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Testing of applicability and flexibility of isotherm equations to fit sulphate kinetics desorption data in Nigerian savanna soils

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Abstract

Most agricultural soils exhibit minimal recovery of sulfate (S), the accuracy of isotherms to describe anion desorption data is very useful in establishing the fertilization schedule to promote optimal crop yield. The desorption of S by savanna soils and its applicability to isotherm equations in reserve form are both poorly understood. To fill this gap, soil samples were collected from three distinct parent materials: Basement Complex Rock, Chad Formation Rock, and Kerri-Kerri Formation Rock. Experimental soils were mixed with a 15 ml solution of Calcium dihydrogen phosphate containing 500 mg P/l for sulfate desorption analysis. Mixed samples were then shaken for different durations (30, 60, 150, 180, and 240 minutes). The data indicate a significant va-riation in soil pH among different parent materials. The isotherm equations were successfully applied to the de-sorption data of sulfur, with R^2 values exceeding 0.98 for both Langmuir and Freundlich equations. The Langmuir equation proved to be the most suitable for the desorption data, as evidenced by low standard error. The order of desorption and fitness was found to be CFR > BCR > KKFR. Langmuir desorption qmax and K_L were found to be favorably and significantly associated with pH, Org C, and Alox. A negative and statistically significant relationship between Alox and Freundlich desorption n_F was observed. The results showed that different mechanisms contribute to sulfate desorption from soils. To use fertilizers in the soil more efficiently, it is necessary to consider contact time, add forms of oxides as a filler to the S-formulated fertilizer, and apply organic management methods to support sustainable agriculture in the studied area.

Keywords
Testing, Applicability, isotherm equations, desorption, Sulphate

Introduction

The description of sulfate ions by isotherms is of great practical interest. Sulfur was once considered an undesirable pollutant, but is now recognized as an im-

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portant nutrient impeding crop production (Abdu *et al.*, 2021b). The availability of sulfur in soils for plant assi-milation has become an issue of international concern. The efficiency of soil nitrogen use by plants is based on the bioavailability of sulfur (Ahmad and Abdin, 2000; Abdu *et al.,* 2021b). Natural systems are intrinsically intricate, susceptible to instability, and frequently in a state of dynamic imbalance (Cichota, 2007). Soil sulfur imbalance is an ongoing problem worldwide, particularly in the Nigerian savanna (Raji, 2008; Abdu *et al.,* 2021b and Aliyu *et al.*, 2022a), which has necessitated modeling to make S bioavailable in savanna soils in Sudan. Additionally, modeling significantly enhances our understanding of sulfur bioavailability by simulating complex interactions within the soil ecosystem. Such insights are necessary for developing sustainable agricultural practices. Therefore, nu merous computer-aided isotherm models to describe and predict the dynamics of an essential have been developed in the past decades (Cichota, 2007; Chen, 2015). However, this development was based on increasing capacities and improved scientific knowledge. Isotherm models aimed to serve both scientific and practical purposes. Testing the applicability and flexibility of isotherms to agricultural systems has led to significant increases in agricultural production, and increased awareness of environmental concerns (Van den Berg and Driessen, 2002; McCray *et al.*, 2005). Several researchers have also used isotherms to study the environmental impact of nutrient additions to agricultural soils (Lergard *et al.*, 2001; Dragten and Thorrold, 2005). Less complex isotherm models are frequently employed due to their ease of use and ability to give a satisfactory representation of actual data. Several mathematical isotherm models were used to characterize ion adsorption and desorption processes. The best-known isotherm equations are the Langmuir and Freundlich equations (Essington, 2005). As a result, these isotherm models often fit experimental data fairly well and can be used to assess sulfate desorption behavior across soils (Alves and Lavorenti, 2006), although they do not provide mechanistic insights (Sparks, 2005a). These models were used to gather information on binding sites, strength, and types of sorption mechanisms concurrently with S desorption data (Alves and Lavorenti, 2006). Furthermore, many soil chemists have used the Langmuir isotherm model to describe S adsorption in soils and soil components with success (Osodeke and Ubah, 2006; Farahmand *et al.*, 2015; Maida and Nalivata, 2016). In recent decades there has been much evidence for the applicability of isotherms for S sorption data, but S desorption data have little in common, particularly in Sudan soils produced from various parent materials. The desorption of sulfates in the Nigerian savanna and the applicability of the Langmuir and Freundlich isotherms equation to them is poorly underswtood. This research is intended to test the applicability of Langmuir and Freundlich equations to estimate the fate of added S fertilizer due to its simplicity and convenience through linear analysis. Therefore, to use fertilizers in the soil more efficiently, the use of model isotherms for S-fertilizer formulation and recommendations would be beneficial.

