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Original Research

Potassium Adsorption Characteristics of Soils Derived from Different Parent Materials in Southeastern Nigeria

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Abstract

This study investigated potassium (K) adsorption characteristics of soils derived from five contrasting parent materials (alluvium, basement complex, coastal plain sand, sandstone, and shale) at three soil depths (0-20, 20-40, and 40-60 cm) in Southeastern Nigeria. Soil samples were collected from multiple locations across Abia, Imo, Anambra, Ebonyi, Enugu, and Cross-River States. Three adsorption models (Langmuir, Freundlich, and Temkin) were employed to characterize K adsorption behavior. Results showed that K adsorption rates varied significantly among parent materials, ranging from 1537 mg/kg (coastal plain sand) to 1694 mg/kg (sandstone), with significant depth-related variations. The Freundlich model provided the best fit (R^2 = 0.56-0.99, mean = 0.88) compared to Langmuir (R^2 = 0.58-0.89, mean = 0.72) and Temkin (R^2 = 0.21-0.88, mean = 0.45) models. Sandstone-derived soils exhibited the highest mean K adsorption rate (1694 mg/kg), while coastal plain sand showed the lowest (1537 mg/kg). Adsorption parameters varied considerably among parent materials, with alluvium showing positive adsorption maximum in the Langmuir model, indicating favorable K retention. These findings provide crucial insights for developing parent material-specific K fertilization strategies in Southeastern Nigerian soils.

1. Introduction

Potassium (K) is an essential macronutrient required by plants in relatively large quantities for various physiological and biochemical processes, including enzyme activation, protein synthesis, photosynthesis, osmoregulation, and stress tolerance (Brady and Weil, 2008). Despite its abundance in most soils, K availability to plants is often limited due to its strong adsorption onto soil colloids, particularly clay minerals and organic matter (Guo,. *et. al*., 2014). Understanding K adsorption characteristics is therefore crucial for optimizing fertilizer management strategies and ensuring sustainable agricultural productivity.

Soil K exists in various forms: solution K, exchangeable K, non-exchangeable K, and mineral K (White, D., 2012). The equilibrium between these forms is primarily controlled by adsorption-desorption processes, which are influenced by soil properties such as clay mineralogy, organic matter content, pH, cation exchange capacity (CEC), and parent material composition (Mengel and Kirkby, 2001). Parent material, being the fundamental geological substrate from which soils develop, exerts a profound influence on soil mineralogical composition and consequently on K adsorption behavior (McBratney, *et. al*., 2005).

Southeastern Nigeria is characterized by diverse parent materials including coastal plain sands, alluvium, shale, sandstone, and basement complex rocks, resulting in soils with contrasting physical and chemical properties (Ufot *et al*., 2016). The region experiences a humid tropical climate with mean annual rainfall ranging from 1500 to 2500 mm and temperatures between 24-28°C (Igwe, 2012). These climatic conditions promote intense weathering and leaching of basic cations, resulting in acidic, nutrient-depleted soils (Nnaji *et al*., 2002). The predominant soil order is Ultisol, characterized by low base saturation, low CEC, and kaolinitic clay mineralogy (FDALR, 1985; Nwaogu and Ebeniro, 2009).

Previous studies on K dynamics in tropical soils have predominantly focused on K availability and plant uptake, with limited attention to parent material-specific adsorption characteristics (Osman *et al*., 2010). The heterogeneous nature

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of Southeastern Nigerian soils, coupled with intensive agricultural practices, necessitates a comprehensive understanding of K adsorption behavior across different parent materials and soil depths. Such information is essential for developing site-specific nutrient management recommendations that optimize K use efficiency and minimize environmental losses.

Mathematical models such as Langmuir, Freundlich, and Temkin equations have been widely employed to describe adsorption phenomena in soils (Goldberg, 2005). The Langmuir model assumes monolayer adsorption on homogeneous surfaces with finite adsorption sites, the Freundlich model describes multilayer adsorption on heterogeneous surfaces, while the Temkin model accounts for the heat of adsorption (Sparks, 2003). Comparative evaluation of these models provides insights into the mechanisms and energetics of K adsorption in different soil environments.

This study was therefore designed to: (1) determine K adsorption rates in soils derived from five contrasting parent materials at different depths in Southeastern Nigeria; (2) characterize K adsorption behavior using Langmuir, Freundlich, and Temkin models; (3) evaluate the best-fit adsorption model for describing K adsorption in these soils; and (4) assess the influence of parent material and soil depth on K adsorption parameters. The findings will contribute to improving K fertilizer recommendations and management practices in the diverse agroecological zones of Southeastern Nigeria.

2. Materials and Methods

2.1 Study area

The study was conducted in Southeastern Nigeria, located within latitudes 4°47'35''N and 7°7'44''N, and longitudes 7°54'26''E and 8°27'10''E (Anejionu *et al.*, 2013). The region covers approximately 29,095 km², representing about 3.19% of Nigeria's total land area. Southeastern Nigeria encompassing six states: Abia, Imo, Anambra, Ebonyi, Enugu, and Cross-River (Figure 1).

2.2 Climate and Vegetation

The study area is classified as humid tropical, characterized by uniformly high temperatures and bimodal rainfall distribution (Anyadike, 2002). Mean minimum temperatures range from 21-30°C along the coast to 29-33°C in the interior regions (Chukwu, 2007). Annual temperatures average between 24°C (75.2°F) and 27°C (80.4°F), with slight seasonal variations of approximately 25°C (77°F) during the rainy season and 28°C (82.4°F) during the dry season. Relative humidity typically exceeds 90% in early morning, declining to 60-80% in the afternoon. Annual rainfall is substantial, ranging from over 2500 mm in coastal areas to approximately 1500 mm inland (Chukwu *et al.*, 2009; Ezemonye and Emeribe, 2012; Igwe, 2012). The region experiences two distinct seasons: a rainy season from April to October and a dry season from November to April, with a brief dry spell ("August break") occurring mid-rainy season.

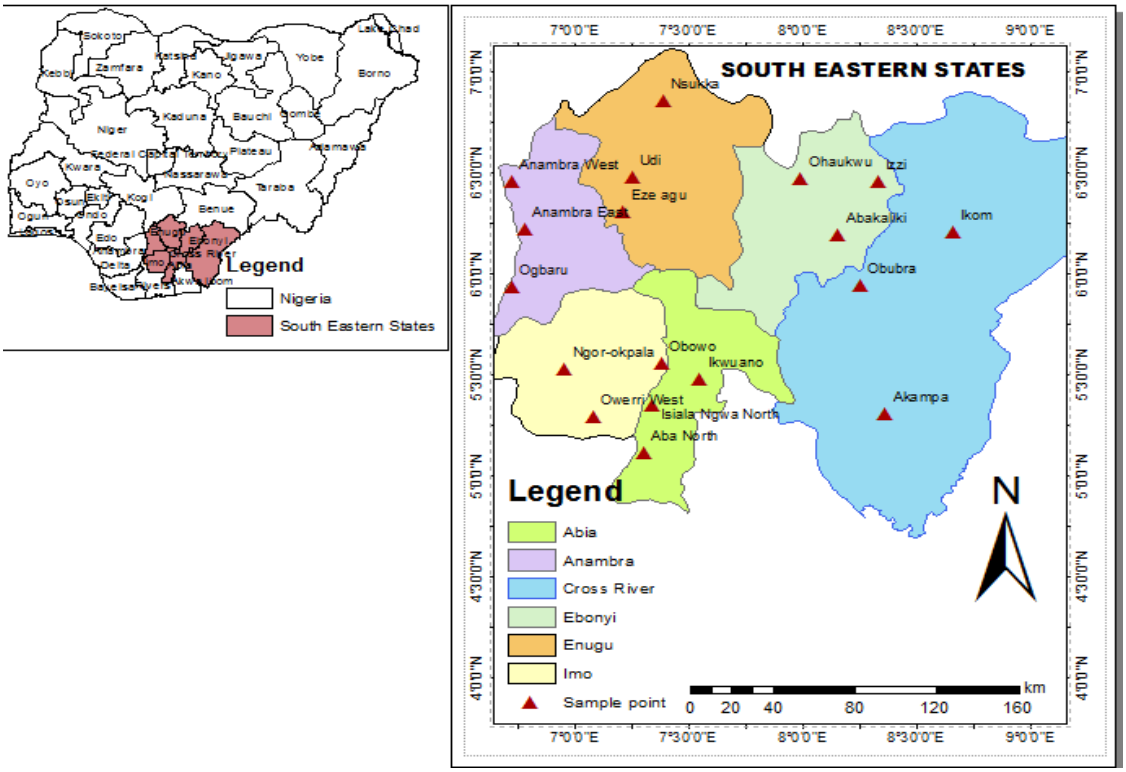


Figure 1. Map of Selected States in Southeastern Nigeria Showing Sampled Locations

The vegetation comprises three main zones: mangrove forests in coastal areas characterized by muddy sheltered creeks and tidal waters, freshwater swamp forests with floating grasses and screw pines, and rainforests featuring wet evergreen forests with multiple tree species (Onweremadu *et al*., 2007).

