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Evaluation of phosphorus sorption characteristics of soils from the Bambouto sequence (West Cameroon)

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ABSTRACT

The evaluation of phosphorus sorption characteristics of soils and their relation to soil properties from the Bambouto sequence of Baranka 1, Baranka 2, Femock 1 and Femock 2 has been studied. Phosphorus, an essential plant nutrient, is often not readily available to plants and this deficiency tends to limit plant growth. It is thus, necessary to investigate the quantity that is readily available to plants in order to avoid excesses and reduce water pollution by fertilizers. The Freundlich, Langmuir, Temkin, Van Huay and Linear adsorption isotherms were used to describe the P adsorption processes. Phosphorus adsorption capacity decreased in the order Femock 2 > Femock 1 > Baranka 2 > Baranka 1 with maximum adsorption values of 3464.21, 3112.17, 2866.00 and 2758.38 mg kg^{-1} respectively. Accuracy of fitness of data of the four soil series into the adsorption equations increased in the order Langmuir, Linear, Van Huay, Temkin and Freundlich isotherm. The capacity of each soil sample to adsorb phosphorus was significantly correlated with the clay content (r = 0.949*) of the soils. The use of organic materials and liming as a basis for phosphorus sorption reduction will be useful for crop production in the Bambouto sequence.

Keywords: Phosphorus fixation, volcanic soil, free aluminium, clay, soil pH.

INTRODUCTION

Soils derived from volcanic ash are characterized by unique physical and chemical properties, such as high stabilization of organic matter, high water-holding capacity, low bulk density and high phosphorus (P) retention. They are among the most productive soils in the world, the main constraint for plant growth being usually low P availability (Ugolini and Dahlgren, 2002; Satti et al., 2007). High P retention in these soils is attributed to active Al and Fe associated with organic (mainly Al-humus complexes) and mineral fractions (allophanes and ferrihydrite), which form in the course of soil development. The formation of non-crystalline materials and accumulation of organic matter are the dominant pedogenic processes in soils derived from volcanic

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materials, and are known as “andosolization” (Ugolini and Dahlgren, 2002).

In tropical and subtropical acidic soils, low P availability is a factor that limits plant growth (Tsado et al., 2012; Muindi et al., 2015). When soil phosphate levels are too low, phosphorus deficiency in plants represents a major constraint to world agricultural production (Palomo et al., 2006). Phosphorus is an essential mineral nutrient required for plant growth because it is a major component of important molecules (Fankem et al., 2015).The fate and efficiency of native and applied phosphorus therefore remain one of the biggest problems in arable crop production in the tropics. One problem is that fertilizer P can largely be fixed by oxides, hydroxides and oxyhydroxides of Fe and Al and clay minerals in acidic soils, which makes it less available or effectively unavailable to plants (Shen et al., 2001; Idris and Ahmed, 2012; Yaser and Rahim, 2013). This is because the availability of both applied and native phosphorus is largely controlled by sorption and desorption characteristics of the soil. Declining soil fertility has greatly reduced food production in sub-saharan Africa (Koura et al., 2015). Variable charge minerals are also major components of most soils in the tropics that make phosphorus unavailable to plants. Njoyim et al. (2016) stated that P deficiency in plants constitutes the first most important soil fertility problem throughout the world.

Many researchers have studied and proposed diverse techniques for evaluation of phosphorus status in soils. Application of isotherms for phosphorus fixation by soil is among the techniques proposed in recent years for analyzing phosphorus status in soil. Using this method, the following parameters can be estimated: phosphorus concentration in the aqueous phase of soil, energy of phosphorus concentration variations in solution and maximal value of its adsorption by soil, buffer strength of soil against phosphorus concentration variations in solution, and equilibrium states between phosphorus in aqueous and solid phases and their relationships (Onweremadu, 2007).

Phosphorus adsorption isotherms can also help in making phosphorus fertilizers recommendations. Several researchers during early studies in this field realized that adsorption isotherms could be used in various soils for predicting the amount of fertilizer requirements for crops provided that the required amount of soluble phosphorus in plants was specified. The concentration of this nutritional element in soil solution is closely linked to adsorption processes through soil constituents such as clay minerals, oxides, iron and aluminum hydroxides, calcium carbonate, and organic matter. Adsorption is usually characterized by fitting of adsorption isotherms and their mathematical description using one or more adsorption equations (Liang et al., 2011).

The general objective of this study was to compare the P adsorptive capacity of four surface volcanic influenced soils of the Bambouto sequence and understand their P adsorption mechanism by applying chemical analytical and theoretical principles. Specifically, this study was aimed to evaluate the phosphorus adsorption isotherms of surface horizons (0-20 cm) of the volcanic influenced soils of the Bambouto sequence using five important equations which are: Freundlich, Langmuir, Temkin, Van Huay and Linear adsorption isotherms. Correlation relationships between P adsorbed and some important soil physico-chemical properties were also investigated and consequently recommendations on the soil management practices made in order to favour the availability of P to plants and to control water pollution.

