DOI: 10.22620/agrisci.2025.45.011

Phosphorus adsorption-desorption mechanisms in a typical alfisol soil under rice husk biochar application: a batch sorption study

Kehinde O. Affinnih[1]*, Sikiru Y. Alasinrin[1], Theophilus O. Isimikalu[1], Maryam M. Woru[2], Tayo D. Fajobi[1]

[1] University of Ilorin, Kwara State, Nigeria
[2] Kwara State College of Education, Ilorin, Nigeria
***Corresponding author: affinnih.ko@unilorin.edu.ng**

Abstract

The sustainable production of food is hindered by environmental issues caused by human activities, particularly the management of vast amounts of waste generated by modern agriculture. To address this, batch sorption studies were conducted to investigate the impact of varying levels of rice husk biochar (0, 10, 20, 30, and 40 tons ha^{-1}) on phosphorus availability in a typical alfisol. The adsorption data was analyzed using Langmuir and Freundlich isotherm models. The results showed that the application of 10 tons per ha of rice husk biochar (Treatment B) had the highest phosphorus sorption capacity, bonding energy, and buffering capacity, with values of 24.39 mg kg^{-1}, 23.23, and 566.7, respectively. The Freundlich model revealed high adsorption constants and slopes greater than 1, indicating unfavorable phosphate sorption. Both models showed high coefficients of determination (r^2), with the Langmuir model providing a slightly better fit. The study concludes that the Langmuir isotherm model more accurately describes the adsorption process, suggesting that rice husk biochar can improve soil phosphorus availability, although other factors may influence the process.

Keywords: alfisol, modern agriculture, phosphorus sorption, rice husk biochar, waste management

INTRODUCTION

The cumulative impact of agricultural and industrial advancements, combined with unsustainable farming methods, has severely degraded global soil health. As a result, the world faces pressing challenges in producing food sustainably, including climate change, land degradation, and water resource depletion, all of which are exacerbated by excessive fertilizer use and harmful soil management practices. Soil health continues to decline due to acidification and erosion, leading to reduced crop yields worldwide. While using compost and manure to enhance soil organic matter (SOM) is a viable option, it has limitations, including the potential for organic pollutant accumulation, increased pathogen pressure, and excess nutrient leaching, which can lead to waterway eutrophication (Amoah-Antwi et al., 2020). Therefore, maintaining soil quality and reclaiming marginal lands remain critical priorities. In this context, biochar – a porous, carbon-rich material with excellent adsorption and cation exchange capacity, high chemical stability, and reactivity for surface modification (Das et al., 2023) – is gaining attention for its potential to enhance soil properties and support sustainable agriculture.

Agricultural processing generates vast amounts of waste, which can be repurposed as a cost-effective alternative to expensive soil sustainability precursors. In West Africa, approximately 1.5 million metric tons of rice mill waste are generated annually, presenting an environmental challenge (FAO, 2000). Converting this waste into a valuable resource can help mitigate pollution. Rice husk biochar has been found to improve soil fertility and phosphorus availability in various soils (Mukherjee et al., 2019). Additionally, previous research has demonstrated that rice husk dust can enhance the physical properties of clay soil, increasing porosity and hydraulic conductivity while reducing bulk density and penetration resistance (Anikwe, 2000).

In addition, rice husk biochar has been shown to be effective in improving soil adsorption and desorption capacities, with studies demonstrating its ability to increase soil's water-holding capacity, nutrient retention, and carbon sequestration (Luo et al., 2023). The application of rice husk biochar can also modify soil's physical and chemical properties, such as pH, electrical conductivity, and zeta potential, which can influence its adsorption and desorption capacities (Li et al., 2023). Research has shown that rice husk biochar can increase the adsorption capacity of soil for phosphorus, nitrogen, and other nutrients, while also reducing desorption of these nutrients, making them more available to plants (Luo et al., 2023). A study on the use of rice husk biochar for soil remediation found that it can effectively adsorb heavy metals, such as lead and cadmium, and reduce their desorption, making the soil safer for plant growth (Li et al., 2023).