2.3 Soil Characteristics

Soils of Southeastern Nigeria are strongly weathered, heterogeneous in nature, and predominantly classified as Ultisols (typic Hapludult) according to USDA Soil Taxonomy (FDALR, 1985; Nwaogu and Ebeniro, 2009). The soils are characterized by:

Low organic matter content, Low base saturation, Low water storage capacity, High susceptibility to erosion and degradation (Ufot *et al*., 2016). Low silt/clay content resulting in sandy, cohesionless textures, High permeability and infiltration rates (Ezezika and Adetona, 2011), Predominantly kaolinitic clay mineralogy, Low cation exchange capacity (CEC), Low nutrient reserves, Acidic pH due to intensive leaching (Nnaji *et al*., 2002). At least ten soil classes exist in the region: Eutric fluvisols, hystic fluvisols, dystric fluvisols, rhodic ferrosols, lithosols, dystric gleysols, eutric gleysols, eutric nitosols, dystric cambisols, and gleyic cambisols (Ogbonna *et al*., 2011).

2.4 Parent Material Characteristics

Five contrasting parent materials were selected for this study based on their widespread occurrence and agricultural importance in Southeastern Nigeria:

2.4.1 Coastal Plain Sands

Soils derived from unconsolidated sediments deposited by marine and fluvial processes. These soils are characterized by high fertility, good drainage, moderate to high organic matter content, and dark brown surface horizons with active faunal activity. They support diverse agricultural crops including maize (*Zea mays*), yam (*Dioscorea spp*.), cassava (*Manihot esculenta*), fluted pumpkin (*Telfairia occidentalis*), and tree plantations such as oil palm (*Elaeis guineensis*) and mango (*Mangifera indica*) (Osman *et al*., 2010).

2.4.2 Sandstone

Soils formed from weathering of sandstone rocks, characterized by coarse texture, excellent drainage, and generally low nutrient status. The profile typically shows iron-stained, thick friable, fine-textured horizons with occasional clay and stone inclusions. These soils are overlain by considerable thickness of red earth formed through weathering and ferruginization. Dominant crops include cassava, plantain (*Musa spp*.), and African pear (*Dacryodes edulis*) (Brady and Weil, 2008).

2.4.3 Alluvium

Highly fertile soils derived from recent river deposits, characterized by dark colors, fine clayey texture, excellent drainage, and high nutrient content. These soils exhibit high water retention capacity and support a wide range of arable crops including cassava, maize, vegetables, sugarcane (*Saccharum officinarum*), and natural vegetation such *as Aspilia africana* and *Sida acuta* (FAO, 2006).

2.4.4 Shale

Soils formed from fine-grained sedimentary shale rocks, typically exhibiting poor drainage, high clay content, low organic matter, and low fertility (Lal, 2004). The soil color is characteristically grayish-white. Common crops cultivated include yam, cassava, groundnut (*Arachis hypogaea*), African pear, and plantain.

2.4.5 Basement Complex

Soils formed from weathered crystalline rocks such as gneisses and schists, characterized by moderate fertility, good drainage, and composition of sand, clay, and gravel. These soils typically require fertilization for optimal crop production. Common crops include cassava, cocoyam (*Colocasia esculenta*), fluted pumpkin, groundnut, and natural grasses such as elephant grass (*Pennisetum purpureum*), wireweed (*Sida acuta*), and mimosa (*Mimosa spp*.) (Ojeniyi and Ojeniyi, 2013).

2.5 Soil Sampling

Soil samples were collected from representative sites across the five parent materials using a systematic sampling approach. The geological map of Southeastern Nigeria served as the reference base for sample collection. A hand-held Global Positioning System (GPS) was used to record the geographical coordinates of each sampling location.

Soil samples were collected in triplicate from each parent material at three depth intervals: 0-20 cm (topsoil), 20-40 cm (subsurface), and 40-60 cm (subsoil), using a soil auger. The three-depth sampling strategy was employed to assess vertical variations in K adsorption characteristics within the soil profile. A total of 45 soil samples (5 parent materials × 3 depths × 3 replications) were collected. Sampling locations were selected to represent typical land uses and vegetation cover associated with each parent material (Table 1). Sample locations were distributed across multiple Local Government Areas (LGAs) in Abia, Imo, Anambra, Ebonyi, Enugu, and Cross-River States.

Soil samples were collected from areas under different land uses including fallow land, active croplands (cassava, maize, vegetables), and mixed cropping systems, reflecting the predominant agricultural practices in the region.

2.6 Laboratory Analyses

2.6.1 Sample Preparation

Collected soil samples were air-dried at room temperature, crushed using a wooden mortar and pestle, and passed through a 2-mm sieve to remove coarse particles, plant roots, and debris. The sieved samples were stored in properly labeled polythene bags for subsequent laboratory analyses.

Table 1. Soil Parent Materials and Sample Locations

Parent Material	Location	LGA	State	Latitude	Longitude	Land use
Coastal plain sand	Umudike	Ikwuano	Abia	5.47573	7.55244	Fallow
Coastal plain sand	Umuchima	Isiala-Ngwa North	Abia	5.34801	7.34521	Cassava
Coastal plain sand	Umuamachi	Aba North	Abia	5.11422	7.30507	Fallow
Coastal plain sand	Umulogho	Obowo	Imo	5.55285	7.38484	Fallow
Coastal plain sand	Obokwe	Ngor-okpala	Imo	5.52541	6.95813	Cassava and fluted pumpkin
Coastal plain sand	Ubomori	Owerri West	Imo	5.29324	7.08316	Maize, Okro and oil palm
Sandstone	Univ.Rd Nsukka	Nsukka	Enugu	6.85333	7.39361	Cassava, plantain and pear
Sandstone	Amankwo	Udi	Enugu	6.47516	7.25502	Cassava
Sandstone	Ndiagu	Eze agu	Enugu	6.30524	7.21511	Fallow
Shale	Ngbo	Ohaukwu	Ebonyi	6.46722	7.99417	Fallow
Shale	Osebi	Izzi	Ebonyi	6.45305	8.33226	Cassava
Shale	Nwafo Ogu	Abakaliki	Ebonyi	6.19116	8.15923	Fallow
Alluvium	Nzam	Anambra West	Anambra	6.45639	6.72472	Fallow
Alluvium	Onono	Anambra East	Anambra	6.21731	6.78621	Yam, pear, and plantain
Alluvium	Umunankwo	Ogbaru	Anambra	5.93416	6.72904	Cassava and oil palm
Basement Complex	Awi	Akampa	Cross-River	5.30361	8.36455	Cassava
Basement Complex	Ibine	Ikom	Cross-River	6.20702	8.65921	Cocoyam and pumpkin
Basement Complex	Abinti Abangork	Obubra	Cross-River	5.94102	8.25218	Fallow

2.6.2 Potassium Adsorption Experiment

Adsorption studies were carried out according to the method by Rowell (1994). 2.5g of the soil samples was weighed and transferred into 50ml solution of 0.01M CaCl containing potassium concentrations of 0, 25, 50, 75, 100, 125, 150, 175, 200, 225, and 250mgL^{-1} and shaken for 2 hours at 25 ± 1^0C to achieve equilibration. The content was filtered using Whatman filter papers No. 42 and centrifuged at 3000 revolutions per minute for 10 minutes. Soil samples (predetermined weight) were equilibrated with K solutions in centrifuge tubes at a constant soil-to-solution ratio. The suspensions were shaken at constant temperature for a predetermined equilibration time to achieve adsorption equilibrium. After equilibration, the suspensions were centrifuged, and the supernatant solutions were analyzed for equilibrium K concentration using flame photometry. The amount of K adsorbed was calculated as the difference between the initial and equilibrium K concentrations.

2.7 Adsorption Models

Three widely used adsorption models were employed to describe K adsorption behavior:

2.7.1 Langmuir Model

The Langmuir equation assumes monolayer adsorption on a homogeneous surface with a finite number of identical sites:

$$q = (a \times b \times Ce) / (1 + b \times Ce) \quad (1)$$

Where:

q = amount of K adsorbed (mg/kg)
Ce = equilibrium K concentration in solution (mg/L)
a = maximum adsorption capacity (mg/kg)
b = bonding energy constant related to adsorption energy (L/mg)
The linearized form: $Ce/q = (1/ab) + (Ce/a)$ (2)

2.7.2 Freundlich Model

The Freundlich equation describes multilayer adsorption on heterogeneous surfaces:

$$q = a \times C_e(1/n) \quad (3)$$

Where:
a = adsorption capacity constant (mg/kg)
n = adsorption intensity constant (dimensionless)
1/n = adsorption energy parameter
The linearized form: $\log q = \log a + (1/n) \log Ce$ (4)

2.7.3 Temkin Model

The Temkin equation accounts for the effects of indirect adsorbate-adsorbate interactions and assumes that the heat of adsorption decreases linearly with surface coverage:

$$q = a + b \ln Ce \quad (5)$$

Where a = Temkin constant related to maximum binding energy (mg/kg), b = Temkin constant related to heat of adsorption (mg/kg).

2.8 Statistical Analysis

Experimental data were subjected to analysis of variance (ANOVA) using a factorial design with parent material and depth as factors. The least significant difference (LSD) test at 5% probability level was used to separate treatment means. Coefficient of determination (R^2) values were calculated to evaluate the goodness of fit for each adsorption model. Linear regression analysis was performed to determine adsorption parameters (a, b, and n) for each model. All statistical analyses were conducted using appropriate statistical software.

