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Original Research

Potassium Adsorption Characteristics of Soils under Contrasting Land-Use Systems at the University of Benin, Benin City, Nigeria

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Abstract

Potassium (K) retention in soils is often low and varies with soil and Land-use type due to its high mobility. This study evaluated K adsorption in soils from four land-use types at University of Benin Nigeria, given widespread application of K fertilizers to address K nutrient deficiencies. Auger Soil samples were collected from 0-30 cm soil depth, in three replicates from four land-use types: Arable, Forested, Sports and Plantain-Farm, making a total of 12 samples. Potassium adsorption capacity was determined by equilibrating 1 g soil with 30 ml varying concentrations (20, 40, 60, 80 and 100 mg L^{-1}) of K prepared from potassium chloride with 0.01 M $CaCl_2$ as background electrolyte, for 2 hours, allowed to stand for 24 hours at 25 ± 1 °C, shaken again filtered and K in filtrate was estimated using a flame photometer. The amount of K adsorbed was calculated by difference, while Freundlich and Temkin adsorption isotherm models were applied to describe K adsorption behavior. Results showed that arable land exhibited highest Freundlich K adsorption capacity (100.60 mg kg^{-1}), followed by forested (35.08 mg kg^{-1}), sports (17.43 mg kg^{-1}) and Plantain-Farm (1.78 mg kg^{-1}) land-use, suggesting reduced K fertilizer loss in arable Land-use soils compared to other Land-use. Freundlich adsorption heterogeneity parameter (1/n) ranged from 0.91 (Arable land) to 3.18 (Plantain-Farm) indicating unfavorable adsorption in all Land-use except the Arable Land-use. The Freundlich model provided the best fit (R^2 > 0.983) for Plantain-Farm Land-use, compared to Temkin model fit of R^2 = 0.883 for Plantain-Farm, indicating the suitability of Freundlich model, in describing K adsorption in the Plantain-Farm, while highlighting the influence of Land-use on K adsorption in the soils studied. Higher K adsorption in arable land soil may indicates enhanced K retention and fertilizer-use efficiency while lower K adsorption in Plantain-Farm and sports land practically implies greater K loss potential.

1. Introduction

Potassium (K) is an essential macronutrient required for key physiological functions in plants (Srinivasarao *et al*., 2023; Sardans & Peñuelas, 2021). Despite its abundance within the mineral matrix of most agricultural soils, the immediate water-soluble and exchangeable pool accessible for crop usage is frequently insufficient due to dynamic adsorption and fixation mechanisms or loss (Poonpakdee *et al*., 2025). Soil properties regulating K equilibria—such as clay mineral composition, soil reaction (pH), organic matter distribution, oxide concentrations, and native exchangeable bases—are deeply influenced by Land-use alterations and human management histories. Land-use types have been reported to primarily influence several soil properties and nutrient availability (Wahab *et al*., 2026; Yeshaneh, 2015). In the highly weathered soils of the tropics, land-use effects may modify K exchange reactions,

K availability to crops and, consequently, the adsorption characteristics of the soils. Sorption controls the chemical mobility, availability, and retention behavior of key nutrients within soil systems (Mandal *et al*., 2026; Patel, 2025). Converting exchangeable or solution K into less accessible pools directly alters fertilizer-use efficiency (Zhang *et al*., 2021). Accurate and precise fertilizer recommendations for soils can be made possible by evaluating the nutrient adsorption capacities of soils and providing a better index of soil fertility, while Potassium concentration in soil solutions may serve as an index of potassium accessibility. The adsorption behavior of nutrients and pollutants in the soil and their availability to plants have been described by many authors with various models such as Langmuir, Freundlich, Temkin and Gunary amongst others. These models represent the equilibrium

