SUMMARY

Background: Phosphorous is a limiting crop nutrient in highly weathered tropical soils due to fixation, and its availability for plants’ uptake is influenced by soil physico-chemical characteristics, land use type and management practices. **Objective:** To evaluate the relationship between selected physico-chemical properties and phosphorous sorption characteristics of a humic nitisol (Alfisol) from Tigoni, Kiambu County, central Kenya. **Methodology:** The soil was sampled from the same area with different land uses that include tea plantation, maize field and natural forest at 0-25, 25-50 and 50-75 cm depths. P solution at the rates of 50, 100, 150, 200 mg P L⁻¹ in a 24 h contact time were used in the study for maximum sorption. The data was analysed by simple regression and Pearson correlation analysis. **Results:** The adsorption data was fitted more to Langmuir model (R² = 0.9100-0.9994) compared to Freundlich (R² = 0.6815-0.9971). The values of P sorption maxima (Q_max) determined by Langmuir model ranged from 3,333-5,000 mg kg⁻¹ and bonding energies (k) ranged from 0.2308-1.5385 L mg⁻¹. The buffering capacity of soil ranged from 769-5000 L kg⁻¹ and the external P requirement at 0.2 mg kg⁻¹ (EPR(0.2)) ranged from 147-1176 mg P kg⁻¹ both increasing with soil depth. P sorption maxima were negatively and significantly correlated with organic carbon (r² = -0.700*) and Ca²⁺ (r² = -0.703*) contents. The pH of soil and clay content were negatively correlated with adsorption parameters (Q_max, k, K_f, EPR(0.2)) while Al content was positively correlated though none of them was statistically significant. **Implication:** The data revealed a highly P-sorbing soil particularly tea plantation, a situation that can be alleviated by management practices such as liming and enhancing soil organic matter content. Field experiments are however, recommended to validate the findings of this study. **Conclusion:** Land use type influences P-sorption capacity of soil hence, fertilizer recommendations should be based on soil physico-chemical characteristics besides crop nutrient requirements.

**Key words:** p-sorption; pH; land use; soil physico-chemical properties; humic nitisol.

RESUMEN

Antecedentes: El fósforo es un nutrienté limitante para los cultivos en suelos tropicales muy meteorizados debido a que la fijación, y su disponibilidad para la absorción por las plantas está influenciada por las características fisicoquímicas del suelo, el tipo de uso de la tierra y las prácticas de manejo. **Objetivo:** Evaluar la relación entre las propiedades fisicoquímicas seleccionadas y las características de sorción de fósforo de un nitisol húmico (Alfisol) de Tigoni, condado de Kiambu, Kenia central. **Metodología:** El suelo fue muestreado de la misma área con diferentes usos de suelo que incluyen plantación de té, campo de maíz y bosque natural a 0-25, 25-50 y 50-70 cm de profundidad. En el estudio se utilizó solución de P a razón de 50, 100, 150, 200 mg P L⁻¹ en un tiempo de contacto de 24 h para obtener la máxima sorción. Los datos fueron analizados por regresión simple y análisis de correlación.

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Kiplangat Rop¹, George N. Karuku² and Caroline W. Nduhiu²

¹Department of Chemistry, University of Nairobi, P.O. Box 30197-00100, Nairobi, Kenya, E-mail kiplangatrop@uonbi.ac.ke
²Department of Land Resource and Agricultural Technology, University of Nairobi, P.O. Box 29053-00625, Kangemi, Nairobi, Kenya

*Corresponding author
de Pearson. Resultados: Los datos de adsorción se ajustaron más al modelo de Langmuir (R² = 0.910-0.999) que al de Freundlich (R² = 0.681-0.997). Los valores máximos de sorción de P (Q_max) determinados por el modelo de Langmuir oscilaron entre 3.333 y 5.000 mg kg⁻¹ y las energías de enlace (k) oscilaron entre 0.2308 y 1.5385 L mg⁻¹. La capacidad amortiguadora del suelo osciló entre 769 y 5000 L kg⁻¹ y el requerimiento externo de P a 0.2 mg kg⁻¹ (EPR_((0.2))) osciló entre 147 y 1176 mg P kg⁻¹, ambos aumentando con la profundidad del suelo. Los máximos de sorción de P se correlacionaron negativamente y significativamente con los contenidos de carbono orgánico (r² = -0.70*) y Ca²⁺ (r² = -0.703*). El pH del suelo y el contenido de arcilla se correlacionaron negativamente con los parámetros de adsorción (Q_max,k,K_f,EPR_((0.2))) mientras que el contenido de Al se correlacionó positivamente aunque ninguno de ellos fue estadísticamente significativo. Implicaciones: Los datos revelaron un suelo altamente absorbente de P, particularmente plantaciones de té, una situación que puede aliviarse con prácticas de manejo como el encañado y la mejora del contenido de materia orgánica del suelo. Sin embargo, se recomiendan experimentos de campo para validar los hallazgos de este estudio. Conclusión: El tipo de uso de la tierra influye en la capacidad de adsorción de fósforo del suelo, por lo tanto, las recomendaciones de fertilizantes deben basarse en las características fisicoquímicas del suelo además de los requisitos de nutrientes de los cultivos.

Palabras clave: sorción de P; pH; uso del suelo; propiedades fisicoquímicas del suelo; nitisol húmico.