3. Results

3.1 Potassium Adsorption Rates

Potassium adsorption rates varied significantly among parent materials and soil depths (Table 2). Mean K adsorption rates across all depths ranged from 1537 mg/kg for coastal plain sand to 1694 mg/kg for sandstone. The overall mean K adsorption rate across all parent materials and depths was 1634 mg/kg.

Among the parent materials, sandstone-derived soils exhibited the highest mean K adsorption rate (1694 mg/kg), followed by alluvium (1668 mg/kg), shale (1649 mg/kg), basement complex (1624 mg/kg), and coastal plain sand (1537 mg/kg). The LSD value for parent material comparison was 104.9, indicating significant differences among parent materials.

With respect to soil depth, K adsorption rates showed a general increasing trend with depth. The mean K adsorption rates were 1613 mg/kg at 0-20 cm, 1633 mg/kg at 20-40 cm, and 1657 mg/kg at 40-60 cm. However, the LSD value for depth comparison was notably high (499.5), suggesting that depth-related differences were not statistically significant at the 5% probability level.

Table 2. K adsorption rates by different parent materials and depth under study

Parent material	Depth (cm)			Mean
	0-20	20-40	40-60	
Alluvium	1656.0	1666.0	1683.0	1668.0
Basement complex	1640.0	1610.0	1622.0	1624.0
Coastal plain sand	1502.0	1595.0	1516.0	1537.0
Sandstone	1606.0	1671.0	1804.0	1694.0
Shale	1662.0	1623.0	1663.0	1649.0
Mean	1613.0	1633.0	1657.0	
LSD (0.05)	PM = 104.9, Depth = 499.5 PM X Depth = 503.7			

The interaction between parent material and depth was significant (LSD = 503.7), indicating that the effect of depth on K adsorption varied among parent materials. For instance, sandstone showed a pronounced increase in K adsorption with depth (1606 to 1804 mg/kg from 0-20 to 40-60 cm), while coastal plain sand exhibited less consistent depth-related trends.

3.2 Langmuir Adsorption Characteristics

The Langmuir model parameters varied considerably among parent materials and depths (Table 3). The adsorption maximum (a) ranged from -1219 to 344.5 mg/kg across all samples, with both negative and positive values observed. Negative values indicate that the Langmuir model may not be appropriate for describing K adsorption in certain soils, particularly those derived from basement complex and coastal plain sand at specific depths.

Alluvium-derived soils consistently showed positive adsorption maxima values (83.49 to 209.6 mg/kg) across all depths, with a mean of 135.3 mg/kg, suggesting favorable K retention characteristics. In contrast, basement complex soils exhibited consistently negative values (-754.4 to -1219 mg/kg, mean = -898.6 mg/kg), indicating poor fit of the Langmuir model for these soils.

Table 3. Potassium adsorption characteristics of the study area using Langmuir equation

Parent material	Depth (cm)	a	b	R^2
Shale	0-20	-355.4	275.5	0.8706
	20-40	-115.0	317.1	0.8774
	40-60	-290.5	254.5	0.8856
	Mean	-253.6	282.4	
Basement complex	0-20	-754.4	298.8	0.8365
	20-40	-722.3	260.8	0.7037
	40-60	-1219	363.9	0.6602
	Mean	-898.6	307.8	
Alluvium	0-20	83.49	198.6	0.8883
	20-40	112.8	203.1	0.8805
	40-60	209.6	206.9	0.8491
	Mean	135.3	202.9	
Coastal plain sand	0-20	-264.3	212.3	0.5884
	20-40	-1037	276.7	0.7546
	40-60	-5.957	202.2	0.5834
	Mean	-435.7	230.4	
Sandstone	0-20	-966.3	278.5	0.7800
	20-40	56.16	213.3	0.8516
	40-60	344.5	214.0	0.8490
	Mean	-188.54	235.3	

Note: a = adsorption maximum, b =bonding energy constant.

The bonding energy constant (b) ranged from 198.6 to 363.9 L/mg across all samples. Basement complex soils showed the highest mean bonding energy (307.8 L/mg), followed by shale (282.4 L/mg), sandstone (235.3 L/mg), coastal plain sand (230.4 L/mg), and alluvium (202.9 L/mg).

Coefficient of determination (R^2) values for the Langmuir model ranged from 0.5834 to 0.8883, with a mean of 0.72 (Table 5). The highest R^2 values were generally observed in alluvium-

derived soils (0.8491 to 0.8883), while coastal plain sand showed the lowest R^2 values (0.5834 to 0.7546), indicating variable fit quality across parent materials.

3.3 Freundlich Adsorption Characteristics

The Freundlich model demonstrated superior performance compared to the Langmuir and Temkin models across all parent materials and depths (Table 4). The adsorption capacity parameter (a) ranged from 0.1462 to 2.288 mg/kg, with alluvium showing the highest mean value (1.937 mg/kg) and shale the lowest (0.9474 mg/kg).

The adsorption intensity parameter (n) varied from 0.6445 to 2.994 across all samples. Values of n greater than 1 indicate favorable adsorption, while values less than 1 suggest unfavorable adsorption conditions. Most samples exhibited n values greater than 1, indicating predominantly favorable K adsorption. The mean n values ranged from 1.2608 (alluvium) to 2.3193 (shale), with basement complex, coastal plain sand, and sandstone showing intermediate values (1.4477 to 1.7967).

The Freundlich model provided the best overall fit to the K adsorption data, with R^2 values ranging from 0.5581 to 0.9870 and a mean of 0.88 (Table 5). The highest R^2 values were observed in shale at 20-40 cm depth (0.9870), sandstone at 0-20 cm (0.9867), basement complex at 20-40 cm (0.9827), and coastal plain sand at 20-40 cm (0.9811). The lowest R^2 value was recorded for alluvium at 40-60 cm depth (0.5581).

Table 4. Potassium adsorption characteristics of the study area using Freundlich equation

Parent material	Depth (cm)	a	n	R^2
Shale	0-20	0.953	2.376	0.8807
	20-40	0.1462	2.994	0.9870
	40-60	1.743	1.588	0.9671
	Mean	0.9474	2.3193	
Basement complex	0-20	1.441	1.732	0.8813
	20-40	1.508	1.665	0.9827
	40-60	1.278	1.993	0.9671
	Mean	1.4090	1.7967	
Alluvium	0-20	1.768	1.528	0.9280
	20-40	1.755	1.610	0.8810
	40-60	2.288	0.6445	0.5581
	Mean	1.937	1.2608	
Coastal plain sand	0-20	1.867	1.317	0.8057
	20-40	1.474	1.660	0.9811
	40-60	1.639	1.507	0.8628
	Mean	1.660	1.4947	
Sandstone	0-20	1.421	1.737	0.9867
	20-40	2.053	1.293	0.8176
	40-60	2.127	1.313	0.7941
	Mean	1.867	1.4477	

Note: a = adsorption capacity, n = adsorption energy

3.4 Temkin Adsorption Characteristics

The Temkin model generally showed the poorest fit among the three models tested (Table 5). The constant 'a' (related to maximum binding energy) ranged from -1048 to 1165 mg/kg, with considerable variability among parent materials and depths. Sandstone soils exhibited the highest mean 'a' value (1030.7 mg/kg), while shale showed the lowest mean (314.5 mg/kg).

The constant 'b' (related to heat of adsorption) ranged from 467.0 to 1514 mg/kg across all samples. The mean 'b' values varied considerably: shale (924.7 mg/kg), basement complex (761.6 mg/kg), sandstone (763.4 mg/kg), alluvium (659.1 mg/kg), and coastal plain sand (652.9 mg/kg).

R^2 values for the Temkin model were consistently lower than those of the Freundlich and generally lower than the Langmuir models, ranging from 0.2116 to 0.8812 with a mean of 0.45 (Table 5). The highest R^2 value was observed for shale at 40-60 cm depth (0.8812), while the lowest was recorded for shale at 0-20 cm (0.2116). Most R^2 values were below 0.70, indicating poor to moderate model fit.