MATERIALS AND METHODS

Description of the sampling site

Mount Bambouto is located in the Bamboutos division of the West Region of Cameroon. Bambouto sequence is one of the major volcanic mountains of the continental part of the Cameroon volcanic line, belonging to the West Cameroon Highlands. Bambouto reaches 2740 m at Mount Mélétan; the main slopes being the southern and eastern slopes. Soils considered in this area were typical Dystrandept soils and Oxic Dystrandept soils (Tematio et al., 2004). The field work was carried out in mid April 2014, with the study site having two distinct seasons (rainy and dry seasons). Four surface (0-20 cm) soil samples were collected from Baranka 1, Baranka 2, Femock 1 and Femock 2. In each site, a random sampling technique was used. The geographical coordinates of the study site obtained using a hand held Global Positioning System-GPS Garmin Etrex Vista C and the soil colour obtained using a Munsell Colour Chart, MI 49512 are shown in Table 1. Baranka 1 is located at about 150 m away from Government Bilingual Primary School Ntemndzeh-Mmouch-Leteh on the left along the road to Femock-Baranka centre. Baranka 2 has a kilometric point of 21300 m from Femock along the Femock-Baranka road. Femock 1 is about 2000 m from Femock junction on the left, along the Femock-Baranka road. This area was currently being cultivated for irish potatoes. Femock 2 is about 500 m from the Femock Civil State Centre and about 1500 m from Femock junction on the right along the Bafou-Femock road. The area was currently being cultivated for carrots.

Laboratory analysis

Freshly collected soil samples were air dried in the laboratory, ground in a porcelain mortar using a pestle and passed through a 2 mm sieve. The soil samples were then analysed for the various physico-chemical properties using standard methods (Pauwels et al., 1992) prior to sorption studies. All chemicals used in these analyses were of analytical grade.

The bulk density of the soils was determined over a soil volume of 100 cm^3 by oven drying the soil at 120 ^{o}C. Bulk density was calculated using the following formula:

Bulk density = mass of oven dry soil / volume of soil core……….................... (1)

Soil pH was measured in a 1:2.5 soil : solution ratio in 1N KCl (pH-KCl) and distilled water (pH-H_2O). Exchangeable acidity (H^+ and Al^{3+}) was determined by titration with NaOH after extraction with 1 N KCl in the soil – solution ratio of 1:20. Electrical conductivity (EC) was determined after extraction with distilled water in the ratio 1:5 with a conductimeter (WTW model). Exchangeable bases were determined by the method of Schollenberger by percolating 2.5 g of soil with 100 mL of 1N ammonium acetate, after which sodium and potassium ions were determined by flame photometry and calcium and magnesium ions estimated by complexometric titration. Cation exchange capacity (CEC) was estimated by percolating 2.5 g of soil with 100 mL of 1N ammonium acetate and then with 1N KCl. The collected NH_4^+ ions were then determined by distillation and titration with a 0.01 N sulphuric acid. Total nitrogen was estimated by exploiting the Kjeldahl's distillation method while soil organic carbon (SOC) was estimated by oxidation with potassium dichromate and titration with iron (II) sulphate (Walkley and Black, 1934). Available phosphorus was determined by Bray II method (Bray and Kurtz, 1945). Particle size distribution was determined by Robinson-Köhn pipette method. Amorphous Fe and Al were determined colorimetrically after their reduction with ammonium oxalate in the dark, whereas free Fe and Al were determined colorimetrically after their reduction with dithionate-citrate-bicarbonate (DCB).

Phosphorus adsorption studies

Phosphorus adsorption isotherms were determined following the procedure of Rao (1993). Aqueous solutions of 0, 1, 5, 10, 20, 40, 60 and 80 mg L^{-1} P were prepared from a mother solution of ammonium dihydrogenphosphate, $NH_4H_2PO_4$ containing 1000 mg L^{-1} P. One gram each of the air dried soil samples was accurately weighed into 100 mL centrifuge tubes and 50 mL of each of the prepared solutions were added to them and shaken for 24 hours at 25 ^oC on an end-to–end shaker (Edmund Buhler SM 25 model) at 125 oscillations per minute. The soil suspension was immediately filtered through a Whatman number 2 filter paper and centrifuged at 3000 rpm for 30 minutes with a model HRT 20MM Multifunctional Intelligent Centrifuge in order to get the clear solution. One millimetre extract of each of the samples and a blank was pipetted into test tubes, and 2.5 mL of a mixture containing ammonium molybdate and sulphuric acid, 2.5 mL of ascorbic acid and 10 mL of distilled water were then added successively and mixed. The test tubes were thereafter put in a water bath at 85 ^oC for 10 minutes for the development of the blue colour. The P concentration was determined by colorimetry at a wavelength of 665 nm. Each soil sample was analysed in duplicate. The quantity of P adsorbed by the soil (X) was calculated by the difference between the quantity of P initially present (C_o) and the quantity of P in the solution (C_e) after treatment using the following formula:

$$X = \frac{(C_o - C_e) * V}{m} \quad \text{……………………}2$$

Where:

V = volume of P solution used,

m = mass of soil sample

The P adsorption data obtained and presented in Table 3 were analyzed graphically by plotting P adsorbed as a function of equilibrium concentration to give non linear adsorption isotherms and using linear forms of Freundlich, Langmuir, Temkin, Van Huay and Linear isotherms to transform the data from where adsorption coefficients were calculated.