INTRODUCTION

The overall productivity and sustainability of agricultural sector are functions of fertile soils and therefore, the application of phosphorous (P) to the soil is essential for optimal crop yields. The limited availability of P is a major constraint in crop production particularly in highly weathered tropical soils such as the oxisols and ultisols (Moazed et al., 2010; Campos et al., 2016; Getie et al., 2021). This is attributed to low activity clays and inherent P content, high weathering incidence and soil reactions, and the situation could be aggravated by improper anthropogenic P management such as intensive cultivation without adequate supply of external P, among others (Moazed et al., 2010; Getie et al., 2021).

The initial growth stages of plants predominantly depend on P due to its role in cell division and root development and hence, retarded growth as deficiency symptom for P may be too late to salvage (Grant et al. 2001). It is estimated that > 80% of P applied to the soil is immobile and unavailable for plant uptake, a phenomenon ascribed to P adsorption/fixation (Muindi et al., 2014; Rop et al., 2018). The degree of P sorption and availability in soil vary from soil to soil due to differences in their physico-chemical properties and management (Moazed et al., 2010; Muindi et al 2014; Ayenew et al., 2018). Therefore, understanding P sorption characteristics is essential in the design of appropriate management strategies and prediction of fertilizer requirements for a particular soil (Ayenew et al., 2018) and crop(s). Physico-chemical properties that influence P sorption include soil texture, organic carbon, soil pH, porosity, clay content, Fe and Al contents, cation exchange capacity (CEC), exchangeable bases, hydraulic conductivity, among others (Moazed et al., 2011; Muindi et al., 2014; Sun et al., 2016). For instance, crop response to P application is often erratic in acidic soil due to formation of insoluble compounds with Al and Fe at low pH values particularly in Luvisols and Nitisols which are deep, well drained, and with high clay content (Getie et al., 2021). High affinity for P sorption in such highly weathered soils is attributed to the clay fraction that is dominated by 1:1 silicate mineral, and oxides, hydroxides and oxyhydroxides of Al, Fe, Mn (Campos et al., 2016). Land use type is also among the factors influencing P-sorption capacity of soil (Moazed et al., 2010).

Up to date, many workers have carried out extensive studies and proposed a number of techniques for evaluating P status in soil. Adsorption isotherm is an important criterion often used to estimate P content in aqueous phase of soil, energy of P sorption, maximum value of adsorbed P and buffer capacity (Muindi et al., 2014 & 2017). Sorption isotherm is a functional relationship that quantifies the amount of P adsorbed as a function of solution concentration in a dynamic equilibrium (Saki et al., 2019). It is explained by fitting P adsorption data into Linear, Langmuir, Freundlich, Tempkin models, among others (Muindi et al., 2014; Campos et al., 2016; Getie et al., 2021). These models are used to describe P sorption characteristics of soil as well as determination of external P requirement (EPR) for crops at equilibrium concentration of 0.2 mg L⁻¹ soil solution (Muindi et al., 2014; Getie et al., 2021).

Among the major challenges faced by farmers in Kiambu County are low crop yields due low available P content in soil attributed to fixation. It is therefore imperative to assess P adsorption behavior of such soil and establish P requirements for optimal crop yields. This study evaluated the influence of selected soil physico-chemical properties and land use type on P sorption characteristics. The data will help in the National and County government policy formulation, farmers and other stakeholders in the
agricultural sector to make informed decisions as regards P management strategies for improved yields.

MATERIAL AND METHODS

Description of the study site

The study was carried out on 9 soil samples collected from Kenya Agricultural & Livestock Research Organization (KALRO) station at Tigoni, 40 km North-West of Nairobi city center, Kenya. The site is located on the latitude 1°9′0″S and longitude 36° 41′0″ E as shown in Figure 1, with an elevation of 2131m above sea level (Jaetzold et al., 2006). The rainfall distribution is bi-modal with long rains from March - May and short rains from October - December. The mean annual rainfall is about 1096 mm and average monthly temperature is 18.0 °C with a minimum of 12°C and a maximum of 24 °C (Jaetzold et al., 2006). The soils are deep, well-drained, reddish-brown friable clays and are classified as humic Nitisol derived from quartz trachyte (Jaetzold et al., 2006; WRB, 2014). The soil pH range from 4.3 to 5.82 (Muthoni and Kabira, 2010). The crops grown in the area include tea, maize, potatoes, and horticultural crops.

Soil sampling and preparation for analysis

Soil sub-samples were collected from 9 sampling points in three different land use types including tea plantation, maize field and forest land (Fig. 1) at the depths of 0-25, 25-50 and 50-75 cm in a zigzag sampling scheme using a 600 cm³ soil auger. Sub-samples from the same depth in each of the land use type were placed in the same plastic bucket then homogenously mixed to make a composite sample (3 land use types × 3 depths = 9 composite samples). 1 kg of each of the composite samples were air-dried at room temperature and sieved to pass a 2 mm sieve. They were each divided into two portions; one portion was used in the determination of physico-chemical characteristics and the rest taken for adsorption experiments.

Determination of soil physico-chemical characteristics

The particle size distribution was determined by hydrometer method (Glendon and Doni, 2002) and soil pH measured in a 1:2.5 soil to water ratio using a pH meter (with glass electrodes). Organic carbon (%OC) was estimated by wet oxidation method (Nelson and Sommers, 1996). Cation exchange capacity (CEC) was determined by leaching the soil with 1 M NH₄OAc at pH 7 and the NH₄⁺ ions quantified in the leachate by steam distillation using micro-Kjeldahl method (Bremner, 1996). Exchangeable cations were extracted using 1 M NH₄OAc and the extract analyzed for Na⁺ by flame photometry, and Ca²⁺ and Mg²⁺ determined by atomic absorption spectrophotometer (AAS). Exchangeable Mn²⁺ and Fe²⁺ were extracted by Mehlich I method using a mixture of dilute acids that include 0.05 M HCl and 0.05 M H₂SO₄ (Mehlich, 1953) and analyzed by AAS. Exchangeable Al³⁺ was determined by extracting with KCl and titrating with NaOH (Yuan, 1959).