Table 5. Potassium adsorption characteristics of the study area using Temkin equation

Parent material	Depth (cm)	a	b	R^2
Shale	0-20	1165	467.0	0.2116
	20-40	-1048	1514	0.5967
	40-60	826.4	793.0	0.8812
	Mean	314.5	924.7	
Basement complex	0-20	729.9	798.0	0.4699
	20-40	839.2	693.6	0.4003
	40-60	724.0	793.1	0.3512
	Mean	764.4	761.6	
Alluvium	0-20	888.4	614.7	0.3829
	20-40	842.0	672.0	0.3787
	40-60	780.7	687.6	0.4128
	Mean	837.0	659.1	
Coastal plain sand	0-20	888.4	614.7	0.3829
	20-40	842.0	672.0	0.3787
	40-60	780.7	672.0	0.4128
	Mean	837.0	652.9	
Sandstone	0-20	1018	741.2	0.6588
	20-40	1018	741.2	0.6588
	40-60	1056	807.7	0.7319
	Mean	1030.7	763.4	

3.5 Comparative Model Performance

Summary statistics of model performance across all parent materials and depths revealed clear differences in predictive capability (Table 6). The Freundlich model demonstrated the best overall performance with:

Minimum R^2 = 0.56, Maximum R^2 = 0.99, and Mean R^2 = 0.88,

Table 6. Potassium adsorption characteristics of soils of the study area

Parent material	Depth (cm)	Model	Linear Equation	R^2
			a b	
Shale	0-20	Langmuir	y = -355.4 + 275.5x	0.8706
		Temkin	y = 1165 + 467.0x	0.2116
		Freundlich	y = 0.953 + 2.376x	0.8807
	20-40	Langmuir	y = -115.0 + 317.1x	0.8774
		Temkin	y = -1048 + 1514x	0.5967
		Freundlich	y = 0.1462 + 2.994x	0.9870
	40-60	Langmuir	y = -290 + 254.5x	0.8856
		Temkin	y = 826.4 + 793.0x	0.8812
		Freundlich	y = 1.743 + 1.588x	0.9671
Basement complex	0-20	Langmuir	y = -754.4 + 298.8x	0.8365
		Temkin	y = 729.9 + 798.0x	0.4699
		Freundlich	y = 1.441 + 1.732x	0.8813
	20-40	Langmuir	y = -722.3 + 260.8x	0.7037
		Temkin	y = 839.2 + 693.6x	0.4003
		Freundlich	y = 1.508 + 1.665x	0.9827
	40-60	Langmuir	y = -1219 + 363.9x	0.6602
		Temkin	y = 724.0 + 793.1x	0.3512
		Freundlich	y = 1.278 + 1.993x	0.9671
Alluvium	0-20	Langmuir	y = 83.49 + 198.6x	0.8883
		Temkin	y = 888.4 + 614.7x	0.3829
		Freundlich	y = 1.768 + 1.528x	0.9280
	20-40	Langmuir	y = 112.8 + 203.1x	0.8805
		Temkin	y = 842.0 + 672.0x	0.3787
		Freundlich	y = 1.755 + 1.610x	0.8810
	40-60	Langmuir	y = 209.6 + 206.9x	0.8491
		Temkin	y = 780.7 + 687.6x	0.4128
		Freundlich	y = 2.288 + 0.6445x	0.5581
Coastal plain sand	0-20	Langmuir	y = -264.3 + 212.3x	0.5884
		Temkin	y = 888.4 + 614.7x	0.3829
		Freundlich	y = 1.867 + 1.317x	0.8057
	20-40	Langmuir	y = -1037 + 276.7x	0.7546
		Temkin	y = 842.0 + 672.0x	0.3787
		Freundlich	y = 1.474 + 1.660x	0.9811
	40-60	Langmuir	y = -5.957 + 202.2x	0.5834
		Temkin	y = 780.7 + 672.0x	0.4128
		Freundlich	y = 1.639 + 1.507x	0.8628
Sandstone	0-20	Langmuir	y = -966.3 + 278.5x	0.7800
		Temkin	y = 1018 + 741.2x	0.6588
		Freundlich	y = 1.421 + 1.737x	0.9867
	20-40	Langmuir	y = 56.16 + 213.3x	0.8516
		Temkin	y = 1018 + 741.2x	0.6588
		Freundlich	y = 2.053 + 1.293x	0.8176
	40-60	Langmuir	y = 344.5 + 214.0x	0.8490
		Temkin	y = 1056 + 807.7x	0.7319
		Freundlich	y = 2.127 + 1.313x	0.7941

Table 6 Cont'd.

Parent material	Depth (cm)	Model	Linear Equation a	b	R^2
		Langmuir	mini		0.58
			max		0.89
			mean		0.72
		Temkin	mini		0.21
			max		0.88
			mean		0.45
		Freundlich	mini		0.56
			max		0.99
			mean		0.88

The Langmuir model showed intermediate performance:

Minimum R^2 = 0.58, Maximum R^2 = 0.89 and Mean R^2 = 0.72 while

The Temkin model exhibited the poorest performance:

Minimum R^2 = 0.21, Maximum R^2 = 0.88 and a Mean R^2 = 0.45

4. Discussion

4.1 Influence of Parent Material on Potassium Adsorption

The significant variation in K adsorption rates among parent materials (LSD = 104.9) reflects fundamental differences in mineralogical composition, clay content, and surface properties inherited from the parent rock material. Sandstone-derived soils exhibited the highest mean K adsorption rate (1694 mg/kg), which can be attributed to their higher iron oxide content and ferruginization processes that create additional adsorption sites (Brady and Weil, 2008). The presence of iron-stained, fine-textured horizons in sandstone profiles provides numerous negatively charged surfaces for K^+ retention through electrostatic attraction.

Coastal plain sand showed the lowest K adsorption capacity (1537 mg/kg), consistent with their coarse-textured, sandy nature and lower clay content (Ezezika and Adetona, 2011). The cohesionless, highly permeable structure of these soils limits their ability to retain cations, including K^+, making them more susceptible to leaching losses. This finding has important implications for K fertilizer management in coastal plain sand soils, suggesting the need for split applications and timing strategies to minimize losses.

Alluvium-derived soils demonstrated moderate to high K adsorption (1668 mg/kg), reflecting their fine texture, high clay content, and nutrient-rich composition derived from river deposits (FAO, 2006). The dark color and high organic matter content of alluvial soils contribute to increased CEC and enhanced K retention capacity. Similarly, shale-derived soils (1649 mg/kg) exhibited considerable K adsorption despite their generally poor drainage and low fertility characteristics (Lal, 2004), likely due to high clay content providing abundant exchange sites.

Basement complex soils showed intermediate K adsorption (1624 mg/kg), consistent with their moderate fertility levels and mixed mineral composition derived from weathered crystalline rocks (Ojeniyi and Ojeniyi, 2013). The variable mineralogy of basement complex materials, including both primary minerals and secondary clay minerals, creates heterogeneous adsorption surfaces.

4.2 Depth-Related Variations in Potassium Adsorption

The general increasing trend in K adsorption with soil depth (1613 to 1657 mg/kg from 0-20 to 40-60 cm) can be attributed to several factors. Deeper soil horizons typically contain higher clay content due to eluviation-illuviation processes, providing more exchange sites for K adsorption ((McBratney, A. *et. al.*, 2005).). Additionally, lower organic matter decomposition rates and reduced biological activity in subsoil layers may result in more stable clay-K complexes.

However, the high LSD value for depth (499.5) indicates substantial variability in depth-related patterns across different parent materials, as evidenced by the significant parent material × depth interaction (LSD = 503.7). This interaction suggests that soil development processes and weathering patterns vary considerably among parent materials, resulting in different depth-related trends. For example, sandstone showed marked depth-related increases (1606 to 1804 mg/kg), while alluvium exhibited only modest changes (1656 to 1683 mg/kg).

The inconsistent depth patterns in some parent materials, particularly coastal plain sand, may reflect the influence of pedogenic processes specific to tropical humid conditions, including intense leaching of the surface horizon and clay translocation to deeper layers (Ufot *et al.*, 2016). The bimodal rainfall distribution and high annual precipitation (1500-2500 mm) in Southeastern Nigeria promote extensive leaching of base cations from surface horizons, potentially creating variable depth-related patterns in K adsorption capacity.

4.3 Adsorption Model Performance and Mechanisms

The superior performance of the Freundlich model (mean R^2 = 0.88) compared to Langmuir (mean R^2 = 0.72) and Temkin (mean R^2 = 0.45) models suggests that K adsorption in Southeastern Nigerian soils occurs predominantly through multilayer adsorption on heterogeneous surfaces rather than monolayer adsorption on homogeneous sites (Goldberg, 2005). This finding is consistent with the mineralogical characteristics of these highly weathered tropical soils, which typically contain mixtures of clay minerals (predominantly kaolinite), iron and aluminum oxides, and organic matter, creating diverse adsorption sites with varying binding energies (Sparks, 2003).

The Freundlich adsorption intensity parameter (n) values greater than 1 in most samples indicate favorable K adsorption conditions, suggesting that K ions are preferentially retained by soil colloids under the experimental conditions employed. The variation in n values among parent materials (1.2608 for alluvium to 2.3193 for shale) reflects differences in surface heterogeneity and adsorption site energy distribution. Higher n values in shale-derived soils suggest more heterogeneous adsorption surfaces with a wider distribution of binding energies, consistent with their complex clay mineralogy.

The poor performance of the Langmuir model, particularly evident in basement complex soils (negative adsorption maxima), indicates that the assumption of monolayer adsorption on homogeneous surfaces does not adequately describe K adsorption in these soils. The positive adsorption maxima observed in alluvium-derived soils suggest that the Langmuir model may be more applicable to these relatively young, less weathered soils with more uniform mineralogy.

The Temkin model's poor overall performance (mean R^2 = 0.45) suggests that the assumption of linear decrease in heat of adsorption with surface coverage may not be appropriate for K adsorption in these soils. However, the model showed better fit in specific cases, such as shale at 40-60 cm depth (R^2 = 0.8812), indicating that adsorption energetics may play a more important role in certain soil environments.