The linear forms of the various adsorption isotherms are defined thus:

Freundlich isotherm expresses the variation of an adsorbed quantity with equilibrium concentration (Sposito, 1984). Its linear equation is thus:

$$\log X = \frac{1}{n} \log C + \log K_f \quad \text{...............(3)}$$

Where:

X = amount of phosphorus adsorbed (mg kg^{-1})

n = constant whose value depends on the adsorbent (L kg^{-1}).

C = concentration of phosphorus in equilibrium solution (mg L^{-1}).

K_f = adsorption equilibrium constant related to the boundary energy at the surface (mg kg^{-1}).

Langmuir proposed his isotherm since 1918 to treat adsorption in gaseous phases and its linear equation for adsorption of solutes in solution is:

$$\frac{C}{X} = \frac{C}{X_m} + \frac{1}{K_L X_m} \quad \text{......................... (4)}$$

Where:

X = amount of phosphorus adsorbed (mg kg^{-1})

X_m = the maximum adsorption capacity (amount of adsorbate needed for a monolayer coverage) in mg kg^{-1}

K_L = constant related to the boundary energy of the soil at the surface (L mg^{-1})

C = concentration of phosphorus in equilibrium solution (mg L^{-1})

For the Temkin adsorption isotherm, the energy of adsorption is a linear function of the surface coverage (Travis and Etnier, 1981). The Temkin isotherm equation is:

$$X = a + b \ln C \quad \text{..........................(5)}$$

Where:

a = amount of P adsorbed of Temkin model (mg kg^{-1})

b = buffer capacity of Temkin model (mL g^{-1})

X = amount of P adsorbed (mg kg^{-1})

C = equilibrium solution concentration (mg L^{-1})

The Van Huay isotherm which relates the amount of solute adsorbed to the equilibrium concentration in the fluid phase is defined as:

$$\frac{X}{m} = m + n\sqrt{C} \quad \text{……......……… (6)}$$

Where:

X = amount of phosphorus adsorbed (mg kg^{-1})

C = concentration in fluid phase (mg L^{-1}),

n = Van Hauy adsorption coefficient (L kg^{-1}),

m = Van Hauy constant parameter.

In the simplest form of chromatographic theory, it is assumed that the adsorption isotherm for solutes is linear (Yaser and Rahim, 2013) and the linear equation is defined by:

$C_s = K * C_m$.................... (7)

Where

C_s = the concentration of the solute on the surface (mg kg^{-1}),

C_m = the concentration of the solute in the mobile phase (mg L^{-1}),

K = adsorption constant of the solute to the stationary phase surface (L kg^{-1}).

Statistical analysis

Correlation and regression analyses were performed to relate some soil physico-chemical properties to P sorption characteristics. Correlation and regression analyses were performed using SPSS Version 19 and Origin Version 6.0 software.

RESULTS

Some physico-chemical properties of the soils studied are presented in Table 2. Results showed that all the four soil samples were acidic with pH values ranging from 4.4 – 5.3. The exchangeable acidity ranged from 0.04 cmol kg^{-1} for Baranka 1 to 2.81 cmol kg^{-1} for Baranka 2. The soils had low bulk density values ranging from 0.53 to 0.68 g cm^{-3}, which is typical of volcanic soils. The electrical conductivities of the soils were generally low and the values were less than 1000 µS cm^{-1}. The organic matter content was found to be average (7.05 to 10.97%) for all the soil samples. The total nitrogen content was very low in all the soils (N<1%). The C/N ratio for most of the soils was high (8.27 to 28.41) indicating that the organic matter content was poorly mineralised. The available phosphorus in the soils was low (3.60 to 8.73 mg L^{-1}). Cation exchange capacity (CEC) was high (9.20 to 18.24 cmol kg^{-1}) for all the soil series. The sum of the exchangeable bases was low (1.22 to 6.58 cmol(+)kg^{-1}) for the soils. Results of particle size analysis showed that the soils were mostly clay in texture, with the sample of Femock 1 being silty-clay. The concentration of free and amorphous Al and Fe were low in most of the soils (0.00 to 12.80 mg/g soil) with that of free Al and Fe greater than amorphous Al and Fe.

The P adsorption isotherm graphs exhibited different curves (Figure 1). Phosphorus adsorption was observed to be very high at the beginning and this value increased with an increase in the concentration of added P with maximum adsorption values of 3464.21, 3112.17, 2866.00 and 2758.38 mg kg^{-1} recorded for Femock 2, Femock 1, Baranka 2 and Baranka 1, respectively as seen in Table 2.

The linear regression graph showing regression equations and coefficients of determination (R^2) for the Freundlich isotherms are presented in Figure 2. Freundlich parameters, that is, boundary energy of the soil at the surface (K_F), P sorption energy (n) and coefficients of determination (R^2) values computed from the data plotted on Figure 2 are shown in Table 4. The goodness of fit of the model was ascertained by looking at the R^2 values. All the plots were highly correlated with R^2 values > 0.95, indicating apparent high conformity of the adsorption data to the Freundlich model. For all the soils, the values of sorption capacity (K_F) ranged from 293.09 mg kg^{-1} for Baranka 1 to 502.34 mg kg^{-1} for Femock 2 and P sorption energy (n) ranged from 0.733 L kg^{-1} for Baranka 1 to 0.852 L kg^{-1} for Femock 2.