Various strategies are being explored for atmospheric carbon dioxide removal, including bioenergy adoption, direct carbon capture, afforestation, and soil carbon sequestration through biochar application (Woolf et al., 2010; Mulligan et al., 2017). Biochar has the potential for long-term carbon sequestration, as soil stores more carbon than atmospheric reserves. Increasing global soil organic matter by 0.4% annually can offset 30% of global greenhouse emissions (Minasny et al., 2017). While indigenous farmers have long enriched soils with recalcitrant carbon, a standardized biochar with consistant properties that enhance plant growth remains unavailable. Similarly, the mechanisms of biochar's on phosphorus sorption-desorption in alfisols are not well understood. Understanding these processes is crucial for optimizing phosphorus management and mitigating phosphorus pollution (Withers et al., 2014). This study investigates the effects of rice husk biochar on phosphorus sorption-desorption in a typic north-central alfisol of Nigeria, aiming to fill the knowledge gap on biochar application rates and adsorption models. Thus, contributing to the development of sustainable phosphorus management strategies for alfisols.

MATERIALS AND METHODS

This study was conducted at the University of Ilorin's Agronomy Laboratory in Kwara State, Nigeria, in 2021. Soil samples for isotherm plotting were collected from the Unilorin Dam site, located at latitude 8°28.11' N and longitude 4°39.46' E. The soil samples were air-dried, ground, and sieved through a 2 mm sieve. The coarse particles were further ground and sieved until all particles passed through the sieve, leaving only pebbles, organic residues, and concretions. The samples were analyzed for pH, organic carbon, exchangeable cations (Ca, Mg, Na, and K), exchangeable acidity, available phosphorus by Bray P1 method, and total nitrogen using standard laboratory procedures (Schindelbeck et al., 2022).

The biochar used in this experiment was obtained from Crestfield Agro Allied Industries, Offa, Kwara State after rice husk was heated at approximately 600°C in a kiln with a 45-minute rest period. An incubation experiment was conducted by mixing 100 grams of soil samples with varying proportions of rice husk biochar (0.77, 1.54, 2.31 and 3.08% corresponding to 10 t ha^{-1}, 20 t ha^{-1}, 30 t ha^{-1}, and 40 t ha^{-1} on a Laboratory Scale Equivalent basis. A control (no amendment) was also included, and the prepared mixtures were incubated for 68 days. The study utilized a completely randomized design (CRD) with two replicates and five treatments.

After incubation, at 50% moisture content (relative to water-holding capacity) and a controlled temperature of 30°C to optimize microbial activity and nutrient cycling, phosphorus sorption was estimated using the procedure outlined by Graetz & Nair (2000). Two grams of soil from each treatment were equilibrated with 25 ml of 0.01 $CaCl_2$ solution containing varying phosphorus concentrations (0, 5, 10, 15 and 20 mg P L^{-1} in the form of potassium dihydrogen phosphate). The suspensions were shaken, filtered, and analyzed for phosphate using the vanadomolybdate blue method (Murphy & Riley, 1962). The adsorbed phosphorus was calculated from the difference between initially applied phosphorus and equilibrium phosphorus concentration. The Langmuir and Freundlich isotherm equations were applied to determine phosphorus adsorption capacity (Yanga *et al*., 2019). The values of phosphorus adsorbed, Q_e, and bonding energy constant, K_L, were computed from the Langmuir plot (Swenson & Stadie, 2019).

(A) ***Langmuir model***:

$$x/m = (K_L \times b \times EPC) / (1 + K_L \times EPC) \quad (i)$$

$$EPC / (x/m) = 1 / (K_L \times b) + (1 / b) \times EPC \quad (ii)$$

$$x/m = (1/b) + (1/(bK_L EPC)) \quad (iii)$$

Where: x/m is the adsorbed phosphorus (mg kg^{-1}); K_L is the bonding energy constant; b is the Langmuir adsorption maximum (mg kg^{-1}); EPC is the equilibrium phosphorus concentration in soil solution (mg P kg^{-1}); and $K_L b$ is the maximum buffering capacity of the soil. The x-axis is 1/EPC (Ce) (reciprocal of the equilibrium phosphorus concentration) while the y-axis is 1/x/m (reciprocal of the amount of phosphorus adsorbed per unit mass of soil). By plotting 1/x/m against 1/Ce, a linear relationship is obtained, where the slope of the line is related to the Langmuir constants

(B) ***Freundlich model***:

$$x/m = K \times EPC^{(1/n)} \quad (iv)$$

$$\log(x/m) = \log K + (1/n) \times \log EPC \quad (v)$$

Where: K and n are empirical constants; x/m is the adsorption; EPC is the equilibrium phosphorus concentration. The x-axis is log EPC (logarithm of the equilibrium phosphorus concentration) while the y-axis is log (x/m) (logarithm of the amount of phosphorus adsorbed per unit mass of soil). A plot of log (x/m) against log EPC gives a linear graph whose slope, 1/n is a function of the strength of adsorption (Al-Ghouti and Da'ana, 2020; Trans et al., 2021). Hence, depict the fitness of the graph, and the intercept of the line represents the logarithm of the adsorption of the adsorption of the adsorption capacity (log K).