Materials and Methods

The research was carried out in the Katagum zone of Bauchi state, which is part of the Nigerian Sudan savannah. The soils in the zone (Fig. 1) consist of complex bedrock (Shira-Yana with latitude 11˚24'N to longitude 10˚21'E) and sedimentary rocks such as the Kerri-Kerri Formation Rock (Giade with lat. 11˚23'N to long. 10˚10'E) and the Chad Formation Rock (Jama'are with lat. 11˚39^{1}N to long. 10˚50'E). The region has trees, either alone or in groups, with non-woody plants up to 3 meters tall. Grasses can grow up to 2 meters high, with Andropogon grasses and occasional Tamarindus trees dominating. Crops include rice, tomato, corn, and peppers. The region experiences a tropical climate with noticeable alternating wet and dry seasons. During the rainy season, the weather is hot and humid, with an average rainfall of approximately 280 mm. Temperatures vary between 16 and 35 degrees Celsius.

Sampling and analysis

Fieldwork was conducted to collect soil samples from three (3) distinct parent materials: Kerri-Kerri formation rock, Chad formation rock, and Basement complex rock. Three (3) locations were chosen per parent material after a survey. At each site, 20 auger soil samples were randomly collected at depths of 0-15 cm (surface) and 15-30 cm (sub-soil), and replicated twice. A composite sample was taken from each depth, resulting in 4 composite samples per location. The same method was employed for the remaining locations with the other parent rocks. A total of 36 composite samples were obtained, stored in labeled bags and transported to the laboratory. Subsequently, the samples were left to dry in a well-aired space for a week before being transferred onto fresh polyethylene