4.4 Implications for Potassium Management

The variation in K adsorption characteristics among parent materials has important practical implications for K fertilizer management in Southeastern Nigeria. Soils with lower K adsorption capacity (coastal plain sand) require different management strategies compared to those with higher K retention (sandstone, alluvium). In low-adsorption soils, split applications of K fertilizers, use of slow-release formulations, and timing applications to match crop demand periods can minimize leaching losses and improve K use efficiency.

Conversely, soils with high K adsorption capacity may require higher initial K fertilizer rates to satisfy adsorption sites before significant amounts become available for plant uptake. However, once equilibrium is reached, these soils may sustain K availability for longer periods, reducing the frequency of K fertilizer applications.

The depth-related variations in K adsorption highlight the importance of considering subsoil K dynamics in nutrient management planning. Deep-rooted crops grown on soils with increasing K adsorption with depth (e.g., sandstone) may benefit from deep placement of K fertilizers or use of cover crops with deep root systems to mine K from lower soil horizons.

4.5 Relationship to Soil Properties and Weathering Intensity

The observed K adsorption patterns reflect the advanced weathering state of Southeastern Nigerian soils under humid tropical conditions. The predominance of kaolinite clay minerals, low base saturation, and acidic pH (Nnaji *et al*., 2002; FDALR, 1985) indicate intense weathering that has depleted readily weatherable K-bearing minerals such as feldspars and micas (Mengel and Kirkby, 2001).

The low CEC and nutrient reserve capacity of these soils (Ufot *et al*., 2016) are consistent with the dominance of 1:1 clay mineral (kaolinite) with low surface charge density compared to 2:1 clay (illite, vermiculite). This mineralogical composition limits K retention capacity and contributes to the high susceptibility to K leaching under the region's high rainfall regime.

The variation in K adsorption among parent materials also reflects differences in weathering susceptibility and rates of soil development. Alluvium-derived soils, being relatively young and formed from recent river deposits, retain more primary minerals and consequently show different adsorption behavior compared to older, more intensely weathered soils derived from basement complex or coastal plain sands.

4.6 Environmental and Agricultural Significance

The K adsorption characteristics documented in this study have significant implications for environmental sustainability and agricultural productivity in Southeastern Nigeria. Low K adsorption capacity in some soils (coastal plain sand) increases the risk of K leaching to groundwater and surface waters, potentially contributing to eutrophication of aquatic ecosystems. Conversely, high K adsorption may reduce K losses but can also decrease K availability to crops, necessitating higher fertilizer inputs.

Understanding parent material-specific K adsorption behavior enables development of targeted nutrient management strategies that balance productivity goals with environmental protection. For example, precision agriculture approaches that account for within-field variability in parent materials and soil properties can optimize K fertilizer placement and rates, reducing environmental footprint while maintaining crop yields.

The predominance of cassava, yam, maize, and vegetable production in the study area (Unamma *et al*., 2004) creates

substantial K demand, as these crops are heavy K consumers. Optimizing K fertilizer management based on soil-specific adsorption characteristics can improve K use efficiency, reduce production costs, and enhance food security in the region.

5. Conclusions

This study provides comprehensive insights into potassium adsorption characteristics of soils derived from five contrasting parent materials in Southeastern Nigeria. Key findings include:

Parent material significantly influences K adsorption, with sandstone-derived soils exhibiting the highest adsorption capacity (1694 mg/kg) and coastal plain sand the lowest (1537 mg/kg).

Soil depth showed a general increasing trend in K adsorption (1613 to 1657 mg/kg from surface to subsoil), but with substantial variability among parent materials, indicating complex pedogenic processes.

The Freundlich model best described K adsorption across all parent materials and depths (mean R^2 = 0.88), indicating multilayer adsorption on heterogeneous surfaces. The Langmuir and Temkin models showed poorer fit (mean R^2 = 0.72 and 0.45, respectively).

Adsorption parameters varied considerably among parent materials, reflecting differences in mineralogical composition, surface properties, and weathering intensity.

Alluvium-derived soils showed favorable K retention characteristics with positive Langmuir adsorption maxima and high Freundlich adsorption capacities, suggesting their suitability for K-demanding crops.

Parent material × depth interactions were significant, indicating that the effects of soil depth on K adsorption varied among different geological substrates, reflecting diverse pedogenic processes.

These findings have important implications for developing site-specific K fertilizer management strategies in Southeastern Nigeria. The parent material-specific variations in K adsorption characteristics should be incorporated into nutrient management decision support systems to optimize K use efficiency, reduce fertilizer costs, and minimize environmental impacts.

6. **Recommendations**

Based on the findings of this study, the following recommendations are proposed:

Parent material-specific K fertilizer recommendations should be developed for Southeastern Nigerian soils, with particular attention to soils derived from coastal plain sand that exhibit low K retention capacity.

Split applications of K fertilizers are recommended for low-adsorption soils (coastal plain sand) to minimize leaching losses during high rainfall periods.

Higher initial K fertilizer rates may be necessary for high-adsorption soils (sandstone, alluvium) to saturate adsorption sites before significant plant-available K accumulates.

Deep placement of K fertilizers or use of deep-rooted cover crops should be considered for soils showing increasing K adsorption with depth, particularly sandstone-derived soils.

Future research should investigate the relationships between K adsorption parameters and other soil properties (pH, organic matter, clay mineralogy, CEC) to develop predictive models for K behavior.

Long-term field experiments are needed to validate laboratory-derived adsorption parameters under actual cropping conditions and to develop calibrated K fertilizer recommendations.

Soil testing laboratories should incorporate parent material information when developing K fertilizer recommendations for farmers in Southeastern Nigeria.

Extension services should educate farmers about the importance of parent material and soil type in determining K fertilizer requirements and management strategies.

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Author Contributions

Nwamuo, L.O: Conceptualization, methodology, investigation, formal analysis, writing original draft, writing - review and editing. Nwamuo, L. O and Tangban, E. E Methodology, validation, supervision, writing - review and editing. Umoh, F. O., Silas, S. U. and Ukpong, I. M: Resources, supervision, project administration, funding acquisition, writing, review and editing.

All authors have read and agreed to the published version of the manuscript.

Conflict of Interest

The authors declare no conflict of interest related to this research.

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Appendices

Appendix A:

Slope (1/n) = 2.376
R^2 = 0.8807

Therefore:

a = $10^{0.953}$ = 8.98 mg/kg
n = 1/2.376 = 0.421
Adsorption capacity (a) = 8.98 mg/kg
Adsorption intensity (n) = 0.421

Interpretation: The n value of 0.421 (< 1) indicates unfavorable adsorption in this particular depth, while the high R^2 value (0.8807) indicates good model fit.

Appendix B: Quality Assurance and Quality Control

Laboratory Analysis Procedures:

All glassware was acid-washed and thoroughly rinsed with deionized water before use.
Analytical grade reagents were used throughout the study.
Calibration curves were prepared fresh for each analysis session.
Duplicate analyses were performed for 10% of all samples.
Certified reference materials were analyzed alongside samples for quality control.
Recovery rates for spiked samples ranged from 95-105%.
Coefficient of variation for duplicate analyses was < 5% for all parameters.

Appendix C: Statistical Analysis Details

Table A: ANOVA Summary for K Adsorption Rates:

Source of Variation	DF	Sum of Squares	Mean Square	F-value	P-value
Parent Material (PM)	4	328,490	82,122.5	28.45	< 0.001*
Depth	2	24,640	12,320.0	4.27	0.024*
PM × Depth	8	156,780	19,597.5	6.79	< 0.001*
Error	30	86,550	2,885.0		
Total	44	596,460			

Note: Significant at P < 0.05; **Significant at P < 0.001

Appendix D: Glossary of Terms

Adsorption: The adhesion of atoms, ions, or molecules from a gas, liquid, or dissolved solid to a surface.

Bonding Energy Constant (b): A parameter in the Langmuir equation representing the strength of binding between the adsorbate and adsorbent surface.

Cation Exchange Capacity (CEC): The total capacity of a soil to hold exchangeable cations, expressed in centimoles of charge per kilogram (cmol(+)/kg).

Freundlich Isotherm: An empirical adsorption model describing multilayer adsorption on heterogeneous surfaces.

Kaolinite: A 1:1 layer silicate clay mineral with low cation exchange capacity, common in highly weathered tropical soils.

Langmuir Isotherm: An adsorption model assuming monolayer coverage on homogeneous surfaces with finite adsorption sites.

Parent Material: The unconsolidated organic or mineral material from which soil develops.

Temkin Isotherm: An adsorption model that accounts for the effects of indirect adsorbate-adsorbate interactions.

Ultisol: A soil order characterized by intensive weathering, low base saturation, and clay accumulation in the subsoil.