The parameters of Langmuir and Freundlich isotherms were estimated by means of linearization of the hyperbolic model. The essential features of the Langmuir and Freundlich isotherms were further expressed in terms of equilibrium parameter $R_{L,}$ which is a dimensionless constant referred to as separation factor or equilibrium parameter as given equation (vi) (Webber & Chakravarti, 1974).

$$RL = \frac{1}{1+(1+KLCo)} \quad (vi)$$

RESULTS AND DISCUSSION

Soil Characteristics

The chemical properties of soil used in this study are presented in Table 1. The soil exhibits high acidity, with a pH of 3.90 in water and 3.44 in KCl. It had low levels of organic carbon (1.06%), available phosphorus (1.16 mg kg^{-1}), and total nitrogen (0.44%). The exchangeable cations concentrations were 1.65, 1.20, 1.83, and 3.07 cmol kg^{-1} for calcium, potassium, magnesium, and sodium, respectively. According to FAO (2017), soils with organic carbon content between 1-2% are classified as low, indicating that the sample used in this study has low organic carbon and organic matter content. The available phosphorus level can be categorized as very low based on critical limit description of Hazelton & Murphy's (2007).

The low pH value may be attributed to the high degree of weathering (Moreira & Fageria, 2009), leading to iron and aluminum oxides being the primary factors responsible for phosphorus adsorption in this soil (Bortoluzzi *et al*., 2015; Gérard, 2016). The low soil pH value influences soil phosphorus reactions (Brady & Weil, 2017), while organic matter may reduce connections between organo-mineral complexes by blocking adsorption sites on oxides and clay minerals with organic acids (Yang *et al*., 2019). The soil's sandy loam texture results in low water and nutrient holding capacities. Therefore, this acidic soil with low organic matter content requires significant phosphorus fertilization to achieve optimal phosphorus levels for sustainable crop yield.

Table 1. Selected physical and chemical properties of soil sample used in the study

Parameters	Values
Particle size Analysis	
% Sand	73.52
% Silt	20.00
% Clay	6.48
Textural class	Sandy loam
pH (water)	3.90 ± 0.30
pH (KCl)	3.44 ± 0.41
Exchangeable acidity (cmol kg^{-1})	16.63 ± 0.45
Exchangeable bases (cmol kg^{-1})	
Calcium	1.65 ± 0.11
Potassium	1.2 ± 0.10
Magnesium	1.85 ±0.20
Sodium	3.07 ± 0.21
Effective cation exchange capacity (cmol kg^{-1})	24.40
Organic carbon %	1.06 ± 0.14
Organic matter %	1.82 ± 0.24
Available phosphorus (mg kg^{-1})	1.12 ±0.14

Legend: Data are presented as mean ± standard deviation

Rice husk biochar characteristics

The chemical properties of the rice husk biochar used in the study are presented in Table 2. The table revealed that the pH in water was alkaline (9.5) with a high organic carbon (C) content of 385 g kg^{-1}. The alkaline condition can affect nutrient availability, such as phosphorus (P), which may become less accessible in such environments (Li et al., 2023). Similarly, it suggests that the biochar has a significant amount of organic matter, which can influence nutrient cycling as organic matter can act as a source or sink for nutrients like phosphorus. The relatively low nitrogen (N) content of 0.53 g kg^{-1} compared to the high phosphorus content of 2334.5 mg kg^{-1} may indicate an imbalance in the N:P ratio, potentially leading to P being less available for plant uptake. The high amount of silica in the feedstock (rice husk) contributed to the alkaline pH and high (20.9%) ash content (Gamage et al., 2018). Also, the high P content (2334.5 mg kg^{-1}) can be attributed to the feedstock (Karam et al., 2022). The values for calcium, magnesium, potassium and sodium suggested that the biochar has a moderate to high cation exchange capacity (CEC). Hence, the biochar used in this study has a high phosphorus sorption evident from the high alkaline pH, high organic matter content and moderate to high CEC.