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connections between the quantities of adsorbed and dissolved ion species at a constant temperature, quantitatively describing this relationship (Khan *et al.,* 2010). Although Awgchew *et al*. (2024), reported Freundlich model to best describe potassium adsorption capacity and release kinetics for Ethiopian highland soils, The suitability of any model is usually determined by factors such as R squared (R^2) value, root mean squared error (RMSE), Akaike information criterion (AIC), amongst others, however R^2 is popular because it is easy to calculate, interpret, and report. (Yang *et al*., 2024: Al-Hussein *et al*., 2026; Ordoñez-Avila *et a*l., 2026). The study of Potassium adsorbing potential of soils could help clarify the relationship that exists between K supply, adsorption capacity and other soil properties, which is undertaken by investigating the relationship that exist between amounts of soil solution K and amount adsorbed by the soil, through adsorption experiments and adsorption isotherm modelling. This provides information on whether applied K nutrients are fixed, react or form complexes in soils and thus helps optimize fertilizer use efficiency, to enhance crop productivity (Hartono *et al*., 2023; Bell *et al*., 2021). Thus, K adsorption isotherm can be used to evaluate the ability of soils to supply K to plants, understand its dynamics in soil, and to describe its exchange from the soils by other ions particularly, Calcium (Misskire *et al*., 2019). Although multiple sorption models have been utilized to predict nutrient dynamics across diverse landscapes (Poonpakdee *et al*., 2025; Idehen *et al*., 2023; Orhue and Emomu, 2022; Umoh *et al*., 2021; Umoh *et al*., 2014), studies of K sorption under contrasting Land-use in mid-western Nigeria remain sparse. This study therefore aimed at evaluating K adsorption capacity across four Land-use within the University of Benin, examining model suitability to predict K sorption aimed at providing baseline information for understanding soil K retention. It was hypothesized that differences in Land-use may produce measurable differences in soil physical and chemical properties and consequently alter K and other nutrient adsorption behavior and the relative performance of adsorption models such as Freundlich and Temkin isotherm models.

2. Materials and Methods

2.1 Description of the study area

The study was conducted at the University of Benin, Benin City, Edo State Nigeria, located at 06^{0}24'59.70'' N, 05^{0}37'15.80'' E. The soils of University of Benin and surrounding area are developed from coastal plain sand parent material derivative of highly weathered sedimentary rock resulting from high rainfall and temperature (Nigeria Geological Survey Agency, 2008), the area falls within the tropical rainforest zone and the soils are classified as an Ultisol (Ewansiha *et al*., 2023; Olatunji *et al*., 2014). The environment falls within the humid tropical rain forest zone of Nigeria, with an average annual rainfall of 1886.90 - 2078.80 mm over the last three decades (Ofordu *et al*., 2022), and an average yearly temperature of 27 ^{0}C. The land-use types, locations and GPS coordinates are:

1. **Arable:** AGR 305 Instructional Farm Plot (06^{0}24'00'' N, 05^{0}37'30'' E)
2. **Forested:** Forestry Arboretum (06^{0}24'03'' N, 05^{0}37'25'' E)
3. **Plantain-Farm:** University of Benin, Project Farm Site (06^{0}24'15'' N, 05^{0}36'37'' E)
4. **Sports:** University of Benin Sports Complex Perimeter (06^{0}23'46'' N, 05^{0}36'39'' E)

The arable land is under continuous cultivation for student practicals with NPK fertilizer use for over 10 years, while the forested land is under permanent tree cover and used as department of forestry arboretum but frequently visited by staff and students searching for fruits and vegetables. The Plantain-Farm is under permanent plantain cropping, predominantly flat with slight ridges and animal husbandry in some sections of the farm, with a history of organic, inorganic fertilizers and herbicides use, while the sport field is under continuous use for various sport activities, supporting different sport facilities.

2.2 Soil sampling and laboratory procedure

One core sample per Land-use was collected for bulk density determination, while composite (5 core bulked) auger soil samples were collected at 0–30 cm depth in three replicates from each of four land-use types, giving 12 auger samples and 4 core samples. The auger samples were labelled, air-dried, ground and sieved through a 2 mm sieve for laboratory evaluations, while the core samples were oven dried at 105 ^{0}C to constant weight for bulk density determination.