Phosphorous sorption experiment

The adsorption experiment was carried out according to Ayenew et al. (2018) and Saki et al. (2020) using KH₂PO₄ containing 0.1 M CaCl₂ solution. Specifically, 2 g of dry soil sample of particles size < 2mm was added 50 mL of KH₂PO₄ at rates of 50, 100, 150, 200 mg P L⁻¹ in 0.01 M CaCl₂ background solution. Each of these concentrations was replicated three times for each soil sample. Three drops of toluene were added to each flask to inhibit microbial activity after which, the flasks were placed in a mechanical shaker rotating at a speed of 180 rpm for 24 h. The supernatant was filtered through a Whatman No. 42 filter paper and P content in the filtrate determined by molybdate blue method (Murphy and Riley, 1962) using a Uv-Vis spectrophotometer (UV-1700, Shimadzu Corporation, Japan). The procedure was carried out alongside a blank which contained the same amount soil and same volume of 50 mL 0.01 CaCl₂ solution (without P) to serve as background control for detection of any contamination or interfering compounds. The amount of adsorbed P was calculated from the difference between the initial and equilibrium concentration of P solution according to Equ 1 (Sun, et al., 2015).

\[
Q_e = \frac{V(C_0 - C_e)}{W}
\]

where, \(Q_e\) is P adsorbed at equilibrium (mg kg⁻¹), \(C_0\) and \(C_e\) are the initial and equilibrium concentrations of P solution (mg L⁻¹), respectively.
Determination of adsorption parameters

The data obtained from P adsorption experiment was fitted to linear forms of Langmuir and Freundlich models.

The linear form of Langmuir model is given by Equ (2).

\[
\frac{C_e}{Q_e} = \frac{1}{kQ_{\text{max}}} + \frac{C_e}{Q_{\text{max}}} 
\]

(2)

where, \(Q_e\) is the adsorbed P at equilibrium (mg kg\(^{-1}\)), \(C_e\) is the concentration of P solution at equilibrium (mg L\(^{-1}\)), \(k\) is the affinity constant related to bonding energy of soil (L mg\(^{-1}\)) (Moazed et al., 2010; Campos et al., 2016; Ayenew et al., 2018). \(Q_{\text{max}}\) is the maximum adsorbed P (mg kg\(^{-1}\)) given by the reciprocal of the slope of the regression curve of \(C_e/Q_e\) verses \(C_e\). The product of Langmuir constants \(k\) and \(Q_{\text{max}}\) gives the buffering capacity of soil, a factor that measures the ability of soil to replenish P ions to the soil solution as they tend to get depleted.
RESULTS AND DISCUSSION

The selected physico-chemical characteristics of studied soil are presented in Table 1. The percentage organic carbon (% OC), cation exchange capacity (CEC) and exchangeable Ca, Mg, Na, Mn and Al all generally decreased with depth except Fe which showed increased content in maize field soil (M1-M3). Exchangeable Al content was the highest in tea plantation soil (T1-T3; 1.28-1.86 cmol kg⁻¹) compared to forest (F1-F3) and maize field (M1-M3), an observation that could be related to the effect of other soil physico-chemical properties including the pH, OC content and CEC. According to Landon (1991), exchangeable Al content > 2 cmol kg⁻¹ is considered excess for many crops though there are no acceptable critical levels. CEC was < 15 cmol kg⁻¹ hence considered low. The % OC content ranged from moderate to high with average and good structural conditions and stabilities, respectively (Landon 1991). The variation in the % OC content may be attributed to management practices such as soil pH, tillage practices, residue management, among others. Basic cations including Na⁺ were low, Ca²⁺ and Mg²⁺ ranged from low to moderate levels hence the varied soil reaction.

The pH values of soil ranged from strong to moderate acidity (Landon 1991), indicating presence of considerable quantities of H⁺, Al³⁺, Fe³⁺, Mn⁴⁺ ions. The soil acidity was attributed to humid conditions in the studied site that causes leaching of basic cations such as Na⁺, Ca²⁺, Mg²⁺ and K⁺. Soil pH showed a decrease with depth in the forest soil whereas an increase was observed in both tea plantation (T1-T3) and maize field (M1-M3) soil. Tea plantation soils recorded the lowest pH value in the surface horizon (0-25 cm) probably due to higher Al content, low base saturation and relatively lower % OC content that create buffering capacity compared to those of forest and maize field. Soil organic matter plays a vital role in enhancing the buffering capacity of soil reducing the strength of P sorption (Yang et al., 2019). Li et al. (2016) assessing possible cause soil acidity in tea plantations using soil column experiments observed downward movement of H⁺, NH₄-N and OC, and the organic matter enhanced top soil pH but not > 80 cm depth. These authors also noted excretion of more H⁺ to the rhizosphere by tea plants at higher planting density relative to those at lower planting density. Wan et al (2018) associates soil acidification in tea plantations with Al enhanced plasma membrane H⁺-ATPase activity and excess cation uptake. The low pH values in tea plantation soil was also linked to lower Ca and Mg contents relative to those of forest and maize field. Ca²⁺ and Mg²⁺ ions are bases that have the effect of neutralizing the acidity of soil (Rop...
et al., 2018). The soil texture was predominantly clayey with some slight variation in clay content which may be attributed to the intensity of cultivation and land use history.