Table 2. Characteristics of the rice husk biochar used in the study

Parameter	**Value**
pH_{water}	9.5
Total carbon (g kg^{-1})	385.0
Total nitrogen (g kg^{-1})	0.53
Total phosphorus (mg kg^{-1})	2334.5
Total cations (g kg^{-1})	
Calcium	1.12
Magnesium	0.23
Potassium	0.72
Sodium	0.96
Ash content (%)	20.9

Effect of rice husk biochar on soil phosphorus sorption

Sustainable soil and crop production depend on maintaining a delicate balance between nutrient supply and minimizing losses through leaching.

Table 3. Phosphorus adsorption data for the treatments used in the study

C_i	EPC (C_e)	x/m (Q_e) mg L^{-1}	EPC/x/m	Log x/m	Log EPC
Treatment A					
0	0.17	-0.17	1.00	0.00	-0.76
5	0.51	4.48	0.11	0.65	-0.28
10	0.94	9.05	0.10	0.95	-0.02
15	1.43	13.56	0.11	1.13	0.15
20	1.64	18.36	0.08	1.26	0.21
Treatment B					
0	0.20	-0.20	1.00	0.00	-0.76
5	0.59	4.41	0.11	0.65	-0.28
10	1.13	8.88	0.10	0.95	-0.02
15	1.67	13.33	0.11	1.13	0.15
20	1.84	18.16	0.08	1.26	0.21
Treatment C					
0	0.20	-0.33	-1.00	1.0	-0.70
5	0.65	7.25	0.15	0.60	-0.19
10	1.16	14.74	0.13	0.95	0.06
15	1.71	22.15	0.13	1.12	0.23
20	1.68	30.54	1.09	1.26	0.22
Treatment D					
0	0.19	-0.19	-1.00	0.00	-0.72
5	0.73	4.27	0.10	0.60	-0.13
10	1.11	8.89	0.12	0.95	0.04
15	1.29	13.71	0.09	1.14	0.11
20	1.50	18.50	0.08	1.27	0.19
Treatment E					
0	0.43	-0.43	-1.00	0.00	-0.36
5	0.70	4.30	0.16	0.60	-0.16
10	0.70	9.30	0.07	0.97	-0.16
15	1.29	13.71	0.10	1.14	0.11
20	1.82	18.19	0.10	1.26	0.26

Legend: *Treatments and biochar inclusion level: A – control, B –10 t ha^{-1}, C – 20 t ha^{-1}, D – 30 t ha^{-1}, and E– 40 t ha^{-1}; ** Parameters: C_i = Initial P applied; EPC = Equilibrium P concentration; $(\frac{x}{m})$ = Quantity of P adsorbed; EPC/$(\frac{x}{m})$ is the equilibrium phosphorus (P) concentration to amount of P adsorbed.

This study examined the influence of rice husk biochar (RBH) on soil phosphorus (P) sorption using Langmuir and Freundlich equations. The experimental P data (Table 3) showed increased equilibrium P concentrations (EPC) with rising P-nutrient concentrations, except for treatment C (20 tons ha^{-1} RH inclusion level).

The Langmuir model (Table 4) revealed that adsorption maximum (b), the extreme amount of P that can be adsorbed per unit mass of RHB was highest at 10 tons ha^{-1} (24.39 mg kg^{-1}, (Treatment B), indicating optimal biochar application rates for P adsorption. The values of b (21.28mg kg^{-1}) at 20- and 40-tons ha^{-1} (Treatment C and E, respectively) are similar, suggesting that excessive biochar application does not enhance P adsorption while the lowest value (19.23 mg kg^{-1}) at the 0 (no inclusion of RHB) tons ha^{-1} (Treatment A) indicates that the control soil has a lower capacity for phosphorus adsorption compared to the RHB-amended soils. The findings of the study imply that without RHB, the soil's ability to retain P is reduced which may lead to increased P leaching or runoff. Consequently, the addition of RHB improved the soil's phosphorus adsorption capacity, as evident from the higher b values in the RHB-amended soils. Thus, suggests that RHB can play a crucial role in enhancing phosphorus retention in soils, which can have important implications for soil fertility and environmental sustainability (Karam et al., 2022).