2.3 Physical and chemical characterization

Particle-size distribution (sand, silt and clay) was determined by the modified hydrometer procedure (Bouyoucos, 1962; Day, 1965), using sodium hexametaphosphate (Calgon) as the chemical dispersing agent. Bulk density was determined by core sampler method after oven-drying samples at 105 ^{0}C to a constant mass (Ibitoye, 2008). Soil pH was measured potentiometrically in a 1:2 soil–water suspension (Tan, 1996). Soil organic carbon was determined by the Walkley–Black wet oxidation method (Walkley & Black, 1934). Total organic nitrogen was determined by dividing values of organic carbon by twenty (Ibitoye, 2008). Exchangeable basic cations (Ca^{2+}, Mg^{2+}, K^+, Na^+) were extracted with neutral 1.0 N NH_4OAc (Udo *et al.,* 2009). Ca^{2+}, Mg^{2+}, Al^{3+} + H^+ were quantified by titration, K^+ and Na^+ were quantified by flame photometry, while exchangeable bases were calculated by summation of valued obtained from Ca^{2+}, Mg^{2+}, K^+, Na^+ quantification. Exchangeable acidity (Al^{3+} + H^+) was extracted with 1.0 M KCl and quantified by titration, and Cation Exchange Capacity values were computed by summing exchangeable bases and exchangeable acidity values.

2.4 Batch adsorption equilibria procedure

Potassium adsorption was determined following the modified procedure of Awgchew *et al.* (2024). One gram soil was weighed into plastic vessels and equilibrated with 30 mL of solution containing graded concentrations (20, 40, 60, 80 and 100 mg K L^{-1}) prepared from analytical grade KCl with 0.01 M $CaCl_2$ as background electrolyte to provide a defined ionic environment during equilibration, but because Ca^{2+} may compete with K^+ for soil exchange sites, the measured K adsorption was interpreted in the context of the $CaCl_2$ electrolyte conditions. The suspensions were agitated for 2 hours at a speed of 240 rpm using a reciprocating mechanical shaker, at 25 ± 1 ^{0}C, left to stand for 24 hours, shaken again for 2 hours and filtered through Whatman No. 42 filter paper. The concentration of remaining K in the filtrates was quantified using a flame photometer (Bibby scientific model: Jenway PFP7). The amount of K adsorbed per unit mass of soil (mg kg^{-1}) was calculated as the difference between the initial and equilibrium K concentrations using the relationship given as:

$$Q = \frac{(Co\text{-}Ce)}{W} V \quad (1)$$

Where, Q = amount of potassium ion adsorbed (mg kg^{-1} soil), Co = initial K concentration (mg L^{-1}), Ce = concentration of K in the equilibrium solution (mg L^{-1}), V = volume (30 mL, i.e. 0.03 L) of K solution used in equilibration, W = weight of soil (1 g, i.e. 0.001 kg).

2.5 Mathematical Modeling and Statistical Analysis

The Freundlich and Temkin isotherm equations were used to model the equilibrium datasets as:

2.5.1 Freundlich equation (linearized):

The linearized Freundlich equation (Kalam *et al*., 2021) is:

$$\log X = \log a + (1/n) \log Ce \quad (2)$$

Where, X = Amount of Potassium adsorbed per unit weight of soil (mg K kg^{-1} soil) at equilibrium, Ce = Concentration of Potassium in the equilibrium solution (mg L^{-1}), a = Constant relating to adsorption capacity, 1/n = is a function of the strength of adsorption in the adsorption process (heterogeneity parameter), n = adsorption intensity (energy) (Dada *et al.*, 2012). Log X was plotted against log Ce, and the parameters were obtained as follows: a = antilogarithm of intercept and 1/n = slope and therefore, n = 1/slope of the graph

2.5.2 Temkin equation (linearized):

Temkin equation as presented by Teweldebrihan *et al.* (2024), and Dada *et al.* (2012), is given as

$$Q_e = \frac{RT}{bt} \ln A_T + \frac{RT}{bt} \ln C_e \quad (3)$$

therefore equation (3) becomes;