The linear regression graph showing regression equations and coefficients of determination (R^2) for the Langmuir isotherms are presented in Figure 3. Langmuir parameters, that is, boundary energy of the soil at the surface (K_L), maximum adsorption capacity (X_m) and coefficients of determination (R^2) values computed from the data plotted on Figure 3 are shown in Table 4. All the plots were not highly correlated with R^2 values ranging from 0.809 to 0.987, indicating a non apparent high conformity of the adsorption data to the Langmuir model.

Langmuir equation gave maximum adsorption values of 4154.55, 4271.68, 5387.93 and 8591.07 mg kg^{-1} soil for Baranka 1, Baranka 2, Femock 1 and Femock 2 respectively and the binding energy values ranged from 0.061 L mg^{-1} for Femock 2 to 0.084 L mg^{-1} for Baranka 2.

The linear regression graph showing regression equations and coefficients of determination (R^2) for the Temkin isotherms are presented in Figure 4. Temkin parameters, that is, P adsorbed of Temkin model (a), buffering capacity of Temkin model (b) and coefficients of determination (R^2) values computed from the data plotted on Figure 4 are shown in Table 4. All the plots were highly correlated with R^2 values ≥ 0.95, indicating apparent high conformity of the adsorption data to the Temkin model. The buffering capacity of Temkin model (b) varied from 739.39 mL g^{-1} for Baranka 2 to 1266.99 mL g^{-1} for Femock 2.

The linear regression graph showing regression equations and coefficients of determination (R^2) for the Van Huay isotherms are presented in Figure 5. Van Huay parameters, that is, Van Huay adsorption coefficient (n), Van Huay constant parameter (m) and coefficients of determination (R^2) values computed from the data plotted on Figure 5 are shown in Table 5. All the plots were highly correlated with R^2 values ≥ 0.92, indicating apparent high conformity of the adsorption data to the Van Huay model. The sorption coefficient (n) ranged from 608.84 L kg^{-1} for Baranka 1 to 1195.08 L kg^{-1} for Femock 2, showing that the higher the Van Huay sorption coefficient, the higher the amount of phosphorus adsorbed and vice versa.

The linear regression graph showing regression equations and coefficients of determination (R^2) for the Linear isotherms are presented in Figure 6. The Linear parameter, that is, the adsorption constant of the solute to the stationary phase surface (K) and the coefficients of determination (R^2) values computed from the data plotted on Figure 6 are shown in Table 5. All the plots were highly correlated with R^2 values ≥ 0.92, indicating apparent high conformity of the adsorption data to the Linear sorption isotherm. Values of the adsorption constant of the solute to the stationary phase surface ranged from 110.27 L kg^{-1} for Baranka 1 to 324.99 L kg^{-1} for Femock 2, showing its value increases with P adsorbed and vice versa.

Examining the accuracy of adsorption isotherms in predicting phosphorus adsorption showed that accuracy increased in the following order: single surface Langmuir isotherm, Linear isotherm, Van Huay isotherm, Temkin isotherm and Freundlich isotherm with coefficients of determination (R^2) values of 0.897, 0.959, 0.962, 0.975 and 0.977 respectively.

Simple linear correlation relationships (r) between soil phosphorus sorption parameters and some selected soil physico-chemical properties are shown in Table 6. Significant correlations were recorded between P adsorption parameters and some soil physico-chemical properties. Clay was shown to be significantly ($p < 0.05$) and positively correlated with P adsorbed. pH-KCl gave a significant ($p < 0.05$) positive correlation with the buffering capacity of Temkin model (b) and a significant ($p < 0.05$) negative correlation with the Langmuir boundary energy of the soil at the surface (K_L). Weak negative correlations ($p < 0.1$) were observed between the content of free aluminium and P adsorbed.

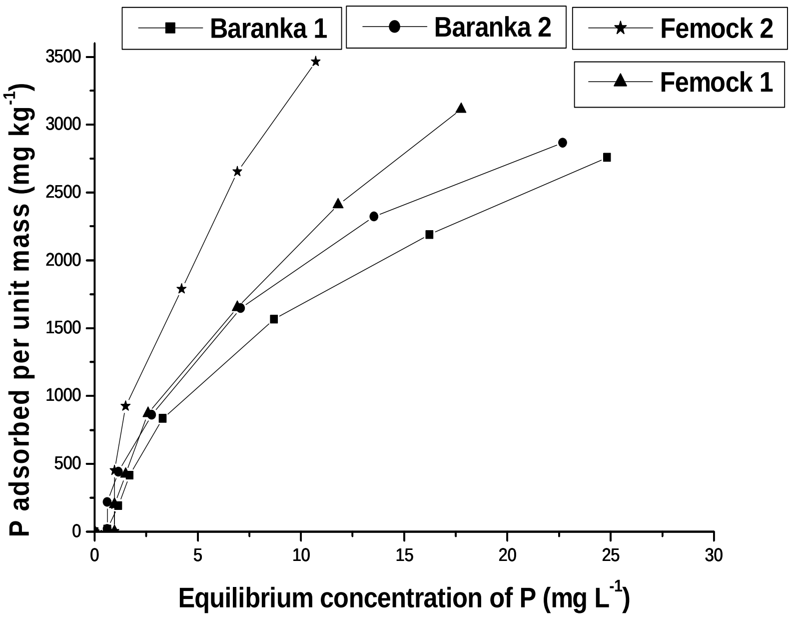

Figure 1: Phosphorus adsorption isotherms of the soils.