The differences in phosphorus-adsorption maxima obtained in this study might be attributed to the relatively low organic matter in the soil at the 10-ton ha^{-1}, since organic matter would significantly reduce phosphate adsorption thereby improving its availability (Gonzalez-Rodriguez & Fernandez-Marcus, 2018). The soils exhibit the capacity for increasing phosphate adsorption owing to the increased pH due to the possibility of calcium-induced phosphate sorption because of the dominance of calcium in the solution and exchange sites even at pH below 5.0. Thus, the role of organic matter in anion adsorption was not evident at higher RHB levels due to the physical blocking of the adsorption sites on the mineral's surfaces, competition of the organic anions with the mono- and divalent forms of phosphate ions for sorption sites in the soil colloids and as well as iron and aluminum oxides. The results of the present study provide evidence of the role of organic matter in inhibiting phosphate adsorption in weathered soils (Agbenin, 2020).

The bonding energy, K_L, which represents the strength of the bond between P and RHB recorded the highest value (29.29) at the 0 (control) tons ha^{-1} inclusion level (Treatment A), indicating strongest bonding energy at this application rate. The values of K_L at the 10- and 30-tons ha^{-1} are relatively similar, suggestive of consistent bonding energy at lower and higher application rates, while the lowest value (20.86) obtained following 40 tons ha^{-1} may indicate weakened bonding due to over-saturation or aggregation of RHB particles. This means that the strength of P binding to soil particles decreases with RHB application (Yao et al., 2012). This further corroborates the submission on adsorption maxima above, that these soils with low available P and a corresponding high K_L had most of their reactive sites saturated with phosphates and orthophosphates ions. Furthermore, separation factor, RL, a dimensionless equilibrium parameter employed in explaining the essential features of Langmuir (Webber & Chakravarti, 1974) results obtained depict a favourable condition.

Table 4. Equilibrium parameters of Langmuir Adsorption isotherm

Parameter	**Treatment**				
	A	**B**	**C**	**D**	**E**
Square r	0.161	0.107	0.323	0.325	0.272
Adsorption maximum (b)	19.23	24.39	21.28	20.83	21.28
Bonding energy (K_L)	29.29	23.23	23.72	21.20	20.86
Buffering capacity (K_Lb)	563.2	566.7	504.8	441.5	443.8

Legend: *Treatments and biochar inclusion level: A – control, B –10 t ha^{-1}, C – 20 t ha^{-1}, D – 30 t ha^{-1}, and E– 40 t ha^{-1}; **Equations for each treatment – A: y = 0.034x + 0.052, B: y = 0.043x + 0.041, C: y = 0.04x + 0.047, D: y = 0.047x + 0.048, E: y = 0.048x + 0.047

The buffering capacity, K_Lb, which represents the ability of RHB to resist changes in phosphorus concentration, showed the highest values, 566.7 at the 10 and 0-tons ha^{-1}, indicative of optimal buffering capacity at this application rate. Similar value (563.2) was obtained at the 0 tons ha^{-1} application rate while the least value of 441.5 was obtained at the 30 tons ha attributable to over-saturation or aggregation of RHB particles. The trend of increasing buffering capacity with RHB application rates up to 10 tons ha^{-1}, followed by a decrease at higher rates, indicates that optimal RHB inclusion level can enhance phosphorus sorption and retention in soils, while excessive application rates may not provide additional benefits (Yao et al., 2017; Wang et al., 2018).

Data for the Freundlich model presented in Table 5 revealed that log K, an index of the adsorption capacity of RHB varied from 0.887 to 0.977, indicating varying capacities at different RHB application rates. However, the highest log K value (0.977) was obtained at the 20 tons ha^{-1} which implied optimal adsorption capacity at this application rate. On the other hand, the slope (1/n) which represents the adsorption intensity or heterogeneity of the adsorbent ranged between 1.250 – 1.844, also, indicating varying adsorption intensities. The highest slope value, 1.844, at the 10 tons ha^{-1} suggests the most favourable adsorption conditions among the studied application rates. Both indexes (log k and 1/n) are indicative that the sorption of phosphate following RHB application was unfavourable with a coefficient of determination (r^2) value of 0.994 approximately 1.0 (Goldberg, 2005).