Where, Q_e = amount of K adsorbed per unit soil mass (mg kg^{-1}), R = universal gas constant (8.314 J/mol/K), T= Absolute temperature (298K), Bt = Temkin constant (J kg mol^{-1} mg^{-1}) related to the heat of adsorption of K, A_T = Temkin isotherm equilibrium binding constant, C_e= equilibrium K concentration (mg L^{-1}). The graph was plotted as Q_e in Y-axis versus $\ln C_e$ in X-axis, while A_T and bt values were calculated from the graph plot according to the following formula as:

$$A_T = e^{\frac{intercept\ of\ the\ graph\ plot}{Slope\ of\ graph\ plot}} \quad (4)$$

And

$$\frac{RT}{Bt} = slope\ of\ the\ graph \quad (5)$$

Therefore;

$$bt = \frac{RT}{Slope\ of\ the\ graph} \quad (6)$$

Data obtained were analyzed with GenStat 12th Edition statistical package and subjected to one way analysis of variance with each land-use considered as a block, while treatment means were separated using Duncan's Multiple Range Test at P ≤0.05 significance threshold, however bulk density data were not analyzed as the samples were not replicated during soil sampling.

2.6 Limitations of the study

The study was limited to approximately 2 ha space within one (each) site per land-use type, the three auger samples were sub-samples (pseudo-replication) of the same plot and Bulk density samples had one (no replication) core sample, not independent replicates of the Land-use.

3. Results and Discussion

3.1 Physical and chemical properties of the soils

Table 1 shows some physical properties of the soils with bulk density ranging from 1.12 to 2.02 g cm^{-3} across the Land-use. Sand was the dominant separate, giving a sandy loam texture in all Land-use except arable land, which was loamy sand, indicating that the soil was light, maybe easily worked with probable good drainage except Sport field with high bulk density (Bhatt *et al.*, 2025).

Table 1. Some physical properties of the soils studied across different Land-use types

Land-use	Sand	Silt	Clay	B_d	Texture
	%			g cm^{-3}	
Arable	83.85a	5.33a	10.81a	1.15	LS
Forested	81.85a	5.33a	12.81a	1.17	SL
Sport	81.52a	4.67a	13.81a	2.02	SL
Plantain-Farm	80.85a	7.00b	12.15a	1.12	SL
SEM	1.69	1.31	1.57	-	-

Note: B_d = Bulk density; LS = Loamy sand; SL = Sandy loam

Table 2 shows some chemical properties of the soil and indicating extremely acidic soil pH of 4.15 for Arable land, in

contrast with forested land, Plantain-Farm, and sports land which recorded strongly acidic soil pH values of 5.11, 5.30, and 5.44 respectively. The Plantain-Farm had the highest organic carbon (1.04%), exchangeable K (0.16 cmol kg^{-1}) and CEC (3.88 cmol kg^{-1}). This may be attributed to organic matter enrichment from surrounding vegetation, Plantain-Farm canopy and reduced tillage practices (Yakob *et al.*, 2023). Conversely, the arable land had lower values of most chemical properties, probably due to nutrient mining and repeated tillage under continuous cropping (Kartini *et al.*, 2024).

Table 2. Some chemical properties of soils

Land-use	pH	OC	TON	K	EB	EA	CEC	BS
		%		cmol kg^{-1}				%
Arable	4.15a	0.42a	0.02a	0.03a	0.51a	0.48a	0.99a	51.20a
Forested	5.11a	0.93a	0.05a	0.01a	1.44b	0.27b	1.70a	84.71b
Sport	5.44a	0.95a	0.05a	0.04a	1.44b	0.48a	1.92a	75.00b
Plantain-Farm	5.30a	1.04a	0.05a	0.16b	3.37c	0.51a	3.88b	86.86b
SEM	0.31	0.20	0.01	0.03	0.45	0.13	0.39	5.96

Note: OC = Organic carbon, TON = Total organic nitrogen, EB = Exchangeable bases, EA = Exchangeable acidity, CEC = Cation exchange capacity, BS = Base saturation. Means having the same alphabets within columns are not significantly different at P≤ 0.05, using Duncan multiple range test.

