

## REVIEW ARTICLE

# INFLUENCE OF PARENT MATERIAL ON ALUMINUM OXIDE FORMATION AND DISTRIBUTION IN SOUTHWESTERN NIGERIAN SOILS

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## ARTICLE DETAILS

## Article History:

Received 17 March 2025  
Revised 21 April 2025  
Accepted 23 April 2025  
Available online 29 May 2025

## ABSTRACT

This study investigated the physical and chemical properties and aluminum (Al) oxide dynamics in soils across four agro-ecological zones of Southwestern Nigeria: NIFOR (Coastal Plain Sands), Uhonmora (Shale), Idanre (Basement Complex), and Koko (Hydromorphic). Composite soil samples were collected at depths of 0–30 cm, 30–60 cm, 60–90 cm, and 90–120 cm to analyze pH, organic carbon (Org C), nitrogen (N), phosphorus (P), exchangeable cations, texture, and Al oxide forms (crystalline, amorphous, organically bound). Results revealed significant variations in soil properties driven by parent material. Acidic soils dominated Koko (pH 4.43–4.8) and NIFOR (Rhodic Paleudult), while Idanre's near-neutral soils (pH 5.77–6.23) reflected Basement Complex weathering. Organic carbon and nitrogen declined with depth, with surface layers (0–30 cm) retaining the highest values (e.g., Uhonmora: Org C 10.43 g kg<sup>-1</sup>). Phosphorus availability was higher in shale-derived (Uhonmora: 7.72–14.48 mg kg<sup>-1</sup>) and Basement Complex soils (Idanre) due to mineral apatite. Aluminum oxides exhibited parent material-specific trends: crystalline Al (DCB-Al<sub>2</sub>O<sub>3</sub>) dominated shale soils (Uhonmora: 3.01–3.23 mg kg<sup>-1</sup>), while hydromorphic soils (Koko) accumulated organically bound Al (P-Al<sub>2</sub>O<sub>3</sub>: 0.03–0.44 mg kg<sup>-1</sup>). Coastal Plain Sands (NIFOR) showed mixed Al sources, with sandy textures promoting leaching. Correlations highlighted organic matter's role in binding Al (P-Al<sub>2</sub>O<sub>3</sub>–Org C: r = 0.965 in NIFOR) and clay's influence on oxide retention. These findings underscore the need for location-specific soil management to address Al toxicity, nutrient deficiencies, and sustainable land use in Nigeria's diverse agro-ecosystems.

## KEYWORDS

four agro-ecological, variations, hydromorphic soils, Al sources, sandy textures

## 1. INTRODUCTION

The soils of Southwestern Nigeria, a region characterized by its tropical climate and diverse geological formations, are shaped by parent materials that include Precambrian Basement Complex rocks, Coastal Plain Sands (CPS), sedimentary Shale, and Hydromorphic deposits. These parent materials govern soil formation processes, mineralogical composition, and the distribution of aluminum (Al) oxides, which play a critical role in soil fertility, nutrient retention, and environmental sustainability (Ojanuga, 2006). Aluminum oxides, existing in crystalline (e.g., gibbsite), amorphous, and organically bound forms, are key indicators of pedogenic processes. Their dynamics are influenced by weathering intensity, drainage conditions, and organic matter interactions, with significant implications for agricultural productivity in a region where soil acidity and aluminum toxicity are persistent challenges (Esu, 1991; Ogunkunle and Eghaghara, 1992).

The Basement Complex, composed of granites, gneisses, and migmatites, weathers into kaolinitic soils with moderate Al oxide content. These soils are prone to leaching under high rainfall (1,500–2,000 mm annually), leading to the formation of crystalline gibbsite in acidic surface layers (Akinyemi and Ojo, 2014). In contrast, Coastal Plain Sands, derived from the Benin Formation, are quartz-rich and highly permeable, resulting in acidic soils with low organic matter and amorphous Al oxides due to rapid leaching (Asadu et al., 2010). Shale-derived soils, such as those in Uhonmora, exhibit higher clay content and cation exchange capacity (CEC) due to phyllosilicate minerals like smectite, which stabilize Al oxides through isomorphic substitution (Odigie and Okuo, 2013). Hydromorphic soils, found in waterlogged depressions like Koko, accumulate organo-Al

complexes under reducing conditions, limiting crystalline oxide formation but enhancing phosphorus fixation (Ojeniyi et al., 2012).

The vertical distribution of Al oxides along soil profiles further reflects these parent material influences. For instance, Shale soils show increasing DCB-Al<sub>2</sub>O<sub>3</sub> (dithionite-citrate-bicarbonate extractable Al) with depth due to clay illuviation, while Hydromorphic soils exhibit surface enrichment of pyrophosphate-extractable Al (P-Al<sub>2</sub>O<sub>3</sub>) from organic matter interactions (Asadu and Nnaji, 1991). These variations underscore the need to understand how lithology-driven weathering processes dictate Al oxide speciation and mobility. Aluminum toxicity, a major constraint in acidic soils of the region, inhibits root growth in staple crops like maize and cassava, while phosphorus fixation in clay-rich soils reduces nutrient availability (Adeoye and Agboola, 1985). Previous studies by Nigerian researchers have demonstrated the efficacy of liming and organic amendments in mitigating these issues (Agbede and Ojeniyi, 2007). However, gaps remain in linking vertical Al oxide distribution to soil properties across contrasting parent materials, particularly at varying depths (0–120 cm).