The results indicate that RHB's sorption efficiency decreases at higher phospohorus concentrations, leading to reduced P retention. Also, saturation of sorption sites on the RHB may occur with increased concentration, further limiting phosphorus removal from the soil solution. Conversely, increased equilibrium concentrations may enhance desorption of previously sorbed phosphorus, potentially re-contaminating the soil. Sorption heterosis may occur, making phosphorus sorption and desorption processes not fully reversible and altering the RHB's P retention capacity since phosphorus removal and release by RHB is a concentration dependent phenomenon which affects its performance in the dynamic soil system. The soils exhibited increased phosphate adsorption capacity due to calcium-induced phosphate sorption, even at pH below 5.0. However, organic matter's role in anion adsorption was not evident at higher RH biochar levels due to physical blocking of adsorption sites and competition with phosphate ions.

The Freundlich model (Table 5) assumed heterogeneous adsorption surfaces and decreasing adsorption energy with increasing adsorbate concentration (Ayawei et al., 2017). Soils in the study area showed high phosphorus-sorption capacity, corroborating earlier findings of well-drained soils which were dominated by hydrous oxides of iron and aluminum, and possessed high phosphorus-sorption capacity (Fink et al., 2016). The Freundlich equation's slope (1/n) implied cooperative or multilayer adsorption, indicative of S-type isotherm with a corresponding n suggestive of an unfavourable sorption (Mohan & Karthikeyan, 1997). Although RHB has a high surface area and porosity, as well as various functional groups, the low surface reactivity, competition from other ions such as calcium and magnesium, steric hindrance and electrostatic repulsion could be attributable to the findings of this study. Thus, despite the better parameter fit obtained using the Freundlich model, the high K_f and 1/n values indicated that most P-nutrients were tied to soil colloidal surfaces, with few available to plants.

Although both models employed in this study predict adsorption behavior and optimize RHB application rates, the former model is the preferable option. Consequently, the Langmuir model would better explain phosphorus sorption-desorption in the alfisol used in the study because it assumes a homogenous adsorbent surface, monolayer adsorption, and saturation, which aligns with the dominant phosphorus sorption mechanism in alfisols. The homogeneous surface reflects uniform particle sizes and surface properties, while the maximum adsorption capacity estimated by the Langmuir parameter indicates that P sorption reaches its peak at higher concentrations. Additionally, the linear isotherm shape aligns well with the data. On the contrary, the Freundlich heterogenous adsorbent surface and multi-layer adsorption which might not accurately represent the relatively uniform alfisol surface and dominant phosphorus sorption mechanism did not accurately capture the relationship.

Table 5. Equilibrium parameters of Freundlich adsorption isotherm

Treatment	Intercept (Log K)	Slope (1/n)	R^2
A	0.934	1.362	0.97
B	0.914	1.844	0.81
C	0.977	1.255	0.99
D	0.894	1.250	0.99
E	0.887	1.282	0.98

Legend: Treatments and biochar inclusion level: A – control, B –10 t ha^{-1}, C – 20 t ha^{-1}, D – 30 t ha^{-1}, and E– 40 t ha^{-1};

CONCLUSIONS

This study investigated the adsorption characteristics of phosphorus in soils amended with varying levels of rice husk biochar using Langmuir and Freundlich isotherms. The results showed that phosphorus adsorption maximum, bonding energy, and equilibrium phosphorus concentration are crucial parameters for understanding phosphorus dynamics in soils treated with rice husk biochar. The application of rice husk biochar at 10 tons ha^{-1} resulted in the highest bonding energy and phosphorus adsorption maxima, leading to reduced phosphorus fixation and enhanced availability. This suggests that soils with high phosphorus adsorption maxima can supply sufficient phosphorus for crop growth at lower saturation levels. Although the Freundlich model, which assumes a heterogeneous adsorption surface and multilayer adsorption, did not provide the best fit to the data, it still described the adsorption process reasonably well at lower phosphorus concentrations. However, the Langmuir model's superior fit to the data implies that the soil had a finite number of adsorption sites with application of RHB which became saturated at higher phosphorus concentrations. The Langmuir model more accurately describes phosphate adsorption by RHB, indicating the formation of a monolayer adsorbate on the adsorbent's surface. Therefore, this study concludes that the Langmuir adsorption isotherm is the most suitable approach for fertilizer calculation and adsorption capacity assessment in the given soils and climate. Additionally, the model may serve as a complementary tool for estimating phosphorus (P) requirements for specific crops, pending further yield studies.