3.2 Modeling of potassium adsorption capacities

Isotherm parameters for the four land-use types (Table 3) calculated from Freundlich (Figure 1) and Temkin (Figure 2) isotherms plots indicated that K adsorption patterns varied clearly across the land-use systems. Considering Freundlich adsorption model, the Freundlich adsorption capacity parameter (a) followed the sequence of Arable (100.60 mg kg^{-1}) > Forested (35.08 mg kg^{-1}) > Sports (17.43 mg kg^{-1}) > Plantain-Farm (1.78 mg kg^{-1}).

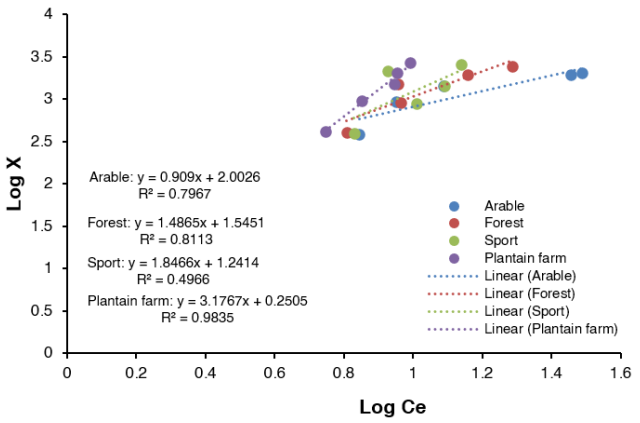


Figure 1. Freundlich isotherm plot for Arable, Forested, Sport and Plantain-Farm Land-use

The elevated K adsorption capacity recorded in arable land may be attributed to low exchangeable K resulting from K depletion in the arable soil and thus increasing K demand which may influence its capacity to expose new active adsorption sites under chemical pressure (Du *et al.*, 2024), how the result is contrary to the findings of Poonpakdee *et al.* (2025), who reported increased K adsorption with increase in clay and organic matter content and cation exchange capacity. While the lowest K adsorption capacity obtained for Plantain-Farm

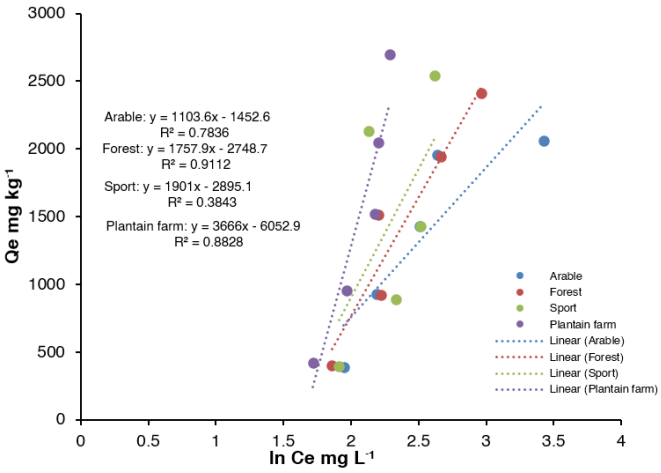


Figure 2. Temkin Isotherm plot for Arable, Forested, Sport and Plantain-Farm land-use

land-use could be due to higher initial K and exchangeable acidity levels compared to the other land-use types, as initial K content and exchangeable acid cations can compete with K ions for exchange sites, resulting in reduced adsorption capacity **(**Awgchew *et al.*, 2024; Han *et al.*, 2019**)**. Conventionally when Freundlich heterogeneity parameter (1/n) is > 0 but < 1, or adsorption intensity (n) is > 1 but < 10, it is an indication of favorable adsorption process (Teweldebrihan *et al.*, 2024; Dada *et al.*, 2012), thus 1/n > 1 values obtained for soils of Forested, Sports, and Plantain-Farm land-use types suggests cooperative or unfavorable adsorption behavior and requires further investigation, while the corresponding Freundlich adsorption intensity factor (n) values, being below 1, support this interpretation (Dada *et al.*, 2012). The unfavorable adsorption behavior observed indicates that cooperative adsorption occurs where existing adsorbed molecules make further adsorption difficult, and may implies that, adsorbed K may make further adsorption of applied K fertilizer to the exchange site difficult and may result in applied K fertilizer loss by leaching and probably due to high K mobility (McCarthy *et al.*, 2026; Nigon and Kaiser, 2025). The Temkin affinity-related parameter (A_T) ranged from