Appendix C:

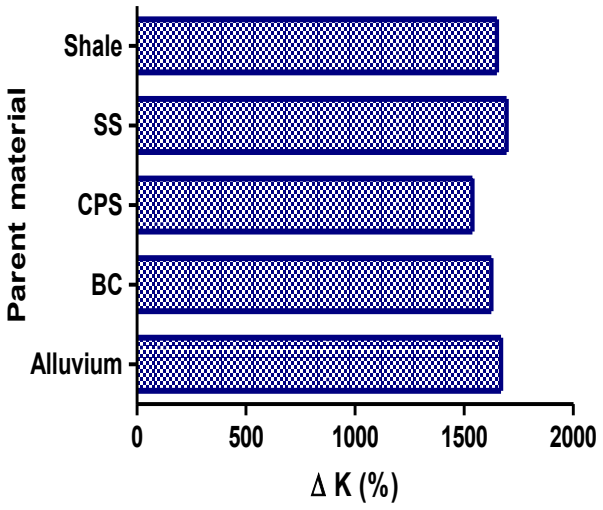


Figure A1. K Adsorption by Different Parent Materials under Study

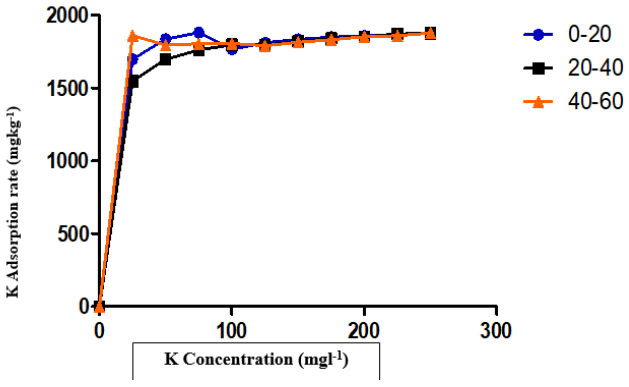


Figure A2. Potassium Sorption Isotherm for Shale

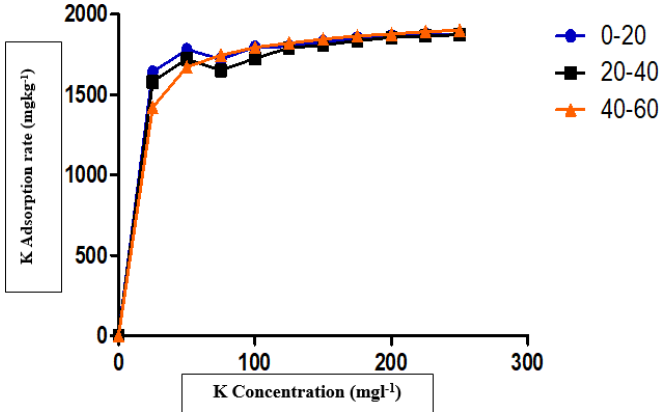


Figure A3. Potassium Sorption Isotherm for Basement complex

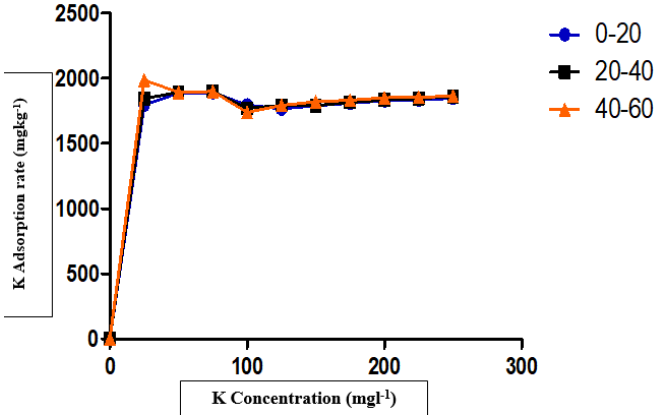


Figure A4. Potassium Sorption Isotherm for Alluvium

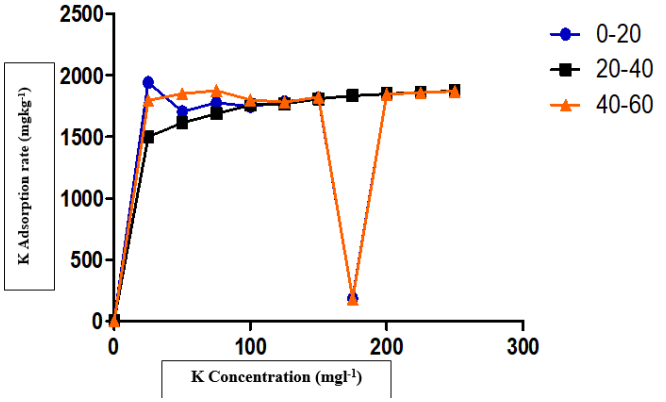


Figure A5. Potassium Sorption Isotherm for Coastal plain sand

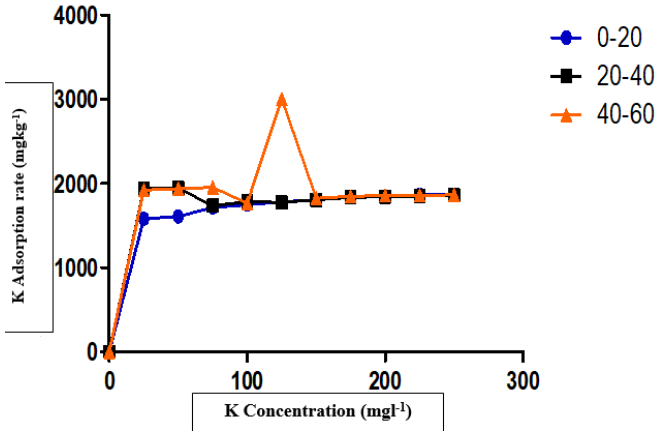


Figure A6. Potassium Sorption Isotherm for Sandstone

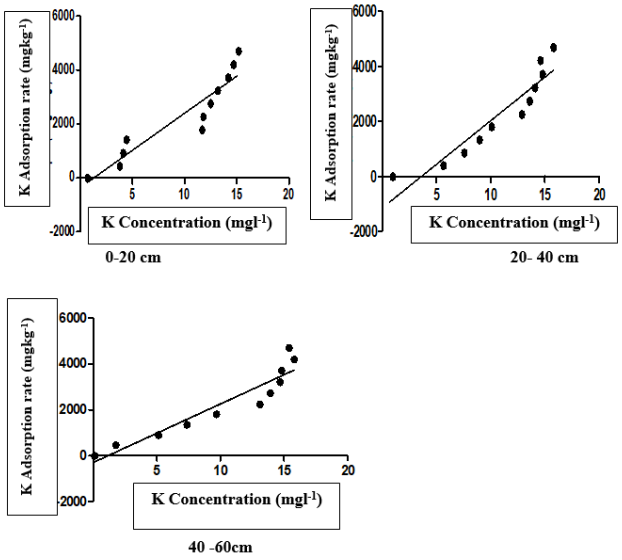


Figure A7. Langmuir adsorption of K for Shale parent material

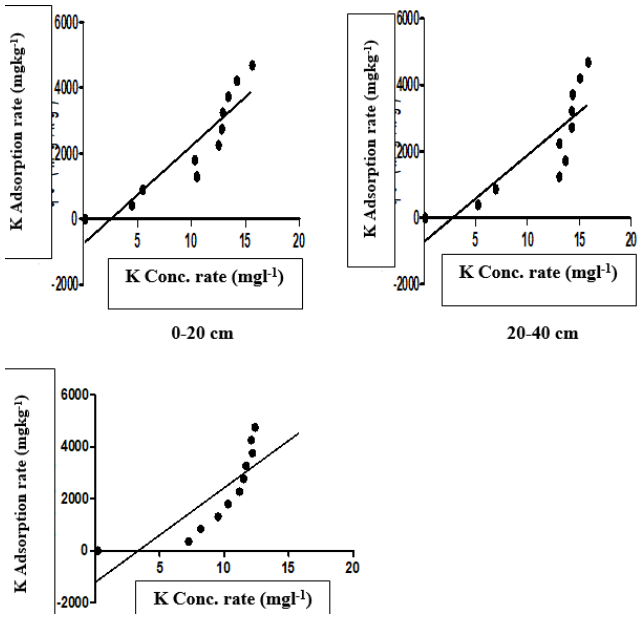


Figure A8. Langmuir adsorption of K for Basement complex parent material

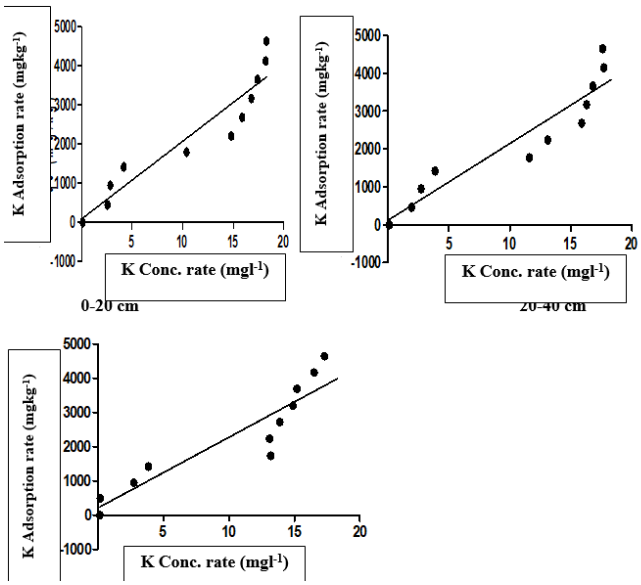