This study addresses these gaps by focusing on three core aspects. First, it evaluates the physical and chemical properties of soils derived from four parent materials, including pH, organic carbon, texture, and exchangeable cations. Second, it assesses the depth-wise distribution of Al oxide forms (DCB-Al<sub>2</sub>O<sub>3</sub>, Ox-Al<sub>2</sub>O<sub>3</sub>, P-Al<sub>2</sub>O<sub>3</sub>) to unravel how parent material governs their formation. Third, it identifies correlations between soil properties and Al oxide forms to inform strategies for managing aluminum toxicity and nutrient retention. For example, in Coastal Plain Sands, low pH (4.3–4.8) and high sand content (816–843 g kg<sup>-1</sup>) may correlate with elevated amorphous Al oxides, while Shale soils' high clay content (350–390 g kg<sup>-1</sup>)

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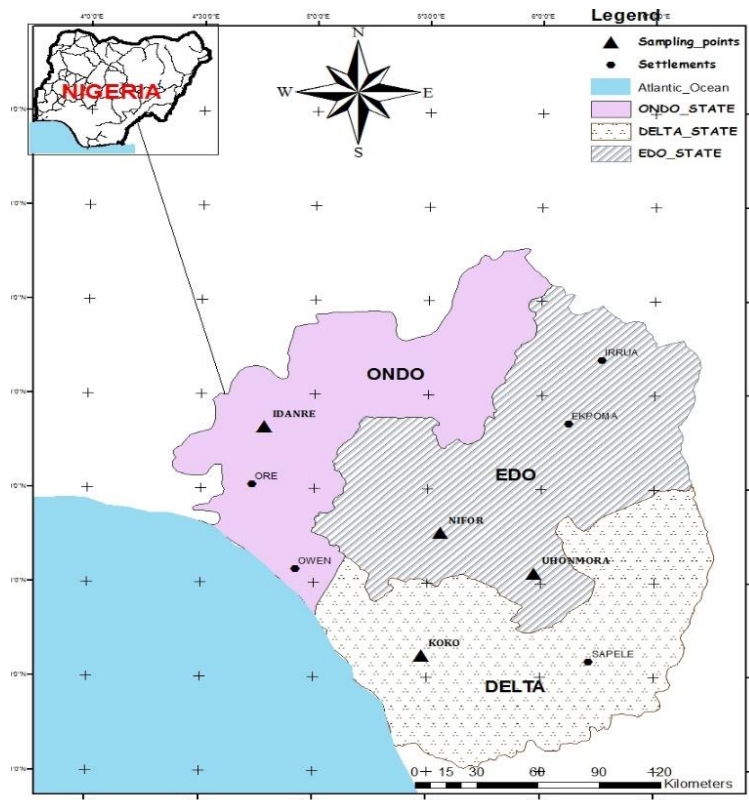
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10.26480/trab.01.2025.24.29

could stabilize crystalline Al oxides (Akinrinde et al., 2005). By synthesizing data from these contrasting lithologies, the study provides actionable insights for improving soil management practices in Southwestern Nigeria's agro-ecological zones. This study aims to: 1. Characterize the physical and chemical properties of soils derived from four parent materials (Basement Complex, Coastal Plain Sands, Shale, Hydromorphic deposits) in Southwestern Nigeria. Parameters include pH, organic carbon (Org C), texture (sand, silt, clay), exchangeable cations ( $\text{Ca}^{2+}$ ,  $\text{Mg}^{2+}$ ,  $\text{K}^+$ ,  $\text{Na}^+$ ), effective cation exchange capacity (ECEC), and base saturation (BS) across four depth intervals (0–30 cm, 30–60 cm, 60–90 cm, 90–120 cm). 2. Analyze the vertical distribution of aluminum oxides (DCB- $\text{Al}_2\text{O}_3$ , Ox- $\text{Al}_2\text{O}_3$ , P- $\text{Al}_2\text{O}_3$ ) along soil profiles to determine how parent material and depth influence their formation. For instance, the study tests

whether Shale-derived soils exhibit higher DCB- $\text{Al}_2\text{O}_3$  at lower depths due to clay translocation, while Hydromorphic soils show surface accumulation of P- $\text{Al}_2\text{O}_3$  from organic matter chelation. 3. Identify statistical correlations between soil properties (e.g., pH, clay content, Org C) and extractable Al oxide forms. This includes examining relationships such as pH vs. Ox- $\text{Al}_2\text{O}_3$  (to assess acidity's role in amorphous Al formation) and clay content vs. DCB- $\text{Al}_2\text{O}_3$  (to evaluate mineralogical controls on crystalline Al oxides). These correlations will inform region-specific strategies to mitigate aluminum toxicity and enhance phosphorus availability.