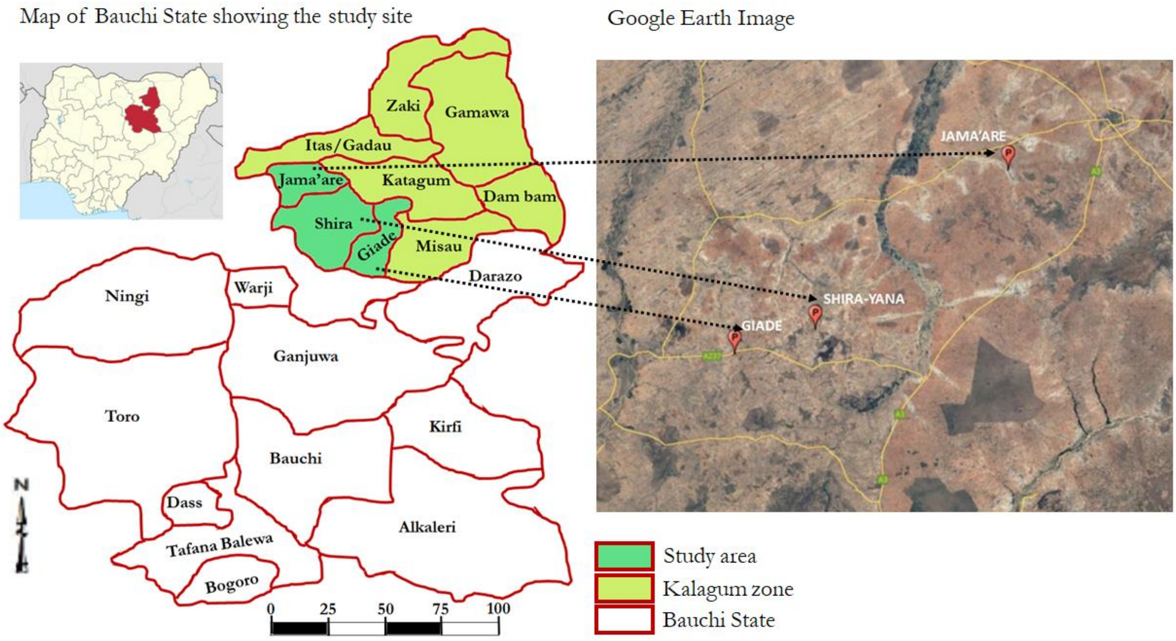

Figure 1. *Showing the study site*

bags. Once dried, the samples were pulverized using a porcelain pestle and mortar and then sieved to eliminate items larger than 2 mm in size. The refined soil samples obtained through screening were utilized for all subsequent laboratory testing. The hydrometer method (Gee and Bauder, 1986) was used to determine particle size distribution. Soil pH was measured with a glass electrode meter (ratio 1:1 soil/water and 1:1 soil/0.01M $CaCl_2$) (Thomas, 1996). Organic carbon (OC) was quantified using the Walkley-Black dichromate wet oxidation method (Nelson and Sommers, 1982). Cation Exchange Capacity (CEC) was calculated using the saturation of NH4OAc (Rhoades, 198). Oxalate-extractable Al and Fe determined by ammonium oxalate extraction in the dark (McKeague and Day 1966). Dithionite citrate bicarbonate extractable Fe and Al determined by McKeague and Day method (1966). Iron was analyzed through AAS while aluminum is determined using the Aluminon method. Total sulfur in soil was determined according to Tabatabai (1982), by wet oxidation of soil sulfur compounds to sulfate using an alkaline sodium hypobromite (NaOBr) solution. Available S in soil was extracted with 500 mg P L^{-1} as Ca $(H_2PO_4)_2$ (Fox et al., 1964) and all filtrate extracts were analyzed for sulfate concentration by the turbidimetric method of Tabatabai (1982).

Desorption analysis

Sorption experiment. Separate plastic tubes were deposited with 2.5g of 2mm sieved soil. The soil sulfur adsorption was characterized by adding 50 mg S/g (K_2SO_4) from a prepared stock solution (1000 mg S /ml in 0.01 M NaCl). An adsorption equilibration of 24 hours was applied to prepared soils and shaken intermittently. After equilibration, the samples were centrifuged and the supernatants were concentrated to sulfate using the turbidimetric technique of Tabatabai (1982). tested. The adsorbed S was measured by subtracting the additional S from the remaining S in the solution.

Analysis of the rate of desorption. After carrying out a sorption analysis, a desorption study of the soil was carried out. The sorption sample was mixed with 15 ml $[Ca(H_2PO_4)_2]$ solution (500 mg P/l) and shaken (30, 60, 150, 180, and 240 minutes). The supernatant was filtered and assayed for sulfate at demonstrated time using the turbidimetric technique of Tabatabai (1982). The desorbed sulfate was computed as follows: SO_4^{2-} desorbed (mg/kg)=SO_4^{2-} recovered (mg/kg) – analyzed SO_4^{2-} in solution (mg/kg)

Langmuir and Freundlich equations in reverse pattern to fit sulphate desorption data

The following is a description of the Langmuir and Freundlich equations in their simplest form.The Langmuir isotherm (Langmuir, 1916) is a semi-empirical isotherm model and its below equation is one of the most commonly used forms:

$$Ce_t/q_et = 1/qt_{max}Ce_t + 1 / (k_L\ qtmax) \qquad [1]$$

where: Ce_t denotes the equilibrium concentration in the liquid phase (gm l^{-1}), qe_t denotes the sulfate release value (mg /g) at a demonstrated time (t), and qtmax denotes the maximum sulfate desorption capacity (mg g^{-1}) at the given time (t). A plot of Ce_t/q_et vs Ce_t should under ideal conditions yield a straight line with a slope equal to 1/qmax from which qmax is estimated. The K_L is constantly determined at the point of contact (Farahmand *et al.*, 2015).

Freundlich isotherm model (Freundlich, 1906) is an empirical isotherm equation based on the equilibrium connection of heterogeneous surfaces. This can be expressed linearly as:

$$\ln qt_e = \ln k_f + 1/\,n_f \log Ce_t \qquad [2]$$

where: Ce_t is the value/quantity of sulfate in solution at each time point (t) and qte means equilibrium value/quantity of desorb S (mg/g) at each time point (t). The Freundlich constants K_F (l/g) and $1/n_F$ are related to desorption capacity and intensity, respectively. The slope and intercept of the log qte versus log Ce_t plot are used to determine the Freundlich constants K_F and $1/n_F$.

Analysis

The data collected were analyzed using IBM SPSS version 20.0 (2012) to compare the mean differences in the soil properties obtained from various parent materials using analysis of variance (ANOVA). Correlation analysis was employed to determine the relationship between desorption rate constants and soil parameters .