Figure A9. Langmuir adsorption of K for Alluvial parent material

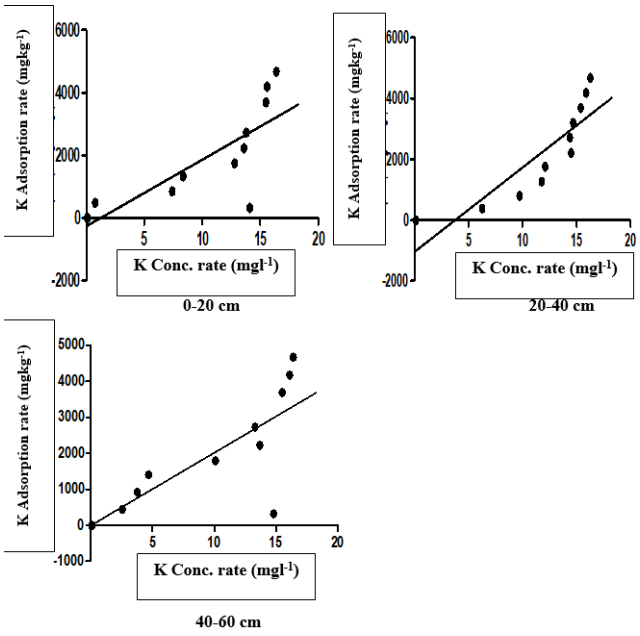


Figure A10. Langmuir adsorption of K for Coastal plain sand parent material

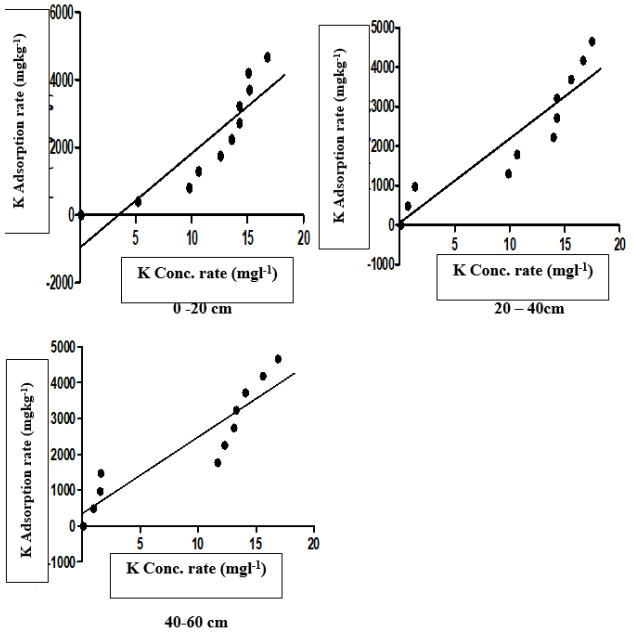


Figure A11. Langmuir adsorption of K for Sandstone parent material

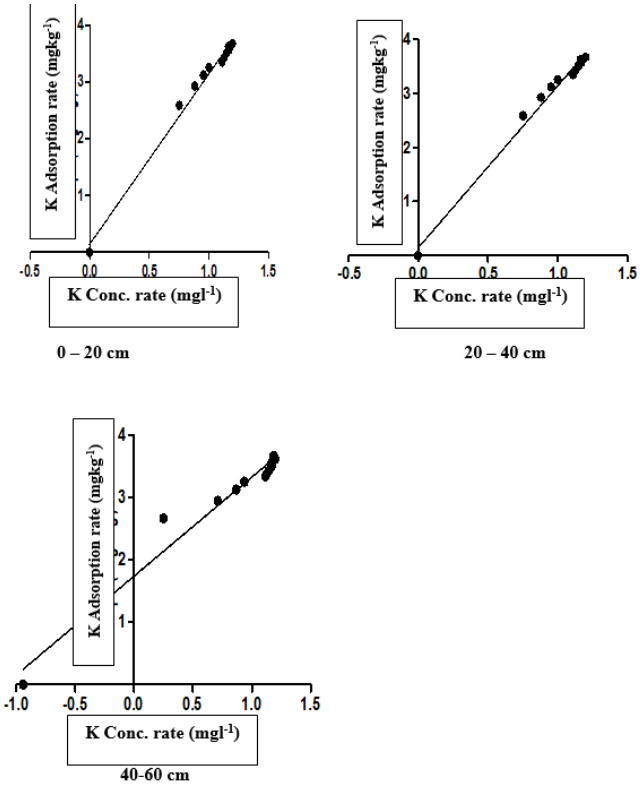


Figure A12. Freundlich K adsorption isotherm for soil developed from shale parent material

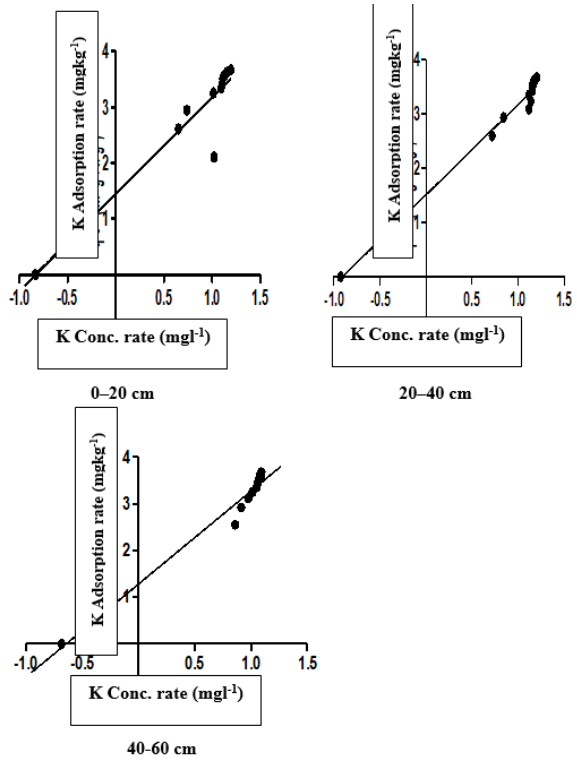


Figure A13. Freundlich K adsorption isotherm of soil developed from basement complex parent material

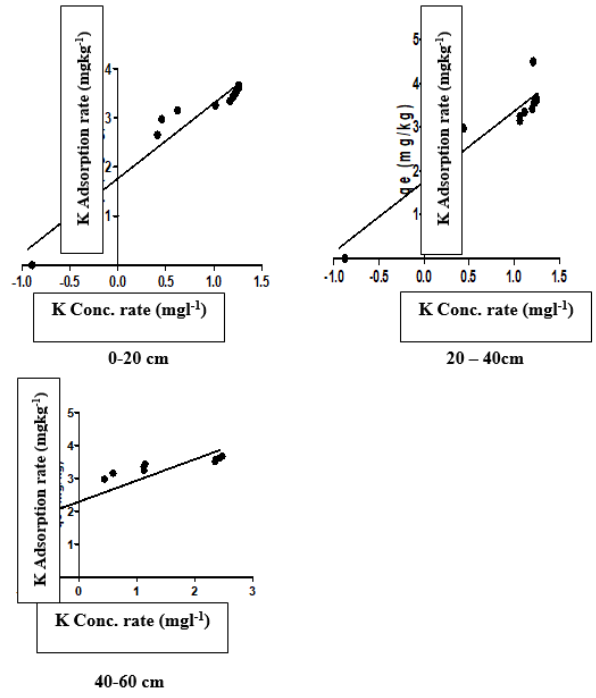


Figure A14. Freundlich adsorption isotherm of soil developed from alluvial parent material

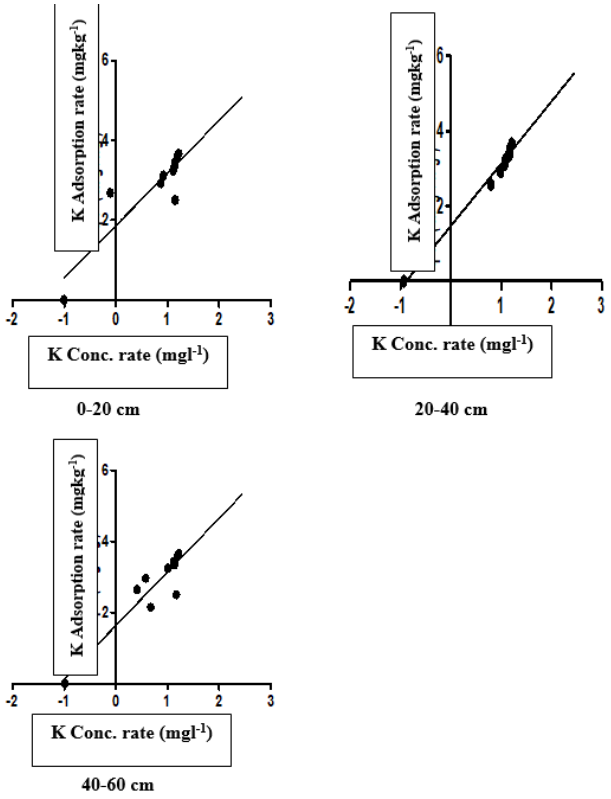


Figure A15. Freundlich adsorption isotherm of soil developed from coastal plain sand parent material