## 2. MATERIALS AND METHODS

### 2.1 Description of the Study Area



**Figure 1:** Map of Edo, Ondo and Delta States showing the sample locations

#### 2.2 NIFOR

The study area at the Nigerian Institute for Oil Palm Research (NIFOR) lies within the rainforest agro-ecological zone of Nigeria, located between latitude  $06^{\circ} 33' \text{ N}$  and longitude  $05^{\circ} 37' \text{ E}$  (Figure 1). The region experiences a humid tropical climate, characterized by a bimodal rainfall pattern (April–October) with an annual average of 1,500–2,500 mm, and a dry season from November to March. Mean daily temperatures range from  $22^{\circ}\text{C}$  (minimum) to  $31^{\circ}\text{C}$  (maximum). The soils, classified as Rhodic Paleudult (Ultisols) under the USDA Soil Taxonomy, are acidic (low pH) and exhibit low organic matter and nutrient content, with multiple nutrient deficiencies (Fagbami, 1985; Brady and Weil, 1999). These soils, derived from coastal plain sands, range in texture from sandy to clay loam.

#### 2.3 Uhonmora

The Uhonmora study site (Figure 1), situated at the Cocoa Research Institute of Nigeria (CRIN) substation in Edo State (latitude  $06^{\circ} 30' 45'' \text{ N}$ , longitude  $05^{\circ} 50' 26'' \text{ E}$ ), features soils classified as Rhodic Tropudalf (Fagbami, 1985). Developed on shale parent material, the area receives an annual rainfall of 1,575–1,725 mm and supports cocoa (*Theobroma cacao*) cultivation.

#### 2.4 Idanre

Idanre (Figure 1), located in Ondo State (latitude  $06^{\circ} 43' 0'' \text{ N}$ , longitude  $05^{\circ} 06' 0'' \text{ E}$ ), lies within the rainforest ecological zone. The region experiences distinct wet (April–October) and dry (November–March) seasons, with a mean annual rainfall of 1,500 mm and an average temperature of  $26^{\circ}\text{C}$ . Humidity peaks during the rainy season and declines during the harmattan period. Soils, derived from Basement Complex rocks, are utilized for cocoa (*Theobroma cacao*) production.

#### 2.5 Koko

Koko (Figure 1), situated in Delta State (latitude  $06^{\circ} 0' 04'' \text{ N}$ , longitude  $05^{\circ} 28' 03'' \text{ E}$ ), falls within the freshwater swamp forest ecological zone. The area receives a mean annual rainfall of 1,500 mm, distributed bimodally with peaks in July and September. Average temperatures range from  $24^{\circ}\text{C}$  to  $37^{\circ}\text{C}$ , with a relative humidity of 77.3% and soil temperatures of  $28^{\circ}\text{C}$  at 100 cm depth. Hydromorphic and humic soils with high water tables dominate the region.

#### 2.6 Sampling Procedure

Composite soil samples were collected from three sampling points across four locations (NIFOR, Uhonmora, Idanre, and Koko) using a soil auger (Figure 1). These sites were selected to represent variations in parent material, vegetation, and soil management practices. Coordinates were recorded, and soils were described following the USDA Soil Survey Manual (Soil Survey Division Staff, 1993). Replicate samples were obtained at depths of 0–30 cm, 30–60 cm, 60–90 cm, and 90–120 cm to minimize bias. A total of 48 samples were collected, stored in labeled polyethylene bags, and transported to the laboratory for analysis.

#### 2.7 Soil Preparation and Analysis

Soil samples were air-dried, sieved (2 mm and 0.5 mm), and stored in labeled bags for analysis. Physical and chemical properties were determined as follows: Particle size distribution: Hydrometer method (Bouyoucos, 1962). Soil pH: Potentiometrically in a 1:2 soil-water suspension. Organic carbon: Walkley-Black method (Allison, 1965). Total nitrogen: Micro-Kjeldahl digestion (Bremner, 1965). Available phosphorus: Bray-1 extraction followed by ammonium molybdate blue method (Bray and Kurtz, 1945). Exchangeable cations ( $\text{Na}^+$ ,  $\text{K}^+$ ,  $\text{Ca}^{2+}$ ,  $\text{Mg}^{2+}$ ). Extracted with 1.0 M  $\text{NH}_4\text{OAc}$  (pH 7.0);  $\text{Na}^+$  and  $\text{K}^+$  measured via flame photometry,  $\text{Ca}^{2+}$  and  $\text{Mg}^{2+}$  via atomic absorption spectrophotometry. Effective cation exchange capacity (ECEC). Sum of

exchangeable cations and exchangeable acidity (extracted with 1 M KCl; International Institute of Tropical Agriculture [IITA], 1979).