The amounts of P adsorbed at equilibrium ($Q_e$) with increased initial solution concentration ($C_o$) of KH$_2$PO$_4$ ranging from 50-200 mg L$^{-1}$ are shown in Table 2. $Q_e$ values of soil at similar depths were comparable at $C_o$ of 50 mg L$^{-1}$ which thereafter recorded significantly ($p \leq 0.05$) higher values at $C_o$ of 100 mg L$^{-1}$ and 150 mg L$^{-1}$ in the soil samples from tea plantation (T1-T3) relative to those of forest and maize field. Statistically significant $Q_e$ values were recorded down the profile in nearly all the sites at $C_o$ of 100 and 150 mg L$^{-1}$ which could probably be due to optimal activity of sorption sites of the studied soil type at these concentrations. The general increase in $Q_e$ values with depth was attributed to the decrease in % OC, basic cations (Ca$^{2+}$, Mg$^{2+}$, K$^+$) content and the pH down the profile causing enhanced P sorption capacity (Table 1).

The values of Langmuir affinity constant ($k$), P sorption maxima ($Q_{max}$), buffering capacity and external phosphate requirement at 0.2 mg L$^{-1}$ (EPR$_{0.2}$) are presented in Table 3. Adsorption data yielded high R$^2$ values ranging from 0.9100-0.9994 indicating good fit to the model. The $Q_{max}$ values were higher in tea plantation soil (T1-T2), lower horizon of forest (F2 & F3) and maize field soil (M3) all recording 5,000 mg kg$^{-1}$ relative to surface and sub-surface soil of F1, M1 & M2 which recorded 3,333 mg kg$^{-1}$. The high sorption values could be due

### Table 1. Selected physico-chemical characteristics of studied soil.

| Sample ID | Clay (%) | Silt (%) | Sand (%) | Textural class | OC (%) | pH | CEC (cmol kg$^{-1}$) | Ca (cmol kg$^{-1}$) | Mg (cmol kg$^{-1}$) | Na (cmol kg$^{-1}$) | Al$_{Ex}$ (cmol kg$^{-1}$) | Mn (mg kg$^{-1}$) | Fe (mg kg$^{-1}$) |
|-----------|----------|----------|----------|---------------|--------|----|---------------------|-------------------|-------------------|-------------------|-------------------------|----------------|-----------|
| F1        | 51       | 16       | 33       | CL            | 2.11   | 5.9| 8.4                 | 1.32              | 4.40              | 0.15              | 1.12                    | 195.4         | 120.1    |
| F2        | 49       | 12       | 39       | CL            | 2.00   | 5.4| 8.2                 | 1.12              | 2.89              | 0.14              | 0.87                    | 137.0         | 70.0     |
| F3        | 47       | 14       | 16       | CL            | 1.97   | 4.4| 7.6                 | 0.99              | 2.48              | 0.14              | 0.74                    | 98.2          | 38.9     |
| T1        | 47       | 14       | 16       | CL            | 1.93   | 4.6| 12.4                | 0.75              | 1.99              | 0.18              | 1.86                    | 197.9         | 101.4    |
| T2        | 47       | 10       | 14       | SCL           | 1.86   | 4.8| 10.6                | 0.50              | 1.38              | 0.15              | 1.56                    | 144.1         | 66.8     |
| T3        | 47       | 18       | 12       | SCL           | 1.58   | 4.9| 10.4                | 0.36              | 1.28              | 0.14              | 1.28                    | 89.7          | 40.8     |
| M1        | 47       | 16       | 33       | SCL           | 2.39   | 5.4| 11.0                | 1.72              | 2.52              | 0.19              | 0.66                    | 166.8         | 37.5     |
| M2        | 47       | 14       | 39       | CL            | 2.37   | 5.7| 10.4                | 1.66              | 2.28              | 0.18              | 0.53                    | 138.5         | 61.1     |
| M3        | 49       | 19       | 39       | CL            | 2.23   | 5.9| 10.2                | 1.51              | 2.10              | 0.17              | 0.43                    | 104.2         | 62.7     |

Note: The reported values are the averages (n=3)

Legend: F1 forest 0-25 cm, F2 forest 25-50 cm, F3 forest 50-75 cm; T1 tea 0-25 cm, T2 tea 25-50 cm, T3 tea 50-75 cm; M1 maize 0-25 cm, M2 maize 25-50 cm, M3 maize 50-75 cm. OC-organic carbon, CEC-cation exchange capacity, CL-clay, SCL-sandy clay

### Table 2. Amount of P adsorbed at equilibrium (mg kg$^{-1}$) with increased initial solution concentration of P (mg L$^{-1}$).