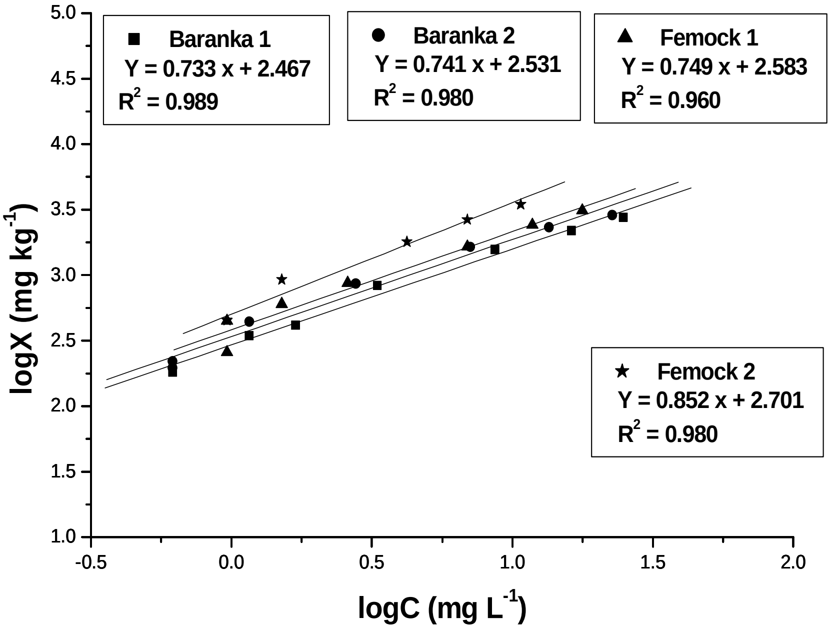

Figure 2: Linear Freundlich adsorption isotherms of the soils.

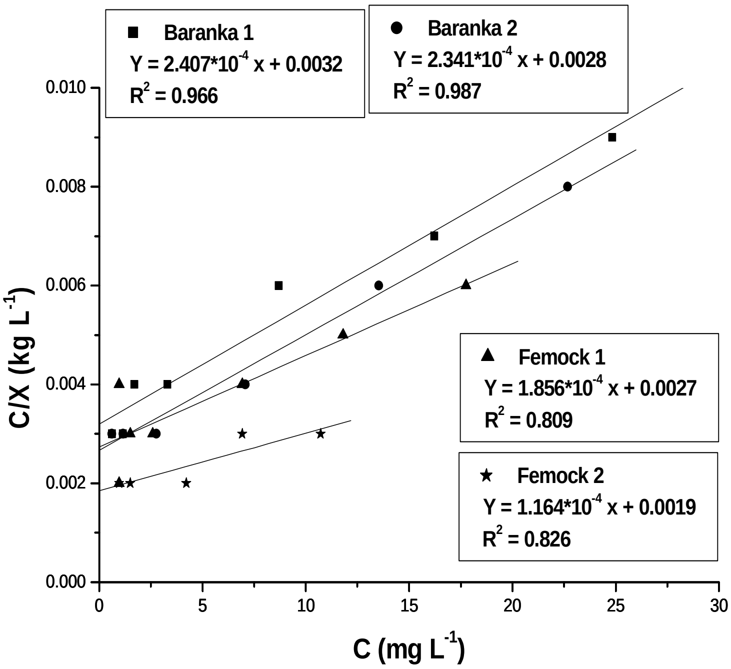

Figure 3: Linear Langmuir adsorption isotherms of the soils.

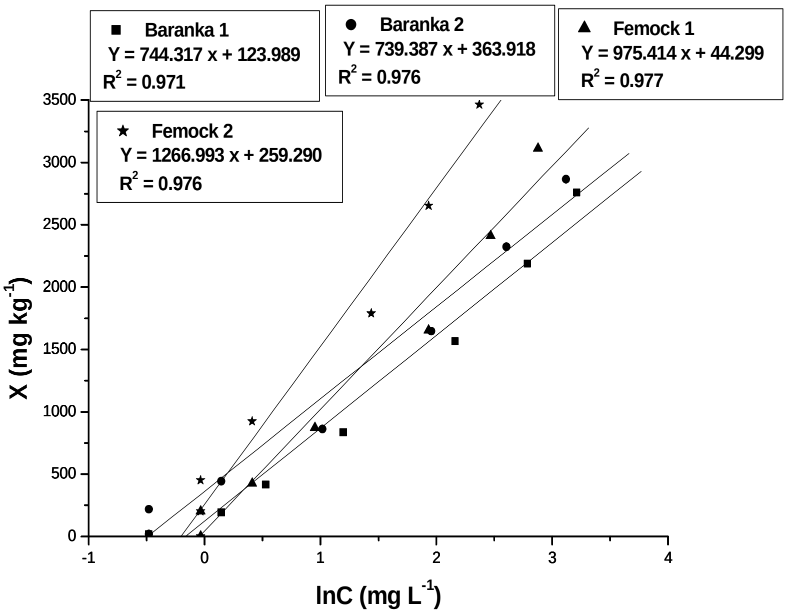

Figure 4: Linear Temkin adsorption isotherms of the soils.