## 2.8 Al-oxide Determination

Total Fe: Digested with a 3:1 HCl-HNO<sub>3</sub> mixture (USDA, NRCS, 2004) and analyzed via atomic absorption spectrophotometry (AAS). Ammonium oxalate-extractable Al (amorphous): Shaken with ammonium oxalate (4 h, dark), filtered, and quantified via inductively coupled plasma (ICP) spectroscopy (Jackson et al., 1986). Dithionite-citrate-extractable Al

(crystalline): Extracted using sodium citrate and dithionite (Soil Survey Staff, 2006) and analyzed via ICP-AES. Pyrophosphate-extractable Al (organic-bound): McKeague (1967) method.

## 2.9 Statistical Analysis

Data were analyzed using Genstat (10th edition). Means were separated via Duncan's Multiple Range Test (DMRT) at p < 0.05.

## 3. RESULTS

**Table 1:** Some Physical and chemical properties of the soils in the locations studied

Locations	Depths (cm)	Parent materials	pH	Org C	N	P	Ca	Mg	K	Na	EA	ECEC	BS	Sand	Silt	Clay
				g kg <sup>-1</sup>	mg kg <sup>-1</sup>	(Cmol kg <sup>-1</sup> )				%	g/kg					
Uhonmora	0-30	Shale	5.87a	10.43a	0.33a	11.28a	3.58a	0.67a	1.51a	0.33a	0.9a	6.18a	98.6a	663.3a	120a	216.7a
	30-60		5.83b	4.92b	0.26b	13.15b	2.5b	0.69b	1.05b	0.26b	0.1b	4.66b	97.77b	633.3b	96.67b	270b
	60-90		5.53c	4.06c	0.24c	13.27c	2.52c	0.62c	0.9c	0.24c	0.12c	4.4c	97.45c	580c	70c	350c
	90-120		5.27d	3.52d	0.23d	7.72d	2.88d	0.52d	0.81d	0.23d	0.24d	4.68d	94.91d	533.35d	76.67d	390d
			<b>5.62</b>	<b>5.73</b>	<b>0.26</b>	<b>11.35</b>	<b>2.87</b>	<b>0.62</b>	<b>1.06</b>	<b>0.26</b>	<b>0.34</b>	<b>4.98</b>	<b>97.18</b>	<b>602.48</b>	<b>90.83</b>	<b>306.67</b>
KOKO	0-30	Hydromorphic	4.8a	10.56a	0.75a	8.91a	0.58a	0.1a	0.47a	0.1a	1.25a	2.5a	51.73a	843.3a	66.67a	110a
	30-60		4.57b	6.42b	0.46b	5.96b	0.47b	0.06b	0.23b	0.06b	0.88b	1.7b	49.04b	843.3b	56.67b	113.3b
	60-90		4.57c	3.68c	0.26c	5.94c	0.43c	0.04c	0.14c	0.08c	0.62c	1.32c	52.88c	830c	46.67c	116.7c
	90-120		4.43d	3.52d	0.25d	5.49d	0.39d	0.06d	0.17d	0.07d	0.52d	1.22d	56.52d	816.7d	36.67d	120d
			<b>4.59</b>	<b>6.04</b>	<b>0.43</b>	<b>6.57</b>	<b>0.46</b>	<b>0.06</b>	<b>0.25</b>	<b>0.07</b>	<b>0.81</b>	<b>1.68</b>	<b>52.54</b>	<b>833.32</b>	<b>51.67</b>	<b>115</b>
NIFOR	0-30	Coastal Plain Sand	4.7a	11.05a	0.79a	9.89a	1.23a	0.27a	1.11a	0.2a	0.56a	3.36a	83.97a	786.7a	43.33a	170a
	30-60		4.43b	5.51b	0.39b	8.05b	0.78b	0.45b	0.52b	0.12b	0.99b	2.87b	67.52b	693.3b	30b	276.7b
	60-90		4.3c	5.28c	0.38c	7.53c	0.69c	0.15c	0.38c	0.09c	1.62c	2.92c	46.02c	646.7c	30c	323.3c
	90-120		4.3d	4.27d	0.31d	6.93d	0.74d	0.08d	0.32d	0.08d	1.68d	2.91d	43.16d	630d	30d	340d
			<b>4.43</b>	<b>6.52</b>	<b>0.46</b>	<b>8.1</b>	<b>0.86</b>	<b>0.23</b>	<b>0.58</b>	<b>0.12</b>	<b>1.21</b>	<b>3.01</b>	<b>60.16</b>	<b>689.17</b>	<b>33.33</b>	<b>277.5</b>
Idanre	0-30	Basement Complex	6.23a	15.13a	1.08a	14.48a	3.7a	1.73a	1.4a	0.36a	0.05a	7.23a	99.14a	633.3a	160a	206.7a
	30-60		5.93b	7.6b	0.54b	11.85b	2.43b	0.48b	0.99b	0.24b	0.06b	4.19b	98.03b	623.3b	156.7b	220b
	60-90		5.87c	6.13c	0.44c	8.64c	1.71c	0.13c	0.76c	0.19c	0.07c	2.85c	97.24c	583.3c	180c	236.7c
	90-120		5.77d	5.51d	0.39d	8.51d	1.48d	0.15d	0.62d	0.16d	0.24d	2.66d	92.1d	583.3d	146.7d	270d
			<b>5.95</b>	<b>8.59</b>	<b>0.61</b>	<b>10.87</b>	<b>2.33</b>	<b>0.62</b>	<b>0.94</b>	<b>0.23</b>	<b>0.1</b>	<b>4.23</b>	<b>96.62</b>	<b>605.8</b>	<b>160.85</b>	<b>233.35</b>