Fitness to S desorption data

The ideal model or equation for describing S desorption data is believed to have an R^2 that has the lowest standard errors of estimates (SE). The following formula was used to calculate the standard error (Abdu, 2006):

$$SE = [(Ms\text{-}Ps)\ 2/(n\text{-}2)]^{\ 1/2} \qquad [3]$$

where: Ms (analyzed value of release sulfate) and Ps (predicted value of S), while n means measured number.

Results and Discussions

The values and distribution of the specified soil parameters among soil parent materials are shown in Table 1. The average amounts of soil separate (sand, silt, and clay) in soils made from different rocks varied but were not statistically at par. Recent works by others (Maniyunda *et al.*, 2014; Abdu *et al.*, 2021b) indicated that the Nigerian savanna soils are severely degraded and aged, which may partly explain the non-significant differences between soil separates derived from various origins. The degree of weathering affects soil properties. For instance, soils from Ewekoro formation show the highest weathering, yet still share mineral characteristics with less weathered soils. (Adekiya *et al* 2024). Another reason for the statistical similarity may be traceable to environmental conditions. Common climatic conditions and environmental factors across regions influence soil formation and composition resulting in similarities in soil properties (Adekiya *et al* 2024). The particle size fractions at study sites were evenly distributed, with a CV of less than 10%, consistent with the results of Mustapha and Fagam (2007) for some soils derived from similar parent materials. The soils were mainly sandy loam. The mean pH values in both water and $CaCl_2$ between the origin of the soil were statistically different (P=0.05) which strengthened by CV greater than 30% (pH widely distributed in the soils), as shown in Table 1. Similar results have been reported by others (Raji and Muhammad, 2000; Abdu *et al.*, 2021b; Abdu, 2006). Soil pH varied in the order CFR > BCR > KKFR among the starting rocks. The organic carbon values in investigated soils are classified as low. This was also reported by Mustapha *et al.* (2007) and Mulima *et al.* (2015). Howerer this result differs from that of Mustapha and Fagam (2007), who found a significant influence of precursors on the distribution of organic carbon in comparable ecological zones. The level of the organic matter distribution (CV < 10%) was in agreement with the result of Mustapha and Fagam (2007). The CEC mean values are low compared to the Esus (1999) limit value of 6 cmol (+)/kg. The sandy nature of the studied soils as well as the persistent weathering, leaching of base cations, and low organic carbon content are the main reasons for the low CEC values, which are not statistically different between the soil origins of the state. This result was also reported by Abdu *et al.* (2021b) in the same savanna soil. The means of Fed and Ald (Table 2) across the various soil origins are statistically different (p = 0.01) and are similar to the values reported by Abdu (2006) for different soil parent materials. This was also found by others (Maniyunda *et al.*, 2015; Olatunji *et al.*, 2015) for some BCR-derived soil in North and south-western Nigeria, respectively.

Table 1. *Physical and chemical parameters across parent material.*

Treatment PM	Sand	Silt g/kg	Clay	Texture	pH H_2O	pH $CaCl_2$	Org. C g/kg	CEC Cmol(+)/kg
CFR	778.3a	128.5a	98.5a	SL	6.5a	5.5a	5.3a	4.9a
BCR	739.7a	144.4a	115.9a	SL-SCL	6.2b	5.1b	5.2a	4.4a
KKFR	674.7a	141.4a	123.9a	SL-SCL	5.9c	4.8c	5.4a	4.9a
CV %	7.1	8.7	6.4	-	30.3	32.1	3.1	1.5
LSD	NS	NS	NS	-	*	*	NS	NS

PM= Parent Material (CFR = Chad Formation Rock; BCR = Basement Complex Rock and KKFR = Kerri-Kerri Formation Rock); NS= Not Significant; LSD= Level of significance Difference (* = significant at $P < 0.05$) and Coefficient of variance (CV). Values having the same letter in a vertical row are not different statistically.

The means of Feox and Alox on soil parent materials differed significantly ($p = 0.001$). The parent material had an impact on the distribution and content of both the iron and aluminum forms in all soils tested, which in turn affected the rate of sulfate desorption. The wide variation of CV values greater than or equal to 50% (Table 2) also supports the conclusion. The Fe and Al oxalate values in the examined soils were found to be lower compared to the extracted dithionate value (Table 2), indicating that crystalline Fe and Al predominated over amorphous forms. Others have made similar observations (Samndi, 2012; Olatunji *et al.*, 2015).