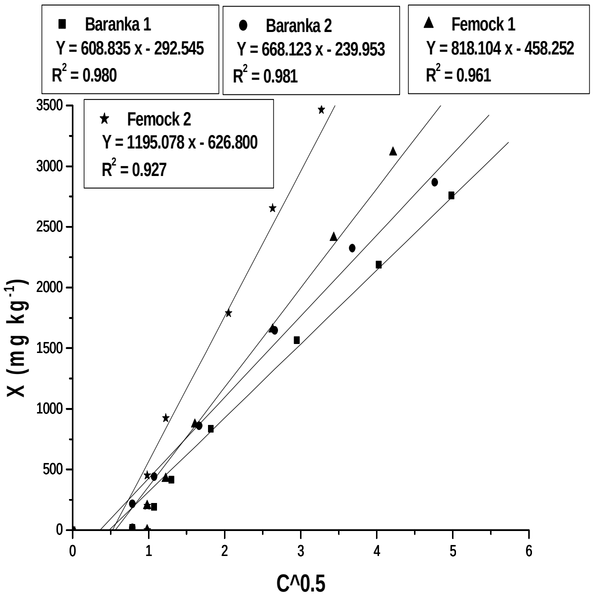

Figure 5: Linear Van Huay adsorption isotherms of the soils.

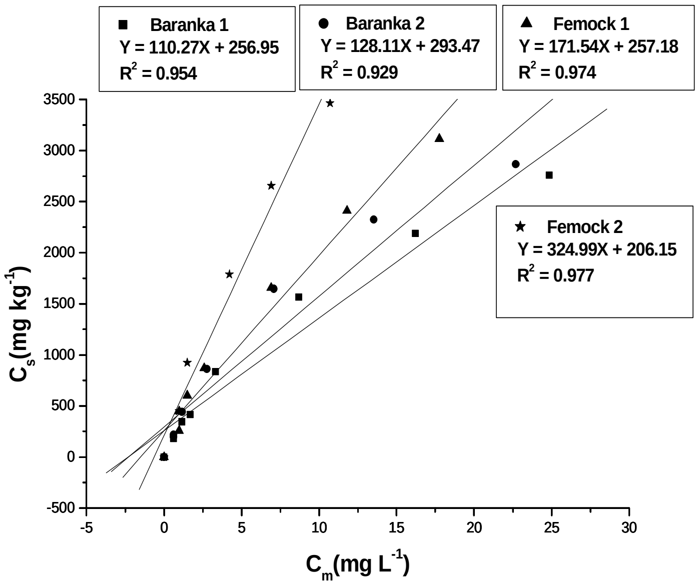

Figure 6: Linear adsorption isotherms of the soils.

Table 1: A description of the study site.

Parameter / Site	**Baranka 1**	**Baranka 2**	**Femock 1**	**Femock 2**
Slope (%)	5.2	9	3	4
Elevation above sea level (m)	2325	2334	2237	2023
Latitude	05^{0}37’25.1’’N	05^{0}36’47.5’’N	05^{0}35’43.4’’N	05^{0}35’28.1’’N
Longitude	010^{0}01’52.4’’E	010^{0}02’04.5’’E	010^{0}02’24.8’’E	010^{0}04’05.6’’E
Soil colour	5YR 3/1, very dark gray	2.5YR 3/2, dusky red	5YR 2.5/1, black	10R 2.5/1, reddish black

Table 2: Selected physico-chemical properties of the soils studied (n = 2).

Soil Series	**pH-H_2O**	**pH-KCl**	**δpH**	**ρ(g cm^{-3})**	**EA(cmol kg^{-1})**	**EC(µS cm^{-1})**	**% OC**	**% OM**	**% N**	**C/N**	**P (mg kg^{-1})**
Baranka 1	5.3	4.3	-1.0	0.65	0.04	70.0	4.66	8.03	0.18	25.35	5.52
Baranka 2	4.4	4.1	-0.3	0.56	2.81	160.0	4.09	7.05	0.19	22.04	3.60
Femock 1	4.8	4.4	-0.4	0.53	0.91	440.0	3.80	6.56	0.46	8.27	8.73
Femock 2	4.7	4.4	-0.3	0.68	0.76	220.0	6.36	10.97	0.22	28.41	3.60

Soil Series	**CEC(cmol kg^{-1})**	**Exchangeable Bases (cmol (+) kg^{-1})**				**S**	**Particle size (%)**			**Free and amorphous Al and Fe (mg g^{-1} soil)**			
		Ca	**Mg**	**Na**	**K**		**Sand**	**Silt**	**Clay**	**Al_f**	**Al_a**	**Fe_f**	**Fe_a**
Baranka 1	10.40	2.56	0.24	0.40	0.02	3.22	32	33	35	5.00	0.00	8.25	0.37
Baranka 2	9.20	1.20	0.72	0.40	0.02	2.34	22	35	42	5.00	0.00	12.80	0.37
Femock 1	18.24	3.44	2.72	0.40	0.02	6.58	17	49	33	2.50	0.00	3.70	1.28
Femock 2	13.20	0.56	0.24	0.40	0.02	1.22	21	20	59	2.50	0.00	8.25	0.82

δpH = net charge, ρ = Bulk density, EA = Exchangeable Acidity, EC = Electrical Conductivity, OC = Organic Carbon, OM = Organic Matter, N = Total Nitrogen, C/N = Mineralization factor, P = Available phosphorus, CEC = Cation Exchange Capacity, S = Sum of Exchangeable Bases, Al_f = Free Aluminium, Al_a = Amorphous Aluminium, Fe_f = Free Iron, Fe_a = Amorphous Iron.