Mean value(s) with the same letters(s) in the column are not significantly different from one another at 5% level of probability

**Table 2:** Al-oxides distribution along the soil depth in the locations studies

P-Fe <sub>2</sub> O <sub>3</sub>	Depths (cm)	Parent materials	DCB-Al <sub>2</sub> O <sub>3</sub>	Ox-Al <sub>2</sub> O <sub>3</sub>	P-Al <sub>2</sub> O <sub>3</sub>	T-Al <sub>2</sub> O <sub>3</sub>
			← (mg kg <sup>-1</sup> ) →			
Uhonmora	0-30	Shale	3.01c	3.46d	1.13a	7.66c
	30-60		3.14b	3.81c	0.9b	7.86b
	60-90		3.23a	4.00b	0.87c	8.14a
	90-120		3.09d	4.11a	0.59d	7.87b
	<b>Mean</b>		<b>3.12</b>	<b>3.84</b>	<b>0.87</b>	<b>7.88</b>
Koko	0-30	Hydromorphic	0.93a	0.7b	0.44a	2.15a
	30-60		0.6b	0.64c	0.08b	1.38b
	60-90		0.5c	0.53d	0.04c	1.3c
	90-120		0.37d	0.79a	0.03d	1.39b
	<b>Mean</b>		<b>0.6</b>	<b>0.66</b>	<b>0.14</b>	<b>1.55</b>
NIFOR	0-30	Coastal Plain Sand	1.75a	0.25a	1.92a	3.7a
	30-60		1.7b	0.03b	1.5b	3.31b
	60-90		1.72c	0.01c	0.69d	2.63c
	90-120		1.35d	0.01c	0.8c	2.19d
	<b>Mean</b>		<b>1.63</b>	<b>0.07</b>	<b>1.22</b>	<b>2.95</b>
Idanre	0-30	Basement complex	0.09c	2.15c	0.15a	2.42b
	30-60		0.08d	2.2b	0.11c	2.39c
	60-90		0.14b	1.95d	0.11c	2.25d
	90-120		0.21a	2.3a	0.13b	2.67a
	<b>Mean</b>		<b>0.13</b>	<b>2.15</b>	<b>0.13</b>	<b>2.43</b>

Mean value (s) with the same letter(s) in the column are not significantly different from one another at 5% level of probability. LSD = Least significant difference

DCB – Dithionite Citrate bi-carbonate

OX – Ammonium oxalate

P – Pyrophosphate

T – Total

**Table 3:** Correlation coefficient between some soil physical and chemical properties and the extractable forms of Al<sub>2</sub>O<sub>3</sub> in the various locations Studied