| Initial conc. of KH$_2$PO$_4$, Co (mg L$^{-1}$) | 50 | 100 | 150 | 200 |
|-----------------------------------------------|----|-----|-----|-----|
| Sample Id.                                    |    |     |     |     |
| F1                                            | 1240 (±1.7)ab | 2250 (±1.7)ab | 2900 (±10)b | 3765 (±106)abcd |
| F2                                            | 1243 (±2.0)b | 2250 (±4.7)ab | 3150 (±2.5)d | 4157 (±206)cd |
| F3                                            | 1245 (±2.0)b | 2375 (±4.2)d | 3525 (±6.1)f | 4289 (±83)c |
| T1                                            | 1238 (±1.2)ab | 2400 (±19.1)e | 3325 (±9.0)e | 3718 (±493)abc |
| T2                                            | 1238 (±3.0)ab | 2450 (±7.0)f | 3325 (±7.2)e | 3947 (±622)bcd |
| T3                                            | 1245 (±3.8)b | 2475 (±4.0)g | 3550 (±60.0) | 4352 (±20)d |
| M1                                            | 1233 (±3.5)a | 2225 (±5.6)ia | 2000 (±18.5)a | 3302 (±139)a |
| M2                                            | 1240 (±3.6)ab | 2275 (±5.7)c | 3025 (±9.0)c | 3560 (±185)ab |
| M3                                            | 1245 (±2.5)b | 2375 (±5.3)d | 3175 (±4.6)cd | 4118 (±146)bcd |

Note: The values in parentheses are standard deviations (n=3). Different letters in the same column are significantly different (Tukey test; $p \leq 0.05$ level).

Legend: F1 forest 0-25 cm, F2 forest 25-50 cm, F3 forest 50-75 cm; T1 tea 0-25 cm, T2 tea 25-50 cm, T3 tea 50-75 cm; M1 maize 0-25 cm, M2 maize 25-50 cm, M3 maize 50-75 cm.
The extent at which P sorption data fit the Langmuir model is denoted by the separation factor ($R_L$) and the external P requirements at concentration of 0.2 mg P L$^{-1}$ ($EPR_{0.2}$) (Table 3). Values range from 0.015 to 0.074 for $R_L$ and from 147 to 1176 mg kg$^{-1}$ for $EPR_{0.2}$. The highest sorption values were recorded in tea plantation soils compared to forest soils (F1). This indicates that tea plantation soils have higher P sorption capacity than forest soils.

The separation factor ($R_L$) for all the samples were within the range of 0 to 1 suggesting favorable P sorption particularly at lower initial concentration of P solution than at higher initial concentration. For instance, at $C_p = 50$ mg L$^{-1}$: $R_L = 0.074$ (F1), 0.063 (F2), 0.057 (F3), 0.029 (T1), 0.019 (T2), 0.013 (T3), 0.080 (M1), 0.074 (M2), 0.057 (M3). This was ascribed to the decreased surface affinity with increased concentration of P, a phenomenon accredited to saturation of high affinity sites and increased electrostatic barriers as negatively charged P ions bind onto the surface of soil (Saki et al., 2020).

The $EPR_{0.2}$ values increased with depth and the highest values were obtained in tea plantation soil (T1-T3; 588-1176 mg kg$^{-1}$) compared to lowest values recorded in surface soil from maize field (M1; 147 mg kg$^{-1}$) and forest (F1; 158mg kg$^{-1}$). According to Fox and Kamprath (1970), soil sorbing < 150 mg kg$^{-1}$ to meet an EPR value of 0.2 mg L$^{-1}$ are considered low P sorbing soils while those with sorbing amounts greater than this value are high P sorbing ones (Getie et al., 2021). This therefore implies that, the EPR values recorded in M1 indicate low P sorbing soil while the rest are high P sorbing. Muindi et al. (2017) evaluating soils from central Kenya highlands using Langmuir model obtained comparable sorption maxima of 3,333 mg kg$^{-1}$ and $EPR_{0.2}$ values ranging from 208-434 mg kg$^{-1}$ at 0-50 cm depth. They attributed high P sorption capacity to highly weathered soil and predominant gibbsite [Al(OH)$_3$] minerals having large surface area for P sorption. The current study however obtained a relatively higher value of 5,000 mg kg$^{-1}$ in tea plantation soil from 0-75 cm depth, lower horizons of forest soils at 25-75 cm depth and maize field at 50-75 cm depth. Similarly, Hartono et al. (2005) evaluating acidic soils of Indonesia observed increasing trend of $EPR_{0.2}$ with increased sorption maxima with soil depth. Kisinyo et al. (2013) studying soil at 0-20 cm depth using Langmuir model obtained higher P sorption capacity and lime requirements in the soils from East of Rift Valley (RV) compared to West of RV and attributed it to higher exchangeable Al and bonding energies between soil colloids and P ions.

Table 3. Langmuir adsorption parameters.

| Sample Id | Regression Equ. | $R^2$ | $Q_{max}$ (mg kg$^{-1}$) | $k$ (Lmg$^{-1}$) | Buffering capacity (L kg$^{-1}$) | $R_L$ | $EPR_{0.2}$ (mg kg$^{-1}$) |
|-----------|-----------------|-------|-------------------------|-----------------|---------------------------------|-------|---------------------------|
| F1        | $Y=0.0003x+0.012$ | 0.9565 | 3333                    | 0.2500          | 833                             | 0.020 | 0.074                     | 158          |
| F2        | $Y=0.0003x+0.010$ | 0.9590 | 5000                    | 0.3000          | 1500                            | 0.016 | 0.063                     | 281          |
| F3        | $Y=0.0002x+0.0006$ | 0.9815 | 5000                    | 0.3333          | 1667                            | 0.015 | 0.057                     | 312          |
| T1        | $Y=0.0002x+0.0003$ | 0.9904 | 5000                    | 0.6666          | 3333                            | 0.007 | 0.029                     | 588          |
| T2        | $Y=0.0002x+0.0002$ | 0.9994 | 5000                    | 1.0000          | 5000                            | 0.005 | 0.019                     | 833          |
| T3        | $Y=0.0002x+0.0013$ | 0.9506 | 5000                    | 1.5385          | 7693                            | 0.003 | 0.013                     | 1176         |
| M1        | $Y=0.0003x+0.0013$ | 0.9100 | 3333                    | 0.2308          | 769                             | 0.021 | 0.080                     | 147          |
| M2        | $Y=0.0003x+0.0012$ | 0.9807 | 3333                    | 0.2500          | 833                             | 0.020 | 0.074                     | 158          |
| M3        | $Y=0.0002x+0.0006$ | 0.9665 | 5000                    | 0.3333          | 1667                            | 0.015 | 0.057                     | 313          |