Table 2. *Oxides (Fe and Al) across distinct parent materials*

Treatment PM	Fed (g/kg)	Ald (g/kg)	Feox (g/kg)	Alox (g/kg)
CFR	12.5c	5.7c	5.8c	4.0c
BCR	39.6a	24.4a	23.0a	11.7a
KKFR	22.6b	14.4b	11.8b	6.7b
CV%	50.01	50.9	52.9	55.22
LSD	**	**	**	**

PM=Parent Material (CFR=Chad Formation Rock; BCR=Basement Complex Rock; KKFR=Kerri-Kerri Formation Rock); d=Dithionite form; ox=Oxalate; NS=Not Significant; LSD=Level of Significance Difference (** and * = significant at $P = 0.001$ and $P < 0.05$, respectively)

Table 3 provided in this study displays the two distinct values of soil sulfur (total and inorganic S) across different parent materials. The total sulfur (TS) levels observed in all analyzed soils ranged from 149.70 to 246.4 mg/kg, aligning closely with the values (117 to 489 mg/kg) recorded by Kang *et al.* (1981) for forest zone soils and by Raji (2008) for dune soils in the Nigerian savanna. These findings also fall within the reported ranges (43 to 398 mg/kg) outlined by Tabatabai (2005a). Conversely, the total sulfur content in this research is lower than the levels (520 to 1082 mg/kg) described by Solomon *et al.* (2001) for Ethiopian soils. The differences in organic matter content, climatic conditions, depth of soil sampling, and parent materials may account for variations in total sulfur content (Solomon *et al.*, 2001; Tabatabai, 2005a; Raji, 2008). The mean values of total sulfur in all soils derived from three parent materials were significantly different ($p > 0.05$) (Table 3), indicating that the parent materials had a significant impact on the levels and distribution of total sulfur. The values of available sulfur (AS) ranged from 30.20 to 46.82 in all the soils across three parent materials and are similar to the values obtained by Bankole *et al.* (2022). However, the mean values were not significantly different ($p>0.05$) (Table 3). In terms of quantity, the total sulfur content in soils from the various parent materials could be ranked as follows: CFR ≥ KKFR ≥ BCR (Table 3).

Table 3. *Average concentration of sulfur forms and content in soils derived from three distinct parent materials*

Parameters	CFR	BCR	KKFR
TS (mg / kg)	246.4a	149.70b	182.20ab
AS (mg/kg)	42.82a	30.20a	41.06a

CFR= Chad formation rock, BCR= Basement complex rock, KKFR= Kerri-Kerri formation rock: Data presented are range with mean in parenthesis: Mean values with the same letter (s) in the horizontal column are not significantly different from one another at $p<0.05$

The differences may be due to variations in parent materials, their formation processes, and the presence of Fe and Al oxides (Table 2). Overall, the sulfur levels (TS and AS) in the soils analyzed were found to be consistently low. This trend has also been noted in previous studies on Nigerian savanna soils by Kang *et al.* (1981) and Raji (2008), as well as in West African lowlands soils by Buri *et al.* (2000). They further reported that low sulfur levels in West African soils are attributed to the limited presence of organic matter and the sandy composition of the soil.

Desorption

Table 4 shows the sulfate desorption at different time intervals. With increasing contact time, the desorption rate of adsorbed S from all tested soils decreased. This was also reported by Ghosh and Dash (2012). They also discovered that the conversion of sulfate to a more solidly held form was a reason for the decreesing rate of the release of adsorbed S as time increased. Koopmans *et al.* (2004b) found a similar time effect on phosphate release. They also further reported that the soil particles continuously disintegrated over time, exposing new surface sites and increasing sorption, and consequently affected the rate of desorption. The time dependence of plant nutrient release in agricultural soils is critical for understanding the efficiency with which plant roots uptake nutrients in particular S. The desorption at 30 minutes was rapid (Borda and Sparks, 2008; Garg *et al.*, 2016) and considered to be a suitable contact time to characterrize the S desorption maxima in all the tested soils (Table 4). This result indicated that the adsorption chemistry between the adsorbing surface and sulfate ion is nonspecific for a first short time as decreased with time. Borda and Sparks (2008) indicate that the diffusion of ions into inorganic mineral micropores and humic matter with time is the reason for having a decreased rate of desorption. The desorption order was CFR > BCR > KKFR (Table 4), which corresponds to the increasing order of soil pH (Table 1). This is because, at high pH, more negative charge is accessible, which in turn has negative effects on the rate of sulfate desorption. Tabatabai (2005a) indicated that as pH increases, sulfate adsorption is almost non-existent. In the Nigerian savannah, Abdu (2006) and Aliyu *et al.* (2022a) both reported differential desorption of anionic soil nutrients from different parent materials. This variation is associated with the origin of soil composition. This shows that sulfate fertilizer formulation and recommendation must be based on the origin of the soil. Hysterical phenomena (Table 4) were observed in this study and considered common in adsorption-desorption processes as found by others (Sammi et al., 2001; Alves and Lavorenti, 2006; Maida and Navilata, 2016). It is indeed true that the soil is constantly changing, and as a whole never reaches a state of equilibrium. Essington (2015) mentioned that the kinetic properties of soil are not thermodynamic properties. He further reported that a study on kinetic adsorption and desorption always results in a state of disequilibrium in a system and the occurrence of irreversible processes and hysteresis. Consequently, this study validates these conclusions.