0.19 L mg^{-1} (Plantain-farm) to 0.27 L mg^{-1} (Arable) land-use. The relatively narrow range suggests less variation but similar trend in K adsorption to the Temkin model fitted parameter compared to Freundlich *a* value. The Temkin constant related to heat of adsorption (Bt), also varied and were positive among the land-use systems, the highest value of 2.25 J kg mol^{-1} mg^{-1} (arable) and lowest 0.68 J kg mol^{-1} mg^{-1} (plantain-farm) land-use indicate differences in the fitted Temkin energy-related parameter, and may be an indication of physical adsorption process as reported by Dada *et al*. (2012). The Freundlich isotherm coefficients of determination (R^2) ranged between 0.497 (Sports) and 0.983 (Plantain-Farm), in contrast, Temkin model yielded R^2 of 0.384 (Sport) and 0.911 (Forested) land-use, indicating that the Freundlich model provided the better linearized fit for soils of Plantain-Farm land-use. The Temkin model performed better for the Forested soil and neither model fitted well to the Sports field data, suggesting that additional adsorption mechanisms or a different model may be needed to describe K adsorption in the soil, and in line with findings of Awgchew *et al*. (2024).

Table 3. Parameter constants extracted from Freundlich and Temkin isotherms

Land-use	Freundlich				Temkin		
-	A	1/n	n	R^2	A_T	Bt	R^2
	mg kg^{-1}	-		-	L mg^{-1}	J kg mol^{-1} mg^{-1}	-
Arable	100.60	0.91	1.10	0.797	0.27	2.25	0.784
Forested	35.08	1.49	0.67	0.811	0.21	1.41	0.911
Sports	17.43	1.85	0.54	0.497	0.22	1.30	0.384
Plantain-Farm	1.78	3.18	0.32	0.984	0.19	0.68	0.883

Note: a = Freundlich adsorption capacity, 1/n= Freundlich adsorption intensity or surface heterogeneity factor, n = Freundlich adsorption favorability/intensity factor, R^2 = coefficient of determination, A_T = Temkin isotherm equilibrium binding constant, Bt = Temkin constant related

4. Conclusion and Recommendations

Potassium adsorption characteristics varied among the four land-use sites investigated at the University of Benin. The highest Freundlich adsorption parameter was obtained for the arable soil (100.60 mg kg^{-1}), while the lowest was recorded for the Plantain-Farm soil (1.78 mg kg^{-1}). Based on the coefficients of determination of the linearized isotherms, the Freundlich model provided a slightly better fit for the arable soil and a better fit for the Plantain-Farm soil, whereas the Temkin model fitted the forested soil better. Neither model adequately described potassium adsorption in the sports-field soil. These comparisons are based on linearized (R^2) values and should not be interpreted as definitive evidence of model suitability or adsorption mechanisms. The findings describe the sampled sites under the laboratory conditions used and cannot independently establish field-scale potassium losses or fertilizer-use efficiency. Further studies using independently replicated land-use sites, additional model-fitting criteria, field leaching measurements, and plant-response experiments are recommended to validate these observations and support soil-specific potassium management.

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Authors Contributions

EA assisted in sample collection and laboratory supervision and wrote the manuscript; AOB assisted in soil, laboratory and statistical analysis; OER designed and supervised the project

Declarations

All authors have read, understood and have complied as applicable with the statement on "Ethical responsibilities of Authors"

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Competing interest

The authors declare that they have no competing interests.

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