Legend: F1 forest 0-25 cm, F2 forest 25-50 cm, F3 forest 50-75 cm; T1 tea 0-25 cm, T2 tea 25-50 cm, T3 tea 50-75 cm; M1 maize 0-25 cm, M2 maize 25-50 cm, M3 maize 50-75 cm. $Q_{max}$ is the maximum adsorbed P, $k$ is the Langmuir constant, $R_L$ is the separation factor, $EPR_{0.2}$ is the external P requirements at concentration of 0.2 mg P L$^{-1}$. The electrostatic barriers as negatively charged P ions bind higher concentration of P to the soil material and increases soil capacity; implying higher P sorption than less weathered soils. This constant is a factor associated with bonding energy and it increases with tenacity of P sorption (Moazed et al., 2010; Wolde and Haile, 2015; Getie et al., 2021), implying more favorable P sorption conditions at the lower horizon than surface and sub-surface horizons of the studied soil. The tea plantation soil recorded the highest values of maximum buffering capacity ranging from 3,333-7,693 L kg$^{-1}$ (T1-T3) compared with those from forest (833-1,667 L kg$^{-1}$) and maize field (769-1,667 L kg$^{-1}$) and this increased with soil depth. It can be observed that, soil with higher exchangeable Al content (T1-T3) appears to exhibit greater buffering capacity implying higher P sorption than less buffered ones (Table 1). The higher values recorded in tea plantation soil (T1-T3; 588-1176 mg kg$^{-1}$) compared to lowest values recorded in surface soil from maize field (M1; 147 mg kg$^{-1}$) and forest (F1; 158mg kg$^{-1}$). According to Fox and Kamprath (1970), soil sorbing < 150 mg kg$^{-1}$ to meet an EPR value of 0.2 mg L$^{-1}$ are considered low P sorbing soils while those with sorbing amounts greater than this value are high P sorbing ones (Getie et al., 2021). This therefore implies that, the EPR values recorded in M1 indicate low P sorbing soil while the rest are high P sorbing. Muindi et al. (2017) evaluating soils from central Kenya highlands using Langmuir model obtained comparable sorption maxima of 3,333 mg kg$^{-1}$ and $EPR_{0.2}$ values ranging from 208-434 mg kg$^{-1}$ at 0-50 cm depth. They attributed high P sorption capacity to highly weathered soil and predominant gibbsite [Al(OH)$_3$] minerals having large surface area for P sorption. The current study however obtained a relatively higher value of 5,000 mg kg$^{-1}$ in tea plantation soil from 0-75 cm depth, lower horizons of forest soils at 25-75 cm depth and maize field at 50-75 cm depth. Similarly, Hartono et al. (2005) evaluating acidic soils of Indonesia observed increasing trend of $EPR_{0.2}$ with increased sorption maxima with soil depth. Kisinyo et al. (2013) studying soil at 0-20 cm depth using Langmuir model obtained higher P sorption capacity and lime requirements in the soils from East of Rift Valley (RV) compared to West of RV and attributed it to higher exchangeable Al and bonding energies between soil colloids and P ions.
properties and sorption sites. For example, sorption data of soil with homogeneous sites are better fitted to Langmuir than Freundlich model, while those having heterogeneous sites are best fitted to Freundlich model (Wolde and Haile, 2015). $K_f$ values ranged from 1310 to 1794 mg kg$^{-1}$ and were generally higher in tea plantation soil compared to the rest at similar depths. High $K_f$ values of soil are indicative of strong affinity of P towards the soil (Ayenew et al., 2018). The variation in $K_f$ values could be attributed to disparity in Al and Fe content as well as soil texture (Table 1). Based on Freundlich model, EPR at 0.2 mg L$^{-1}$ ranged from 942 (F1) to 1246 (M3) mg kg$^{-1}$ and generally increased with depth, and since these values are $> 150$ mg kg$^{-1}$, it is a clear indication of a high P sorbing soil.

The recommended P fertilizer application rates for small scale tea farmers is 600 kg NPK ha$^{-1}$ 25:5:5 (30 kg P ha$^{-1}$) (Wachira, 2012; Kamunya et al., 2019) equivalent to 15 mg P kg$^{-1}$ soil, and that of maize in Kiambu County is 250 kg DAP ha$^{-1}$ 23:23:0 (57.5 kg P ha$^{-1}$) (NAAIAP, 2014) equivalent to 28.75 mg P kg$^{-1}$ soil. These rates are far much lower than the estimated EPR$_{0.2}$ values of 147-1176 mg kg$^{-1}$ by Langmuir model (Table 3) and 942-1179 mg kg$^{-1}$ by Freundlich model (Table 4). For that reason, application of P fertilizer based on the above blanket recommendation may result in poor yields due to P deficiency to the crops grown. The current P content in the fertilizer formula particularly for tea is generally low and hence, it ought to be increased to enhance the amount being supplied to the crop from soil. The availability of P could also be enhanced by devising ways in which high sorption capacity of soil can be reduced.