Table 4. *Sulphate desorption data (mg/kg) at different time intervals*

Statistical Tool	S adsorbed (mg/kg) at 24 hours	Desorption (mg/kg) of adsorbed S at various times (minutes)				
		30	60	150	180	240
		CHAD FORMATION ROCK				
Mean	41.09	32.50	31.94	29.10	28.99	26.08
		BASEMENT COMPLEX ROCK				
Mean	42.79	31.02	30.48	27.22	26.89	22.56
		KERRI-KERRI FORMATION ROCK				
Mean	42.50	30.43	30.13	25.03	24.71	20.88

The fit of S desorption data to reverse isotherm equations

Agricultural systems modeling has led to significant increases in agricultural production as well as increased awareness of environmental concerns (McCray *et al.*, 2005; Cichota, 2007). Table 5 and Figs. 2.1-6 show the quality of the fit of the reverse isotherm equations (Langmuir and Freundlich) to desorption data from the study. The Langmuir and Freundlich isotherm equations in this format were both sufficient to explain desorption data in all soils studied, having R^2 exceeded 0.98 (Table 5) determined by comparing the R^2 values of the equations. The results are consistent with Essington's (2005) findings that both models provide a highly significant fit to the data with an R^2 value of 0.98 for Langmuir and 0.99 for Freundlich. This applies to our R^2 values regardless of soil materials and format. The progressive fitness rank was as follows: CFR>BCR>KKFR. This reflects the reality that soils are made up of different rocks. Soil pH followed a similar pattern (Figures 2 and 3). Sulfate desorption in soil is pH dependent and increases with increasing pH (Tabatabai, 2005a). The S.E fitness to desorption data (Table 5 and Figures 2 and 3), can be reprensented in the order CFR > KKFR > BCR.

However, the Freundlich equation based on S.E did not adequately account for the experimental results in this work; the Langmuir equation did (Table 5 and Figures 2). The Langmuir equation in reserve application provides an excellent description of the desorption data, leading to the conclusion that desorption is the mechanism of sulfate release. However, these results are consistent with those of Alves and Lavorenti (2006), who found the goodness of the Langmuir equation models for some of the soils they tested using mean squared error (MSE), although the Freundlich equation was appropriate for the majority of samples. The results suggest that the sulfate desorption rate from soil parent materials is affected by more than one mechanism. Little attempt has been made to evaluate the applicability of these isotherm equations in reserve form for representing S desorption data in soils at the current study sites. It is known that the Langmuir equation is designed for homogeneous surface adsorption (Sparks, 2002). A good agreement of this isotherm equation demonstrates monolayer desorption. Many soil chemists have recently successfully used the Langmuir isotherm model to describe S adsorption in soils (Osodeke and Ubah, 2006; Farahmand *et al.*, 2015; Maida and Nalivata, 2016), but there is limited data to evaluate these isotherms (reserve case) in S desorption data (Alves and Lavorenti, 2006).