ACKNOWLEDGEMENTS

The authors appreciate the laboratory staff of the Department of Agronomy, Faculty of Agriculture, University of Ilorin for the assistance rendered during the laboratory work.

REFERENCES

Agbenin, J. O. (2020). *The environmental chemistry of soils and sediments: Principles and applications*. University Press Plc. Ibadan.

Al-Ghouti, M. A. & Da'ana, D. A. (2020). Guidelines for the use and interpretation of adsorption isotherm models: A review. *Journal of Hazardous Materials,* 393, 122383.

https://doi:10.1016/j.jhazmat.2020.122383

Ali, V. B., Veli, U., Siyami, K., Orhan, D. & Salih, A. (2008). Phosphorous Sorption in Some Great Soil Groups of Semi-Arid Region of Turkey. *International Journal of Soil Science, 3, 75-82.* https://doi:10.3923/ijss.2008.75.82

Amoah-Antwi, C., Kwiatkowska-Malina, J., Thornton, S. F., Fenton, O., Malina, G. & Szara, E. (2020). *Restoration of soil quality using biochar and brown coal waste: A review*. Published by Elsevier B.V. https://doi.org/10.1016/j.scitotenv.2020.137852

Anikwe, M. A. N. (2000). Amelioration of a heavy clay loam soil with rice husk dust and its effect on soil physical properties and maize yield. *Science direct- Bioresource Technology*, 74(2), 169 – 173. https://doi.org/10.1016/S0960-8524(00)00007-9

Ayawei, N., Ebelegi, N. A. and Wankasi, D. (2017). Modelling and Interpretation of Adsorption Isotherms *Hindawi Journal of Chemistry*, 3039817, 1-11, https://doi.org/10.1155/2017/3039817

Bortoluzzi, E. D., Perez, A. S. & Ardisson, J. D. (2015). Occurrence of iron and aluminum sesquioxides and their implications for the phosphorus sorption soils. *Applied Clay Science*,104, 196-204. https://doi.org/10.1016/j.clay.2014.11.032

Brady, N. C. & Weil, R. R. (2017). *Nature and properties of soil* 15th ed. New York: Pearson.

Das, S. K., Ghosh, G. K. & Avasthe, R. (2023). Application of biochar in agriculture and environment, and its safety issues. *Biomass Conversion and Biorefinery*, 13, 1359–1369. https://doi.org/10.1007/s13399-020-01013-4

Fink, J. R., Inda, A. V., Bavaresco, J., Barrón, V., Torrent, J & Bayer, C. (2016). Adsorption and desorption of phosphorus in subtropical soils as affected by management system and mineralogy *Soil and Tillage Research*, 155, 62-68 https://doi.org/10.1016/j.still.2015.07.017 (https://www.sciencedirect.com/science/article/pii/S0167198715001737)

Food and Agriculture Organisation, FAO (2000). *Land resources potential and constraints at region and country levels.* World Soil Resources Report 90, Rome.

Food and Agriculture Organisation, FAO (2017). *Soil Organic Carbon: the hidden potential*.

Food and Agriculture Organization of the United Nations, Rome.

Gamage, D. N. V., Mapa, R. B., Dharmakeerthi, R. S. & Biswas, A. (2016). Effect of rice husk biochar on selected soil properties in tropical alfisols. *Soil, land care and environmental research*, 54(3), 302-310. https://doi.org/10.1071/SR15102

Gérard, F. (2016). Clay minerals, iron/aluminum oxides and their contributions to phosphate sorption in soils – a myth revisited. *Geoderma*, 262, 213-226

Goldberg, S. (2005). Equations and Models Describing Adsorption Processes in Soils. *Soil Science Society of America*, Madison.

Gonzalez-Rodriguez & Fernandez-Marcos (2018). Phosphate sorption and desorption by two contrasting volcanic soils of equatorial Africa. *Peer Journal*, 6, e5820. https://doi.org/10.7717/peerj.5820

Graetz, D.A., & Nair, V.D. (2000). Phosphorus sorption isotherm determination. In *G.M. Pierzynski, editor, Methods of phosphorus analyses for soils, sediments, residuals, and waters*. Southern Coop. Ser. Bull. 396. SERA-IEG 17 Regional Publ. North Carolina State Univ., Raleigh., 35–38.

https://citeseerx.ist.psu.edu/document?repid=rep1&type=pdf&doi=c3713db4ecdc1f92ca2ea685ef940117bcfd27f2 (accessed 20 Dec. 2023)