The relationship between soil physico-chemical characteristics and P sorption parameters are presented in Table 5. Phosphorous sorption maxima ($Q_{max}$) were negatively but significantly correlated with OC ($r^2 = -0.700^{**}$) and Ca$^{2+}$ ($r^2 = -0.703^{**}$) contents. $k$ and EPR$_L$ values were also negatively but significantly correlated with OC ($r^2 = -0.852^{**}, -0.880^{**}$), Ca$^{2+}$ ($r^2 = -0.864^{**}, -0.902^{**}$) and Mg$^{2+}$ ($r^2 = -0.669^{*}, -0.721^{*}$) contents. The negative correlation between adsorbed P and organic matter was attributed to direct interaction between them which occurs when they compete for soil adsorption sites leading to decreased P sorption (Janardhanan and Daroub, 2010). Muindi et al. (2017) made a similar observation attributing the negative correlation between maximum adsorbed P and organic matter to occupation of adsorptive sites by organic anions thus reducing P sorption capacity of soil. The pH of soil showed a negative but significant ($p \leq 0.05$) correlation with $1/n$ ($r^2 = -0.868^{**}$) while, $K_f$ and EPRF values were negatively but significantly correlated with Mn$^{2+}$ contents ($r^2 = -0.811^{**}, -0.876^{**}$). The pH of soil and clay content were negatively correlated with adsorption parameters ($Q_{max}, k, K_f$, EPR$_L$) while Al content was positively correlated though none of them was statistically significant. The observation could be due to the same type of soil with similar mineral composition and slight variation in physico-chemical characteristics.

The correlations between soil physico-chemical properties and P sorption parameters down the soil profile (0-75 cm) at each sampling site are presented in Table 6. Forest soil showed a negative but significant correlation between (i) $Q_{max}$ and Na content, (ii) $k$ and Ca, Al, Mn & Fe contents (iii) $K_f$ and Ca, Al & Mn contents, (iv) $1/n$ and CEC, (v) EPR$_L$ and % OC & Mg contents. A negative and significant correlation was observed in tea plantation soil between (i) $K_f$ and Al & Mn contents, and (ii)

### Table 4. Freundlich adsorption parameters.

| Sample Id | Regression Equ. | R$^2$  | $K_f$(mg kg$^{-1}$) | EPR$_{0.2}$(mg kg$^{-1}$) |
|-----------|----------------|--------|---------------------|---------------------------|
| F1        | $Y=0.2051x+7.1778$ | 0.6815  | 1310                | 942                       |
| F2        | $Y=0.2180x+7.3774$ | 0.9463  | 1599                | 1126                      |
| F3        | $Y=0.2626x+7.4668$ | 0.9552  | 1749                | 1146                      |
| T1        | $Y=0.2611x+7.3482$ | 0.9813  | 1553                | 1020                      |
| T2        | $Y=0.2578x+7.4193$ | 0.9335  | 1668                | 1101                      |
| T3        | $Y=0.2605x+7.4922$ | 0.9775  | 1794                | 1179                      |
| M1        | $Y=0.1870x+7.1823$ | 0.8599  | 1316                | 974                       |
| M2        | $Y=0.2128x+7.2974$ | 0.9971  | 1476                | 1048                      |
| M3        | $Y=0.2105x+7.4767$ | 0.9774  | 1766                | 1246                      |

**Legend:** F1 forest 0-25 cm, F2 forest 25-50 cm, F3 forest 50-75 cm; T1 tea 0-25 cm, T2 tea 25-50 cm, T3 tea 50-75 cm; M1 maize 0-25 cm, M2 maize 25-50 cm, M3 maize 50-75 cm, $K_f$ is the proportionality constant for Freundlich model, EPR$_{0.2}$ is the external P requirements at concentration of 0.2 mg P L$^{-1}$. 
Table 5. Correlation between soil physico-chemical properties and P sorption characteristics.

| Sorption parameter | % Clay | % OC | pH | CEC | Ca | Mg | Na | Al | Mn | Fe |
|--------------------|--------|------|----|-----|----|----|----|----|----|----|
| $Q_{max}$          | -0.229 | -0.700* | -0.590 | -0.011 | -0.703* | -0.567 | -0.500 | 0.363 | -0.481 | -0.167 |
| $k$                | -0.398 | -0.852** | -0.489 | 0.343 | -0.864** | -0.687* | -0.379 | 0.601 | -0.335 | -0.200 |
| $K_f$              | -0.318 | -0.615 | -0.455 | -0.089 | -0.583 | -0.669* | -0.506 | 0.055 | -0.811** | -0.431 |
| $1/n$              | -0.477 | -0.831** | -0.868** | 0.088 | -0.891** | -0.569 | -0.483 | 0.654 | -0.290 | -0.080 |
| $E_{PRL}$          | -0.411 | -0.880** | -0.546 | 0.341 | -0.902** | -0.721* | -0.399 | 0.632 | -0.347 | -0.189 |
| $EPRF$             | -0.159 | -0.368 | -0.144 | -0.157 | -0.299 | -0.563 | -0.404 | -0.248 | -0.876** | -0.493 |

* Correlation is significant at the 0.05 level (2-tailed).
** Correlation is significant at the 0.01 level (2-tailed).