Table 6 shows a significant relationship between isothermal parameters and soil properties that are independent of parent materials. Soil pH is positively and statistically related to Langmuir q_{max} (r = 1.000**) and K_L (r = 0.998*). This is to be expected since at higher pH values S adsorption may decrease due to the partial dissolution of Fe and Al oxides (Fageria, 2009), leading to the destruction of sorption sites and hence increased S desorption in soils. The silt had a significant and positive correlation with Langmuir K_L (r=1,000**). Freundlich n_F (r = 1.000*) and K_F (r = -0.997*) were both significantly correlated with clay, respectively. Silt has a major impact on S desorption. Langmuir q_{max} (r=1.000*) and K_L (r=0.998*) were both positive and strongly associated with Org C. According to several studies, the Langmuir constant (qmax) and organic carbon have a positive and significant association when it comes to data on sulfate sorption in soils (Murthy, 2004; Alves and Lavorenti, 2004; Uzoho *et al.*, 2014; Maida and Nalivata, 2016). This is because organic matter is a dynamic element that can easily alter the adsorption/desorption of soil anions through multiple pathways (Perdue and Ritchie, 2014; Yang *et al.,* 2019). The favorable high linkage between organic C and S desorption qmax is due to sulfate having lower binding energy and a competitive advantage over organic matter responsible for enhancing S desorption in soils. Maida and Nalivata (2016) discovered that OM can either increase or decrease anion sorption by soils. Alox paired favorably and strongly with Langmuir q_{max} (r=1.000*) and K_L (r=0.998*). Alox and Freundlich n_F have a negative and substantial correlation (r = -0.999*). Freundlich K_F had a positive and significant correlation with CEC (r = 1,000*).

Table 5. *Applicability test of the isotherm equations in reverse forms to describe sulfate desorption data across parent rocks*

Treatment	Langmuir equation		Freundlich equation	
	R^2	SE	R^2	SE
CFR	0.994	1.83	0.984	3.72
BCR	0.991	2.00	0.983	3.46
KKFR	0.988	1.86	0.983	3.32

SE= Standard error

Table 6. *Correlation between soil properties and desorption isotherm parameters*

Soil parameters	Isotherm parameters			
	q_{max}	K_L	n_F	K_F
pH	1.000*	0.998*		
Silt		1.000**	1.000*	-0.997*
Org C	1.000*	0.998*		
Alox	1.000*	0.998*	-0.999*	
CEC				1.000*

qmax is the maximum sulfate desorption capacity (mg g^{-1}), and K_L is the Langmuir constant. K_F (L/g) and n_F are Freundlich constants related to desorption capacity and desorption intensity, respectively. Org C is the organic carbon, and Alox is the Aluminum oxalate. ** and * are the significant differences at 0.001 and 0.05