Soil properties	DCB-Al <sub>2</sub> O <sub>3</sub>	Ox-Al <sub>2</sub> O <sub>3</sub>	P-Al <sub>2</sub> O <sub>3</sub>	T-Al <sub>2</sub> O <sub>3</sub>	DCB-Al <sub>2</sub> O <sub>3</sub>	Ox-Al <sub>2</sub> O <sub>3</sub>	P-Al <sub>2</sub> O <sub>3</sub>	T-Al <sub>2</sub> O <sub>3</sub>
	Uhonmora (Shale)				Koko (Hydromorphic)			
Sand	0.051	-0.356	0.674*	0.242	-0.438	-0.201	0.149	-0.098
Silt	0.387	-0.456	0.594*	-0.450	0.377	0.176	-0.254	-0.426
Clay	0.076	0.410	-0.695*	0.679*	0.257	0.107	0.341	0.202
pH	0.302	-0.601*	0.385	-0.198	-0.422	0.039	-0.151	-0.333
O.C	-0.500*	-0.462	0.824*	0.128	0.816*	0.863*	0.722*	-0.327
N	-0.500*	-0.462	0.824*	0.128	0.816*	0.863*	0.722*	-0.327
A.P	0.151	-0.441	0.373	0.141	0.019	-0.220	-0.121	-0.279
K	-0.222	-0.659*	0.763*	0.205	0.768*	0.821*	0.760*	-0.442
Ca	0.036	-0.359	0.457	0.150	0.665*	0.491	0.612*	-0.130
Mg	-0.534*	0.324	0.074	0.332	0.642*	0.299	0.531	0.128
Na	-0.473	-0.339	0.726*	0.274	0.547	0.354	0.470	-0.238
ECEC	-0.368	-0.312	0.646*	0.294	0.793*	0.640*	0.753*	-0.187
	NIFOR (Coastal Plain Sand)				Idanre (Basement complex)			
Sand	0.764*	0.119	0.768*	0.692*	0.017	-0.039	0.041	0.036
Silt	0.481	0.218	0.488	0.483	-0.222	-0.460	-0.310	-0.551*
Clay	-0.807*	-0.147	-0.812*	-0.738*	0.032	0.152	0.025	0.087
pH	0.559*	0.252	0.596*	0.493	0.026	0.005	0.015	0.058
O.C	0.952*	-0.044	0.965*	0.660*	-0.544*	-0.072	0.624*	-0.243
N	0.952*	-0.044	0.965*	0.660*	-0.544*	-0.072	0.624*	-0.243
A.P	0.421	0.560*	0.410	0.773*	-0.123	0.195	0.089	0.216
K	0.832*	0.025	0.860*	0.643*	-0.460	-0.049	0.142	-0.342
Ca	0.854*	0.180	0.911*	0.653*	-0.496	0.194	0.459	0.123
Mg	0.243	0.217	0.122	0.223	-0.407	0.253	0.578*	0.222
Na	0.842*	0.036	0.856*	0.633*	-0.511*	0.102	0.307	-0.135
ECEC	0.851*	0.129	0.799*	0.681*	-0.530*	0.209	0.507	0.078

\*Significantly correlated at 5% level of probability.

#### 4. DISCUSSION

The physical and chemical properties of soils across four locations (Uhonmora, Koko, NIFOR, and Idanre) at varying depths (Table 1). Key parameters include pH, organic carbon (Org C), nitrogen (N), phosphorus (P), exchangeable cations (Ca, Mg, K, Na), effective cation exchange capacity (ECEC), base saturation (BS), and soil texture (sand, silt, clay). Soil pH generally decreased with depth in all locations except Idanre, which exhibited minimal variation. For instance, Uhonmora's pH declined from 5.87 (0–30 cm) to 5.27 (90–120 cm), reflecting increased acidity in deeper layers, likely due to leaching of basic cations (Brady and Weil, 2016). In contrast, Koko's highly acidic soils (pH 4.43–4.8) align with its hydromorphic parent material, which promotes anaerobic conditions and organic acid accumulation (Fanning and Fanning, 1989). Idanre's near-neutral pH (5.77–6.23) correlates with its basement complex parent material, rich in weatherable minerals that buffer acidity (Juo and Franzluebbers, 2003). Org C and N decreased significantly with depth across all locations, consistent with surface accumulation of organic matter from plant residues (Lal, 2004).

Uhonmora's Org C dropped from 10.43 g kg<sup>-1</sup> (0–30 cm) to 3.52 g kg<sup>-1</sup> (90–120 cm), reflecting reduced microbial activity and slower decomposition in subsoils (Six et al., 2002). Koko's lower Org C (3.52–10.56 g kg<sup>-1</sup>) compared to Idanre (5.51–15.13 g kg<sup>-1</sup>) may stem from waterlogged conditions limiting aerobic decomposition (Reddy and DeLaune, 2008). Plant-available P varied widely, with Uhonmora and Idanre showing higher P levels (7.72–14.48 mg kg<sup>-1</sup>) compared to Koko (5.49–8.91 mg kg<sup>-1</sup>). This disparity may reflect differences in parent material mineralogy; shale and basement complex soils often contain apatite, a primary P source (Sanyal and De Datta, 1991). Exchangeable Ca and Mg followed similar depth-related declines, likely due to leaching and plant uptake (Havlin et al., 2014).

Koko's exceptionally low Ca (0.39–0.58 cmol kg<sup>-1</sup>) and Mg (0.04–0.1 cmol kg<sup>-1</sup>) underscore its acidic, weathered nature. Sand content decreased with depth in Uhonmora (663.3 to 533.35 g kg<sup>-1</sup>) and NIFOR (786.7 to 630 g kg<sup>-1</sup>), while clay increased, suggesting illuviation processes (Bockheim

and Gennadiyev, 2000). Koko's consistently high sand content (816.7–843.3 g kg<sup>-1</sup>) reflects its hydromorphic origin, where coarse textures facilitate drainage. Idanre's clay accumulation in deeper layers (206.7–270 g kg<sup>-1</sup>) aligns with intense weathering of basement complex rocks (Schaeztl and Anderson, 2005). ECEC values were highest in Idanre (2.66–7.23 cmol kg<sup>-1</sup>) due to its higher clay and organic matter content, which enhance nutrient retention (Tan, 2011). Base saturation exceeded 90% in Uhonmora and Idanre, indicative of fertile soils, whereas Koko and NIFOR had lower BS (43.16–67.52%), consistent with their acidic, nutrient-poor conditions (Sumner & Miller, 1996).