Table 3: Phosphorus adsorption data for the soil series.

	Baranka 1		**Baranka 2**		**Femock 1**		**Femock 2**	
C_o (mg L^{-1})	**C_e (mg L^{-1})**	**P_{ad} (mg kg^{-1})**	**C_e (mg L^{-1})**	**P_{ad} (mg kg^{-1})**	**C_e (mg L^{-1})**	**P_{ad} (mg kg^{-1})**	**C_e (mg L^{-1})**	**P_{ad} (mg kg^{-1})**
0	0.0000	0.00	0.0000	0.00	0.0000	0.00	0.0000	0.00
1	0.6180	19.10	0.6180	19.10	0.9670	1.65	0.9670	1.65
5	1.1561	192.20	0.6180	219.10	0.9670	201.65	0.9670	201.65
10	1.6942	415.29	1.1561	442.20	1.5086	424.57	0.9670	451.65
20	3.3085	834.58	2.7704	861.48	2.5918	870.41	1.5086	924.57
40	8.6895	1565.53	7.0752	1646.24	6.9246	1653.77	4.2166	1789.17
60	16.2229	2188.86	13.5324	2323.38	11.799	2410.05	6.9246	2653.77
80	24.8325	2758.38	22.6801	2866.00	17.7566	3112.17	10.7158	3464.21

C_o = Phosphorus added, C_e = Phosphorus in equilibrium solution, P_{ad} = Phosphorus adsorbed

Table 4: Values of Freundlich, Langmuir and Temkin adsorption constants and coefficients of determination (R^2) of the soils.

Soil Series	**Freundlich**			**Langmuir**			**Temkin**		
	1/n	**K_F**	**R^2**	**X_m**	**K_L**	**R^2**	**b**	**a**	**R^2**
Baranka 1	0.733	293.09	0.989	4154.55	0.075	0.966	744.32	123.99	0.971
Baranka 2	0.741	339.63	0.980	4271.68	0.084	0.987	739.39	363.92	0.976
Femock 1	0.749	382.83	0.960	5387.93	0.069	0.809	975.41	44.30	0.977
Femock 2	0.852	502.34	0.980	8591.07	0.061	0.826	1266.99	259.29	0.976

Table 5: Values of Van Huay and Linear adsorption constants and coefficients of determination (R^2) of the soils.

Soil Series	**Van Huay**			**Linear**	
	n	**m**	**R^2**	**K**	**R^2**
Baranka 1	608.84	-292.55	0.980	110.27	0.954
Baranka 2	668.12	-239.95	0.981	128.11	0.929
Femock 1	818.10	-458.25	0.961	171.54	0.974
Femock 2	1195.08	-626.80	0.927	324.99	0.977

Table 6: Linear correlation (r) relationships between soil phosphorus sorption parameters and some selected soil properties of the soils (n = 5).

Soil property	**Freundlich**		**Langmuir**		**Temkin**	**Van Huay**	**Linear**
	1/n	**K_F**	**X_m**	**K_L**	**b**	**n**	**K**
pH-KCl	0.738NS	0.738NS	0.738NS	-0.949*	0.949*	0.738NS	0.738NS
Avail. P	-0.211NS	-0.211NS	-0.211NS	-0.211NS	0.105NS	-0.211NS	-0.211NS
Clay	0.975*	0.969*	0.985*	-0.690NS	0.904*	0.961*	0.970*
Al_f	-0.894^{o}	-0.894^{o}	-0.894^{o}	0.894^{o}	-0.894^{o}	-0.894^{o}	-0.894^{o}
Fe_a	0.738NS	0.738NS	0.738NS	-0.738NS	0.738NS	0.738NS	0.738NS

Avail. P = Available Phosphorus, Al_f = Free Aluminium, Fe_a = Amorphous Iron, * = Significant ($p < 0.05$), ° = Significant ($p < 0.01$), NS = Non-Significant.

DISCUSSION

When the soil is acidic, the availability of nitrogen, phosphorus, and potassium is reduced (Silva and Uchida, 2002). This is probably because at low pH values, oxides and hydroxides of iron and aluminium become soluble and tend to fix these nutrients. Soil pH can be increased by liming (the application of calcium carbonate or calcium hydroxide). When lime is added to a soil, active acidity is neutralized by chemical reactions that remove hydrogen ions from the soil solution. However, there are also acidic cations (H^+ and Al^{3+}) adsorbed on soil colloids which can be released into the soil solution to replace those neutralized by the lime. To effectively raise the pH of the soils studied, both active and exchangeable acidity must be neutralized. Exchangeable acidity, which is reported in units of cmol kg^{-1}, is directly related to the quantity of lime required to increase the pH from its current level to the target level determined by the selected crop (Spargo et al., 2013). The low bulk density values obtained could be the result of a combination of the amorphous volcanic material and organic matter, which results in light fluffy soils that are easily tilled, and have a high water-holding capacity (Yerima and Van Ranst, 2005). Tematio et al. (2004) had similar values of bulk density (0.54 to 0.90 g cm^{-3}) on the soils of mount Bambouto. Low values of electrical conductivities show that the soils are suitable for crop production in terms of EC as shown by Horneck et al. (2011) who reported that soils with EC values less than 1000 µS cm^{-1} are suitable for crop production.

