurface horizons, where OM content was extremely low, the bulk density values of the soil at surface horizons were relatively lower. This implies that OM has improved the structural

resilience to a considerable extent (Jersen *et al.*, 2019; Lal *et al.*, 2023). Strong to slightly acidic was the nature of the soil (pH 4.6–5.8). The valley bottom's high-water table, poor drainage, and prolonged leaching are possible causes of the pedon's strong acidic character (Weil and Brady, 2017). Organic carbon (OC) concentrations generally decrease with depth, occasionally revealing lithological discontinuities linked to pedotransfer processes. In tropical wetlands, OC levels are typically low; recent research suggests this is driven by accelerated microbial priming under high temperature and humidity, which encourages the quick mineralisation of organic matter constituents (Olatunji *et al.*, 2015; Zhang *et al.*, 2023). In contrast to the ranges described by Olatunji *et al.* (2015) and Watham *et al.* (2019), the concentrations of iron and aluminium oxide forms are relatively low. A significant portion of the Fe and Al was present in crystalline form, as indicated by the values of Fe_d and Al_d (dithionite-citrate-bicarbonate extractable) that were found to be higher than those of Fe_o and Al_o (acid ammonium oxalate extractable). In Southwest Nigeria, crystalline Fe and Al oxides are the predominant oxyhydroxides (Ajiboye *et al.*, 2015; Popoola *et al.*, 2019). The observed increase of Fe_o levels in the subsurface horizons relative to the surface soils in every pedon, and these high values of Fe_o were attributed to the poor drainage conditions (Awwal, 2023). Recent geochemical modelling by Liu *et al.* (2022) and Awwal (2023) confirms that poorly drained tropical pedons act as sinks for amorphous Fe due to the inhibited crystallisation of ferrihydrite under prolonged saturation.

The reactivity of sesquioxides is expressed as the ratio of Fe_o and Al_o to Fe_d and Al_d form, which is a metric for wetland soil pedogenic development (age), weathering intensity, and identifies the amount of crystalline and amorphous free oxide (Rennert, 2019; Gao *et al.*, 2026). The ratio of active Fe (Fe_o/Fe_d) has been used to classify soils into well and poorly-drained situations. Values greater

than 0.35 are indicative of poor drainage conditions, while values lower than this represent well-drained conditions and advanced crystallisation (Kalita *et al.*, 2019; Ojetade *et al.*, 2022). Given that the ratios in the study area exceeded 0.35 (and reached 0.65), these soils are classified as pedogenically young and poorly drained. The values of the active Fe obtained are lower than the ranges reported by Ojetade *et al.* (2022), but align with 2024 studies on hydromorphic soils, which utilise sesquioxide ratios to map wetland boundaries more accurately (Oyebiyi, 2024). The $Fe_d/clay$ ratio has been employed as an indicator of the co-migration of clay and iron oxides from the A horizon to the B horizon (Kalita *et al.*, 2019). In this study, the $Fe_d/clay$ ratio decreased with depth, suggesting that clay illuviation occurred independently of, and more rapidly than, Fe oxide migration. The lack of significant correlation between Fe_d , Al_d , and clay content supports the theory of independent translocation, a phenomenon characteristic of poorly drained systems (Osayande *et al.*, 2016; Popoola *et al.*, 2019). Recent meta-analyses on tropical Alfisols suggest that high sand-clay interactions often disrupt the expected synergetic migration of minerals (Osinuga, 2021; Salem, 2022). Texture strongly influences key soil physical properties, including bulk density, porosity, and water movement. The significant correlation between Fe_d and Fe_o further confirms that dithionite extraction remains a reliable method for estimating total free iron oxides, including both crystalline and amorphous forms, as well as complex-humus fractions bound to metals (Surfadi *et al.*, 2019).

Principal component analysis (PCA) is typically carried out to establish possible factors that contribute to the geochemical affinity of the variables (Afonne *et al.*, 2022). Using the Kaiser criterion, factors with eigenvalues > 1 were retained and subjected to Varimax rotation to improve interpretability (Kaiser, 1958, 1960; Khan *et al.*, 2022). The PCA extracted four principal

components (PCs) with eigenvalues greater than 1, collectively explaining 96.16% of the total variance, indicating that the selected variables adequately explained the variability within the soils. The high contribution (62.7%) by the first principal component (PC1) suggests that soil properties such as texture, pH, OM, nutrient status, and Fe/Al oxide fractions are closely interrelated and strongly influence soil development. The dominance of PC1 indicates that pedogenic processes, particularly weathering, OM accumulation, and clay translocation, are the major controlling factors in the wetland soils. The second principal component (PC2) contribution (19.16%) may be associated with variations in poorly crystalline and crystalline Fe and Al oxides, reflecting the influence of hydromorphic conditions, redox reactions, and fluctuating water tables typical of wetland environments. The presence of both dithionite- and oxalate-extractable Fe and Al fractions suggests active mineral transformation processes within the soil profiles.

The third principal component (PC3) contributed 9.71% and likely reflects nutrient dynamics and the interaction between soil organic matter and available nutrients, such as TN and available P, supporting the role of OM in nutrient retention and cycling within the soils. However, the fourth principal component (PC4) explained 4.59% of the variance, which was relatively small. It may represent minor variations related to specific oxide ratios and localised pedogenic processes. Clay, OM, iron fractions (Fe_d , Fe_o , Fe_o/Fe_d , Fe_d/Al_d), and ferrihydrite clustered strongly within the first principal component. This clustering indicates a close geochemical and structural relationship among these

properties and underscores the dominant role of drainage and redox-driven processes in shaping the soils. Overall, the results paint a coherent picture of poorly drained soils whose physical and chemical characteristics are closely tied to parent material and hydrological conditions (Cheng *et al.*, 2020).

Conclusions

The present study, conducted in the Eriti wetlands of Obafemi-Owode Local Government Area in Ogun State, Nigeria, unveils disparities in selected physical and chemical features of the examined region. The soils in this area are generally deep, well-drained at the topsoil level, and have a sandy loam to sandy clay texture. However, the subsoils exhibit poor drainage due to the prominent presence of mottles. The soils in this region are low in sesquioxide content and vary in depth, with subsoil containing more than topsoil in all the pedons. The study also found that Fe_d or crystalline is the dominant form of iron, but its distribution is unrelated to clay migration, as indicated by the non-significant correlation between Fe_d and Al_d . The soils are poorly drained as suggested by the weathering ratios of oxalate Fe (Fe_o) to dithionite Fe (Fe_o/Fe_d) and oxalate Al (Al_o) to dithionite Al (Al_o/Al_d). Correlation analysis and PCA further demonstrated strong interactions among soil texture, acidity, organic matter, nutrient status, and Fe/Al oxide dynamics as the major factors controlling soil variability and development.

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