Aluminum oxide (Al<sub>2</sub>O<sub>3</sub>) concentrations extracted via dithionite-citrate-bicarbonate (DCB), ammonium oxalate (Ox), pyrophosphate (P), and total (T) (Table 2) methods across soil depths. Uhonmora's DCB-Al<sub>2</sub>O<sub>3</sub> increased with depth (3.01–3.23 mg kg<sup>-1</sup>), reflecting progressive weathering of shale, which releases crystalline oxides like gibbsite (McKeague and Day, 1966). In contrast, Koko's low DCB-Al<sub>2</sub>O<sub>3</sub> (0.37–0.93 mg kg<sup>-1</sup>) aligns with its hydromorphic environment, where reducing conditions inhibit crystalline oxide formation (Schwertmann and Taylor, 1989). NIFOR's DCB-Al<sub>2</sub>O<sub>3</sub> (1.35–1.75 mg kg<sup>-1</sup>) suggests moderate weathering of coastal plain sands, while Idanre's minimal DCB-Al<sub>2</sub>O<sub>3</sub> (0.08–0.21 mg kg<sup>-1</sup>) indicates limited crystalline Al formation in basement complex soils. Ox-Al<sub>2</sub>O<sub>3</sub> followed inverse trends to DCB-Al<sub>2</sub>O<sub>3</sub> in some locations.

For example, Uhonmora's Ox-Al<sub>2</sub>O<sub>3</sub> rose with depth (3.46–4.11 mg kg<sup>-1</sup>), suggesting greater amorphous Al in subsoils due to inhibited crystallization under acidic conditions (Parfitt and Childs, 1988). Koko's Ox-Al<sub>2</sub>O<sub>3</sub> peaked at 90–120 cm (0.79 mg kg<sup>-1</sup>), possibly due to transient water saturation promoting short-range-order Al phases (Childs, 1992). NIFOR's negligible Ox-Al<sub>2</sub>O<sub>3</sub> (0.01–0.25 mg kg<sup>-1</sup>) reflects sandy textures with low Al retention, whereas Idanre's higher Ox-Al<sub>2</sub>O<sub>3</sub> (1.95–2.3 mg kg<sup>-1</sup>) may stem from rapid weathering of feldspars (Bigham et al., 2002). P-Al<sub>2</sub>O<sub>3</sub> decreased with depth in Uhonmora (1.13–0.59 mg kg<sup>-1</sup>) and Koko (0.44–0.03 mg kg<sup>-1</sup>), correlating with declining organic matter (Table 1). This aligns with studies showing organo-Al complexes dominate in surface horizons (McDaniel et al., 2012). NIFOR's high P-Al<sub>2</sub>O<sub>3</sub> (0.69–1.92 mg kg<sup>-1</sup>)

suggests strong Al-organic binding in sandy soils, while Idanre's low values (0.11–0.15 mg kg<sup>-1</sup>) indicate minimal organic-Al interaction due to higher pH (Hargrove and Thomas, 1981). Total Al<sub>2</sub>O<sub>3</sub> mirrored DCB-Al<sub>2</sub>O<sub>3</sub> trends in Uhonmora (7.66–8.14 mg kg<sup>-1</sup>) and Idanre (2.25–2.67 mg kg<sup>-1</sup>), highlighting crystalline oxides as the dominant form. Koko's low total Al<sub>2</sub>O<sub>3</sub> (1.3–2.15 mg kg<sup>-1</sup>) underscores its weathered, Al-depleted state, whereas NIFOR's intermediate totals (2.19–3.7 mg kg<sup>-1</sup>) reflect mixed Al sources (Jackson, 2005).

The relationships between soil properties and Al-oxides, with significant correlations (\*) at  $p < 0.05$ . (Table 3). P-Al<sub>2</sub>O<sub>3</sub> correlated positively with Org C ( $r = 0.824$ ) and N ( $r = 0.824$ ), emphasizing organic matter's role in binding Al (McBride, 1994). Negative correlations between Ox-Al<sub>2</sub>O<sub>3</sub> and pH ( $r = -0.601$ ) suggest acidic conditions promote amorphous Al formation (Huang et al., 2002). Clay showed a strong positive correlation with T-Al<sub>2</sub>O<sub>3</sub> ( $r = 0.679$ ), indicating Al oxides contribute to clay mineral stability (Borchardt, 1989). DCB-Al<sub>2</sub>O<sub>3</sub> correlated with ECEC ( $r = 0.793$ ) and Ca ( $r = 0.665$ ), implying crystalline oxides enhance nutrient retention in sandy soils (Sposito, 2008). Positive Ox-Al<sub>2</sub>O<sub>3</sub>-Org C correlation ( $r = 0.863$ ) suggests organo-amorphous complexes form under waterlogged conditions (Kögel-Knabner et al., 2010).