Phosphorus soil tests are an index of P availability (low, medium, high, excess). The phosphorus application rate necessary to correct P deficiencies varies depending on soil properties and the crop grown. In many situations, banded phosphorus applications are more effective than broadcast applications, especially when P soil test values are low as in the soil studied. Cation Exchange Capacity can range from below 5 cmol kg^{-1} in sandy, low organic matter soils to over 15 cmol kg^{-1} in finer textured soils and those high in organic matter. Low CEC soils are more susceptible to cation nutrient loss through leaching (Spargo et al., 2013). Results of low available P and high CEC conform to those of Tematio et al. (2004) and Bitondo et al. (2013). Base saturation which is the percentage of the soil CEC that is occupied by basic cations (calcium, magnesium, potassium, sodium) at the current soil pH value was less than 50% for all the soils, a fact which shows that the soils studied are acidic in nature. Since amorphous materials are a subset of the crystalline forms, the results of free and amorphous Al and Fe obtained were obvious.

P adsorption isotherm graphs in Figure 1 indicated that each soil sample adsorbs phosphorus differently. According to Giles et al. (1960) and Weber (1970), these isotherms are of the L- type, indicating that the soils have a high affinity for P. The results of adsorption isotherms indicate that there are differences in the sorption characteristics obtained from the five different linear isotherms. Insertion of sorption data into the various phosphorus adsorption models showed that all models illustrated well the relationship between adsorbed phosphorus and phosphorus in equilibrium solution. The highest value of adsorption observed for the sample of Femock 2 may be due to its high clay and low available phosphorus content which enhances phosphorus adsorption while the lowest value of adsorption for Baranka 1 series may be due to its high available phosphorus and lower clay content, which does not favour phosphorus adsorption. These results conform to those of Khan et al. (2010), Tsado et al. (2012), Idris and Ahmed (2012) and Tening et al. (2013) who showed that soils with high clay content and low available phosphorus tend to enhance P adsorption.

Comparison of Langmuir adsorption maxima values with those obtained from the sorption data showed that values obtained from Langmuir equation were greater than those obtained from sorption data. This shows that all adsorption sites were not occupied by the adsorbate (P). Similar results have been reported by Anghinoni et al. (1996), Khan et al. (2010), Tsado et al. (2012) and Yaser and Rahim (2013).

The buffering capacity of Temkin model (b) varied from 739.39 mL g^{-1} for Baranka 2 to 1266.99 mL g^{-1} for Femock 2 indicating that the higher the buffering capacity, the higher the sorption capacity of the soil and vice versa. These results are conform to those of Dubus and Becquer (2001) and Khan et al. (2010) who showed that soils with high buffering capacity tend to fix phosphates highly.

Clay was shown to be significantly ($p < 0.05$) and positively correlated with P adsorbed. This result suggests that clay could be highly responsible for P adsorption in these soils and it conforms to the findings of Khan et al. (2010), Tsado et al. (2012) and Tening et al. (2013) who showed that clay had a significant positive correlation with P adsorbed.

No significant correlations were recorded between amorphous iron, amorphous aluminium, available P, soil organic matter and P adsorbed. Lack of a significant correlation between P sorption parameters and one or more soil properties has been reported (Anghinoni et al., 1996). The importance of organic matter, for instance, is ambiguous because it can play both positive and negative roles, either by sorbing P or by blocking sorption sites of inorganic particles (Stuanes, 1982). It is also possible that organic matter reduces positively charged surfaces by lowering the pH, a process that decreases the attraction of P to the soil surface (Yaser and Rahim, 2013). Inspite of the differences among soil properties related to surface area and degree of weathering of these soils, the clay content and pH-KCl were the only tested soil parameters that significantly correlated with constants of the isotherm equations. This conforms to the result of Muindi et al. (2015) who showed that clay significantly correlated positively with P adsorbed.

Conclusion

The adsorption isotherms showed different curves for each of the four soil series. The order for P adsorption followed an increasing trend of Baranka 1< Baranka 2 < Femock 1 < Femock 2. Insertion of sorption data into the various phosphorus adsorption models showed that all models illustrate well the relationship between adsorbed phosphorus and phosphorus in equilibrium solution. Comparing the five equations (Freundlich, Langmuir, Temkin, Van Huay and Linear), it can be concluded that the accuracy of fitness of data of the four soil series into the equations increased in the order: single surface Langmuir isotherm, Linear isotherm, Van Huay isotherm, Temkin isotherm and Freundlich isotherm. Results of this study revealed differences in P adsorption and identified Clay, pH-KCl and free aluminium as the main predictors of P activity in these soils. Periodic soil testing for physical, chemical and mineralogical properties, including the use of organic material and liming as a basis for P adsorption reduction, will be useful for crop production in the Bambouto sequence.

COMPETING INTERESTS

The authors declare that they have no competing interests.

AUTHORS' CONTRIBUTIONS

NEBT supervised the research work at all stages and ADM-Z provided chemicals and equipment for field work and laboratory analysis; directed and edited the manuscript. JNG assisted in supervising the research work while NAM carried out field work, laboratory and data analyses and assembled the manuscript.

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