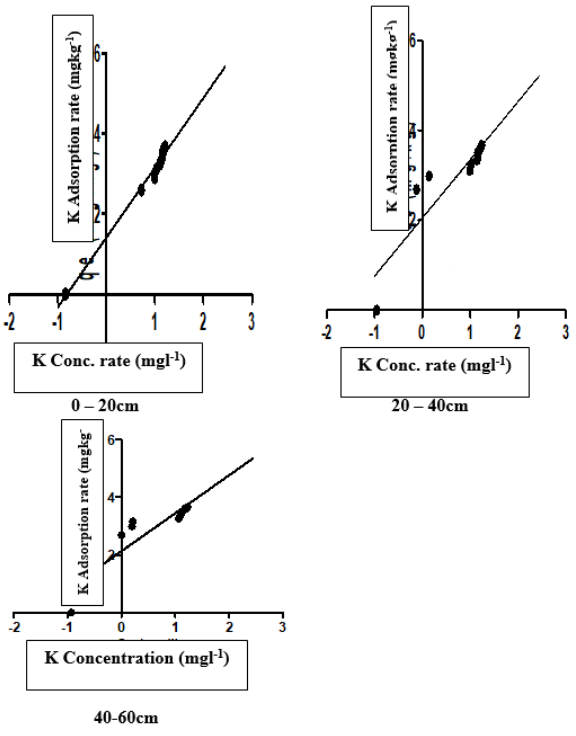


Figure A16. Freundlich K adsorption isotherm of soil developed from sandstone parent material

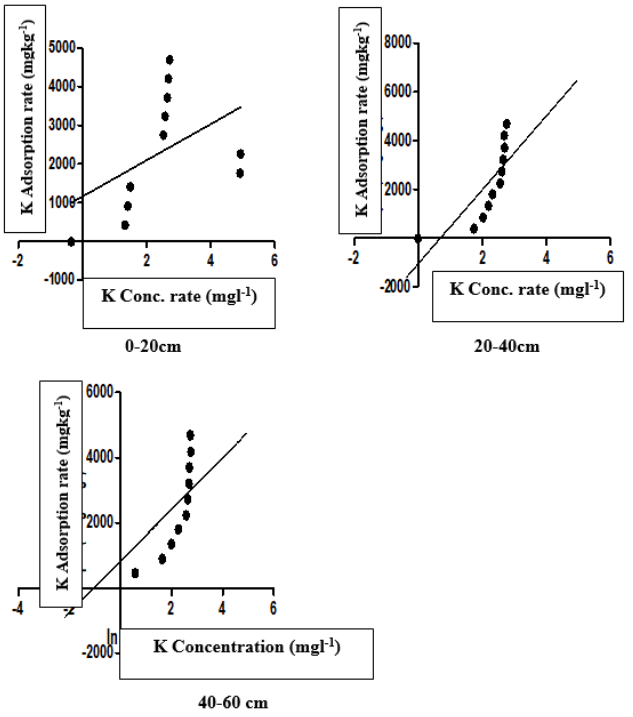


Figure A17. Temkin K adsorption isotherm of soil developed from shale parent material

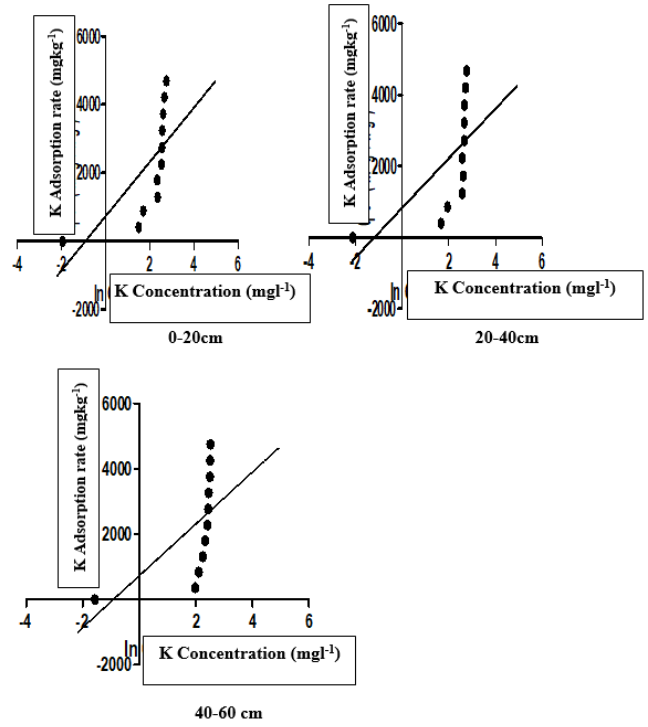


Figure A18. Temkin K adsorption isotherm of soil developed from basement complex parent material

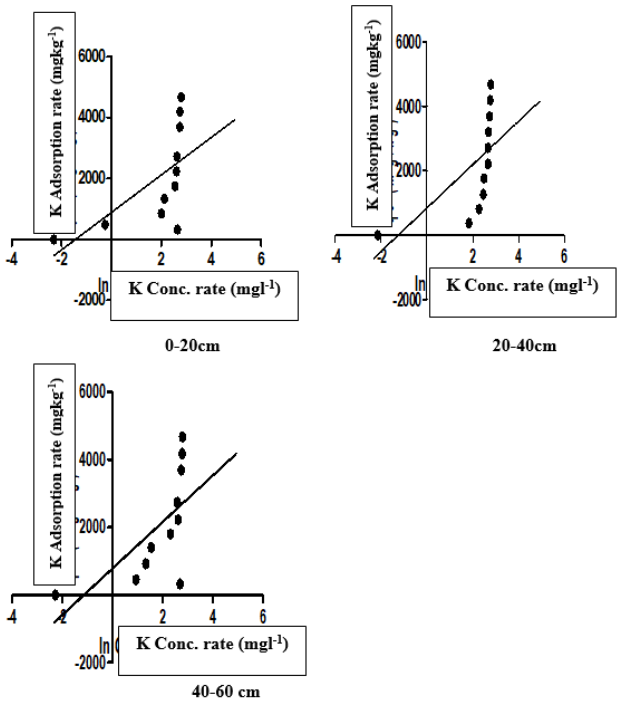


Figure A19. Temkin K adsorption isotherm of soil developed from alluvial parent material

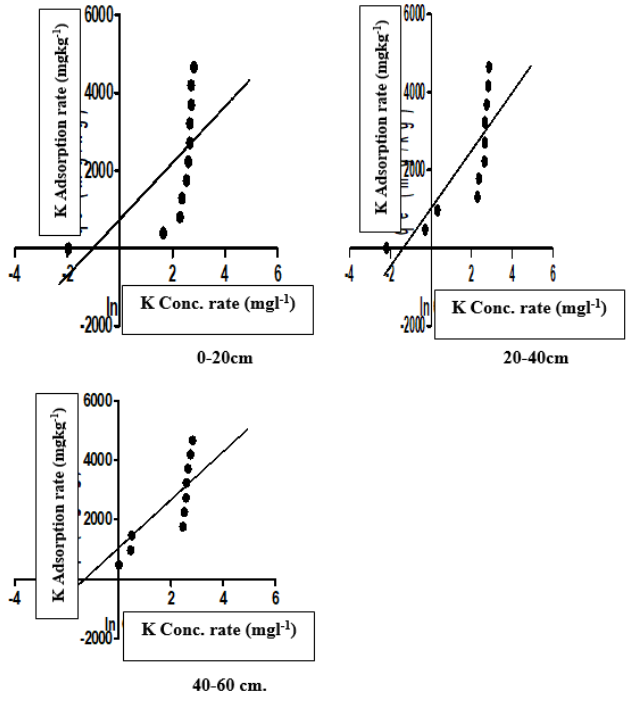


Figure A20. Temkin K adsorption isotherm of soil developed from sandstone parent material

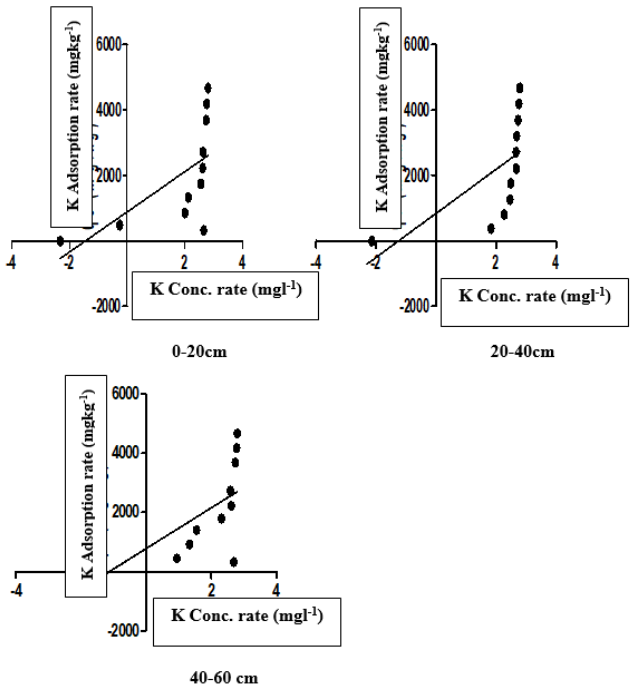


Figure A12. Temkin adsorption isotherm of soil developed from coastal plain sand parent material.