Hazelton, P. & Murphy, B. (2007). *Interpreting soil test results: what do all the numbers mean?* 2nd ed. CSIRO Publishing, 169

Karam, D. S., Nagabovanalli, P., Rajoo, K. S., Ishak, C. F., Abdu, A., Rosli, Z., Muharam, F. M. & Zulperi, D. (2022). An overview on the preparation of rice husk biochar, factors affecting its properties, and its agriculture application. *Journal of Saudi Society of Agricultural Sciences*, 21 (3), 149-159. https://doi.org/10.1016/j.jssas.2021.07.005

Luo, D., Wang, L., Nan, H. Y. (2023). Phosphorus adsorption by functionalized biochar: a review. *Environmental chemistry letter*, 21, 497-524. https://doi.org/10.1007/s10311-022-01519-5

Minasny, B., Malone, B. P., McBratney, A. B., Angers, D. A., Arrouays, D., Chambers, A., … Winowiecki, L. (2017). Soil carbon 4 per mille. *Geoderma*, 292, 59–86. https://doi.org/10.1016/j.geoderma.2017.01.002

Mohan, S. & Karthikeyan, J. (1997). Removal of lignin and tannin colour from aqueous solution by adsorption onto activated charcoal. *Environ. Pollut*., 97, 183-187.

Moreira, A. & Fageria, N. K. (2009). Soil chemical attributes of Amazonas state, Brazil. *Communications in Soil Science and Plant Analysis*, 40, 2912-2925

Mulligan, J., Ellison, G., Levin, K, Lebling, K., Alex Rudee, A. & Leslie-Bole, H. (2017). *6 Ways to Remove Carbon Pollution from the Atmosphere*. World Resources Institute [online] https://www.wri.org/insights/6-ways-remove-carbon-pollution-sky

Murphy, J. & Riley, J. P. (1962). A modified single solution method for determination of phosphate in natural waters. *Analytica Chimica Acta*, 27, 31-36.

Schindelbeck, R., Moebiues-Clune, R. B. N., Moebiues-Clune, D. J., Kurtz, K. S., Ozturk, M., Binkerd-Dale, B., & Van Es, H. M. (2002). *Cornell University comprehensive assessment of soil health laboratory standard operating procedures*. Cornell University, Itjoaca, NY. https://soilhealth.cals.cornell.edu/resources/standard-operating.procedures-sops/

Swenson, H. & Stadie, N. P. (2019). Langmuir's theory of adsorption: a centennial review. *American Chemical Society*, 35(16), 5409-5426. https://doi.org/10.1021/acs.langmuir.9b00154

Tran, H. N., LLima, E. C., Juang, R., Bollinger, J. & Chao, H. Thermodynamic parameters of liquid-phase adsorption process calculated from different equilibrium constants related to adsorption isotherms: a comparison study. *Journal of Environmental Chemical Engineering* 2021; 9(6). https://doi.org/10.1016/j.jece.2021.106674

Wang, S., Kong, L., Long, J., Su, M., Diao, Z, Chang, X Chen, D., Song, G & Shih, K. (2018). Adsorption of phosphorus by calcium-flour biochar: isotherm, kinetic and transformation *Chemosphere*, 195, 666-672

Woolf, D., Amonette, J. E., Street-Perrott, F. A., Lehmann, J., & Joseph, S. (2010). Sustainable biochar to mitigate global climate change. *Nature Communications*, 1 (56), 1-9. https://doiorg/10.1038/ncomms1053

Yang, X., Chen, X. & Yang, X. (2019). Effect of organic matter on phosphorus adsorption and desorption in a black soil from Northeast China. *Soil and Tillage Research*, 187, 85-91.

https://doi.org/10.1016/j.still.2018.11.016

Yang, Y., Liu, S., Zhao, W. & Wang, L. (2019). Intrinsic relationship between Langmuir sorption volume and pressure for coal: Experimental and thermodynamic modeling study *Fuel*., 241, 105-117. https://doi:10.1016/j.fuel.2018.12.008

Yao,Y., Gao, B., Zhang, M., Inyangi, M., & Zimmerman, A. R. (2012). Effect of biochar amendment on sorption and leaching of nitrate, ammonium and phosphate in a sandy soil. *Chemosphere*, 89, 1467-1471. https://doi.org/10.1016/j.chemosphere.2012.06.002