DCB-Al<sub>2</sub>O<sub>3</sub> and P-Al<sub>2</sub>O<sub>3</sub> correlated negatively with clay ( $r = -0.807$  and  $-0.812$ ), likely due to Al leaching in sandy textures (Ulery & Drees, 2008). Strong positive correlations between Org C and P-Al<sub>2</sub>O<sub>3</sub> ( $r = 0.965^*$ ) highlight organic matter's dominance in Al mobilization (Stevenson, 1994). Negative correlations between Org C and DCB-Al<sub>2</sub>O<sub>3</sub> ( $r = -0.544$ ) suggest limited Al-organic interaction in near-neutral soils (Lützow et al., 2006). Mg showed a positive correlation with P-Al<sub>2</sub>O<sub>3</sub> ( $r = 0.578$ ), possibly due to Mg<sup>2+</sup> competing with Al<sup>3+</sup> for binding sites (Berggren and Mulder, 1995). These correlations underscore how parent material, pH, and organic matter govern Al oxide dynamics. Acidic soils favor organo-Al complexes, while near-neutral soils exhibit crystalline dominance. Such insights are critical for managing Al toxicity and nutrient availability in agricultural systems (Kissel et al., 2009).

## 5. CONCLUSION

The study demonstrates that parent material critically shapes soil properties and Al oxide distribution in Southwestern Nigeria. Basement Complex-derived soils (Idanre) exhibited near-neutral pH (5.77–6.23), moderate clay content (206.7–270 g kg<sup>-1</sup>), and crystalline Al oxides (DCB-Al<sub>2</sub>O<sub>3</sub>: 0.08–0.21 mg kg<sup>-1</sup>), supporting cocoa cultivation through balanced nutrient retention. In contrast, Shale soils (Uhonmora) showed increasing crystalline Al oxides with depth (3.01–3.23 mg kg<sup>-1</sup>), linked to smectite clay illuviation, but faced phosphorus fixation challenges due to high Al oxide activity. Hydromorphic soils (Koko), characterized by waterlogging and acidic conditions (pH 4.43–4.8), accumulated amorphous Al oxides (Ox-Al<sub>2</sub>O<sub>3</sub>: 0.53–0.79 mg kg<sup>-1</sup>) and organically bound Al (P-Al<sub>2</sub>O<sub>3</sub>: 0.03–0.44 mg kg<sup>-1</sup>), posing risks of Al toxicity and nutrient leaching. Coastal Plain Sands (NIFOR) displayed sandy textures (630–786.7 g kg<sup>-1</sup> sand), low organic matter, and Al leaching, exacerbating nutrient deficiencies.

Soil acidity emerged as a key constraint, particularly in Koko and NIFOR, where pH < 5.0 promoted Al<sup>3+</sup> mobilization, threatening root growth in crops like cassava and maize. Uhonmora's pH decline with depth (5.87 to 5.27) reflected leaching of basic cations, while Idanre's near-neutral pH buffered Al toxicity. Organic carbon and nitrogen decreased significantly with depth across all locations, with surface layers (0–30 cm) retaining the highest values (e.g., Uhonmora: Org C 10.43 g kg<sup>-1</sup>). This decline underscores the role of surface organic matter in microbial activity and nutrient cycling. Phosphorus availability varied widely, with Shale and Basement Complex soils showing higher P levels (7.72–14.48 mg kg<sup>-1</sup>) due to apatite weathering, while sandy soils (NIFOR) faced P fixation on Al oxide surfaces. Aluminum oxide distribution further highlighted parent material influences. Crystalline Al dominated in well-drained Shale soils (Uhonmora), while amorphous Al prevailed in waterlogged zones (Koko). Organically bound Al correlated with surface organic matter in Coastal Plain Sands (NIFOR), emphasizing ligand chelation. Correlations between soil properties and Al oxides provided mechanistic insights: organic matter's role in binding Al (P-Al<sub>2</sub>O<sub>3</sub>-Org C:  $r = 0.965$  in NIFOR), clay's influence on oxide retention (T-Al<sub>2</sub>O<sub>3</sub>-clay:  $r = 0.679$  in Uhonmora), and acidity's promotion of amorphous Al (Ox-Al<sub>2</sub>O<sub>3</sub>-pH:  $r = -0.601$  in Uhonmora).

## ACKNOWLEDGMENT

The authors appreciate the support from the Department of Soil Science and Land Management, Faculty of Agriculture, University of Benin, Benin City, particularly the laboratory staff who assisted in the laboratory work. Their technical assistance was invaluable to the completion of this research.

## CONFLICT OF INTEREST

The authors declare that there is no conflict of interest between them.

## AUTHOR'S CONTRIBUTIONS

All authors conceived and designed the study, collected and analyzed the data, and drafted the final version of the manuscript.

## STATEMENT OF ETHICS CONSENT

This article does not require ethical approval as there are no experiments with human or animal subjects.

## FUNDING

This research received no external funding.

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