Legend: $Q_{max}$ is the maximum adsorbed P, $k$ is the Langmuir constant, $K_f$ is the proportionality constant for Freundlich model, $n$ is the empirical constant related to binding energy, $E_{PRL}$ is the external P requirement determined by Langmuir model, $EPRF$ is the external P requirement determined by Freundlich model, OC-organic carbon, CEC-cation exchange capacity.

Table 6. Correlation between soil physico-chemical properties and P sorption parameters down the soil profile (0-75 cm).

| Land use         | Sorption parameter | Clay content | % OC | pH | CEC | Ca | Mg | Na | Al | Mn | Fe |
|------------------|--------------------|--------------|------|----|-----|----|----|----|----|----|----|
| Forest land      | $Q_{max}$          | -0.866       | -0.756 | -0.693 | -0.92 | -0.979 | -1.000** | -0.942 | -0.918 | -0.925 |
|                  | $k$                | -0.993       | -0.979 | -0.954 | -0.923 | -1.000** | -0.979 | -0.918 | -0.998* | -1.000** | -1.000* |
|                  | $K_f$              | -0.984       | -0.991 | -0.932 | -0.895 | -0.998* | -0.99 | -0.942 | -1.000** | -0.998* | -0.999* |
|                  | $1/n$              | -0.953       | -0.81 | -0.993 | -1.000* | -0.909 | -0.809 | -0.674 | -0.883 | -0.911 | -0.904 |
|                  | $E_{PRL}$          | -0.945       | -1.000** | -0.867 | -0.818 | -0.978 | -1.000** | -0.982 | -0.989 | -0.977 | -0.98 |
| Tea plantation   | $k$                | -0.98       | 0.948 | -0.843 | -0.956 | -0.864 | -0.915 | -0.988 | -0.991 | -0.977 |
|                  | $K_f$              | -0.953       | 0.977 | -0.896 | -0.982 | -0.913 | -0.953 | -0.999* | -1.000* | -0.994 |
|                  | $1/n$              | -0.161       | -0.354 | 0.568 | 0.327 | 0.535 | 0.437 | 0.19 | 0.168 | 0.251 |
|                  | $E_{PRL}$          | -0.972       | 0.959 | -0.864 | -0.967 | -0.883 | -0.93 | -0.993 | -0.996 | -0.984 |
|                  | $EPRF$             | -0.941       | 0.984 | -0.912 | -0.989 | -0.928 | -0.964 | -1.000** | -1.000** | -1.000** |
| Maize field      | $Q_{max}$          | 1.000**       | 0.803 | -0.693 | -0.961 | -0.822 | -0.866 | -0.826 | -0.892 | 0.548 |
|                  | $k$                | 0.984       | -0.998* | 0.895 | -0.809 | -0.995 | -0.909 | -0.941 | -0.912 | -0.958 | 0.687 |
|                  | $K_f$              | 0.936       | -0.971 | 0.961 | -0.902 | -0.997* | -0.97 | -0.986 | -0.974 | -0.999 | 0.807 |
|                  | $1/n$              | 0.5         | -0.596 | -0.918 | -0.971 | -0.721 | -0.904 | -0.866 | -0.901 | -0.837 | 0.988* |
|                  | $E_{PRL}$          | 0.998*       | -0.98* | 0.837 | -0.735 | -0.976 | -0.854 | -0.894 | -0.838 | -0.918 | 0.959 |
|                  | $EPRF$             | 0.965       | -0.989 | 0.931 | -0.859 | -1.000** | -0.943 | -0.967 | -0.945 | -0.98 | 0.749 |

** Correlation is significant at the 0.01 level (2-tailed).
* Correlation is significant at the 0.05 level (2-tailed).

Legend: $Q_{max}$ is the maximum adsorbed P, $k$ is the Langmuir constant, $K_f$ is the proportionality constant for Freundlich model, $n$ is the empirical constant related to binding energy, $E_{PRL}$ is the external P requirement determined by Langmuir model, $EPRF$ is the external P requirement determined by Freundlich model, OC-organic carbon, CEC-cation exchange capacity.

$EPRF$ and Al, Mn & Fe contents. $Q_{max}$, $E_{PRL}$ positively and significantly correlated with clay content in the maize field soil, whereas a negative and significant correlation was observed between (i) $k$ and % OC, (ii) $K_f$ and Ca content, (iii) $1/n$ and Fe content (iv) $E_{PRL}$ and % OC, and (v) $EPRF$ & Ca content. The negative correlation between sorption parameters and the % OC, Na, Ca, Mg, Al, Mn & Fe is due to decreased contents with depth (Table 1).

CONCLUSIONS

The sorption data better fitted to Langmuir model than Freundlich model. Soil samples from tea plantation had higher capacity to adsorb P compared to those of maize field and forest, suggesting that the type of land use influences P sorption capacity of soil. The $EPRF(0.2)$ values were generally $> 150$ mg kg$^{-1}$ an indication of highly P sorbing soil and hence the need to carry out field experiments to validate the findings of this study. Sorption parameters ($Q_{max}, k, K_f$ and $EPRF$ values) were influenced by OC and cations contents including Ca$^{2+}$, Mg$^{2+}$ and Mn$^{2+}$ while influence by soil pH, clay and Al contents were not statistically significant. The study recommends use of P management strategies such as application of lime and increasing soil organic matter content. The number of soil samples (n=9) and high specific surface area of soil used in the sorption experiments may however limit the findings of this study and therefore, field experiments covering most part of central Kenya highlands are recommended.
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