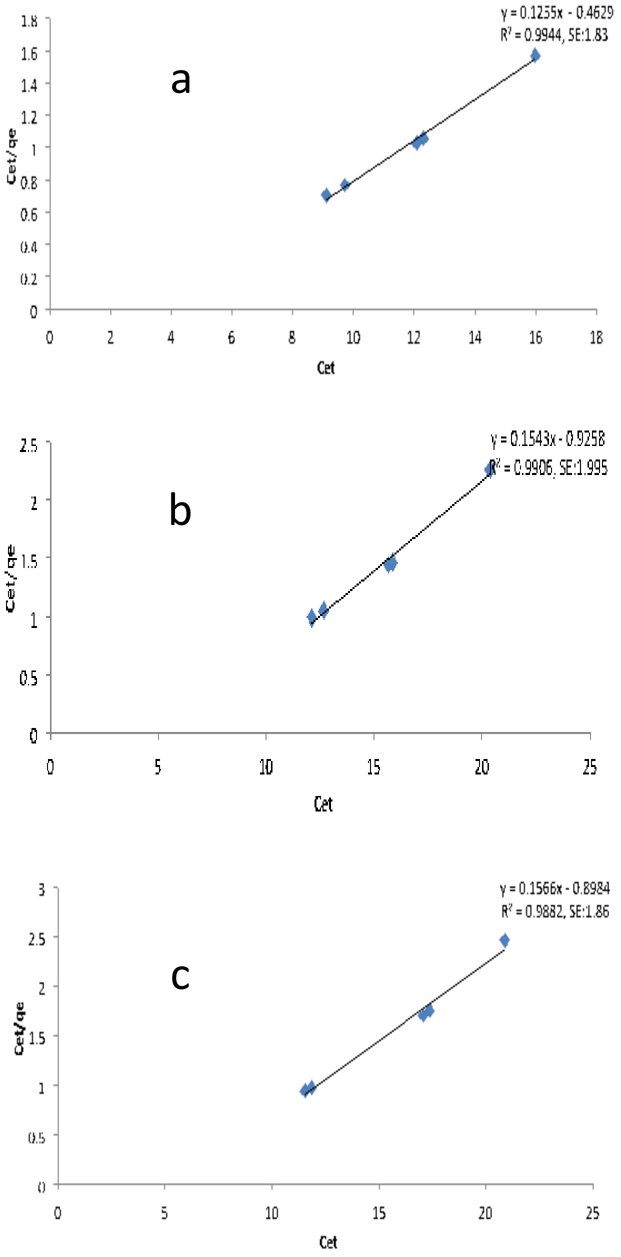

Figure 2. *Plots of Langmuir isotherm to desorption data by soils of CFR-Chad Formation Rock* (a), *BCR-Basement complex rock* (b) *and KKFR-Kerri- Kerri Formation Rock* (c)

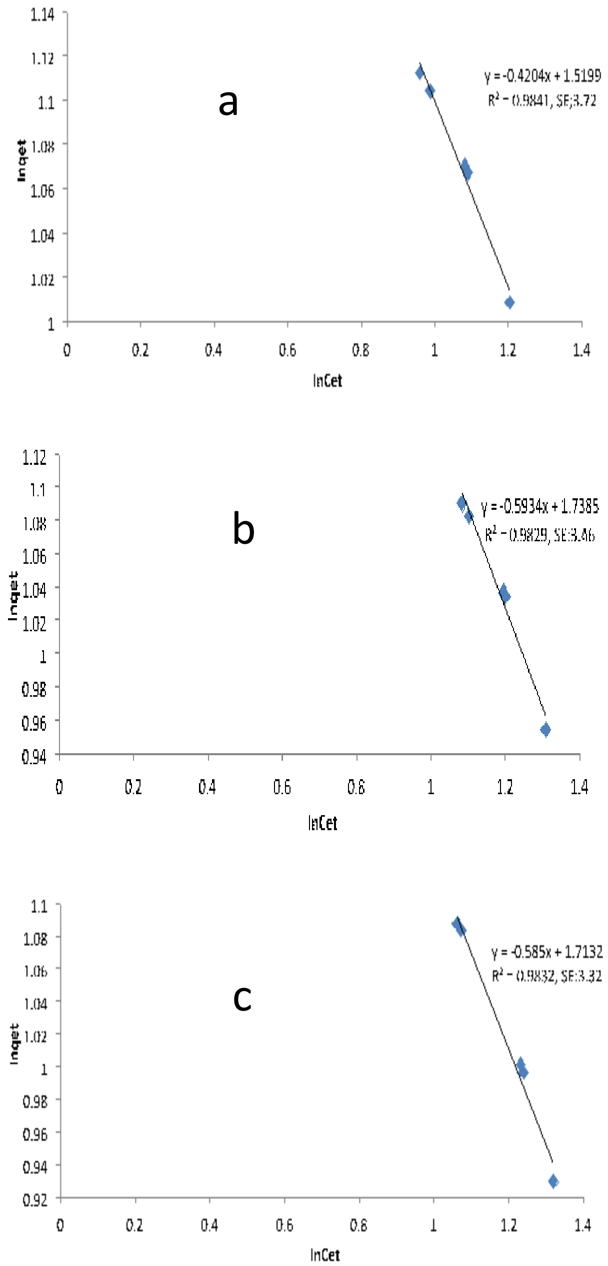

Figure 3. *Plots of Freundlich isotherm to desorption data by soils of CFR-Chad Formation Rock* (a), *BCR-Basement complex rock* (b) *and KKFR-Kerri- Kerri Formation Rock* (c)

Conclusions

The findings revealed that variations in soil parent material influenced the rate of S desorption in all soils investigated. R^2 greater than 0.98 indicates that the desorption S data properly matched both the Langmuir and Freundlich equations in this test. However, due to the low S.E., the Langmuir equation suits better to the experimental values in this investigation. The S fertilizer recipes should be run for 30 minutes. We conclued that the sulfate desorption rate in these soils is mostly biphasic and the flexibility and applicability test of isotherm equations to describe desorption was achieved. Soil pH, organic carbon, and alumina forms all play important roles in influencing the rate of sulfate desorption in soils. To use fertilizers more efficiently in the soil, forms of oxides must be added as a filler to the S-formulated fertilizer, and organic management methods must be implemented to support sustainable agriculture in the investigated area.

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