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Phosphorus Sorption under Changing Soil Drainage Condition of a Wetland –Implications for Sustainable Intensification of Agriculture

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Authors' contributions

This work was carried out in collaboration between all authors. Author GAA designed the study, performed the statistical analysis and wrote the protocol. Authors TF and SAM wrote the first draft of the manuscript and managed the analyses of the study. Author SAM managed the literature searches. All authors read and approved the final manuscript.

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ABSTRACT

Phosphorous is a major limiting factor for plant growth, and its behaviour varies significantly under different soil drainage conditions. Understanding the chemistry of phosphorus availability of wetlands remain imperative for sustainable management of paddies under intensive agriculture and this has not been well documented. A study was therefore conducted to investigate the effect of soil drainage condition on the phosphorus sorption capacity of some wetland soils in south-west Nigeria. Soil samples were taken at 0-30 cm (surface) and 30-60 cm (subsurface) soil depth across some land use types under dry and wet soil conditions, primarily during the rainy and dry seasons. Phosphorus sorption studies were carried out using standard protocols. The results showed that the phosphorus sorption isotherms for the soils had the characteristic L- shape and were best described by Langmuir II adsorption isotherm. The R^2 values of the isotherms varied between 0.97 and 0.99. The adsorption maxima (S_{max}) ranged from 17.09 to 39.22 mg kg^{-1} under wet condition while it ranged from 37.74 to 138.89 mg kg^{-1} in the dry soil. The P sorption capacities of the soils

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were higher in the dry soils which had S_{max} that were 4 to 6 times greater than those of the wet soil. Similarly, the specific P requirement (SPR) of the dry soils were higher than those of the wet soils. This suggests that P fertilizer requirement for crop production during the wet season is essentially determined by the quantity of P applied during the dry season and this should be taken into consideration in fertiliser management programs to avoid eutrophication.

Keywords: Fertiliser use; soil phosphorus; soil moisture; sustainable land use.

1. INTRODUCTION

Phosphorus is a significant limiting element for plant growth [1]. After nitrogen, P is the second most frequently limiting macronutrient for plant growth. Phosphorus is an essential macronutrient for plant growth, and it is added as fertilizer to soils to increase the physiological efficiency of crops [2]. When phosphate fertiliser is applied to soil and dissolved by the soil water, the final fate of the P fertiliser depends on several factors including the soil pH, type of clay minerals and the drainage condition which may affect the oxidation-reduction processes in the soil [3]. Eutrophication of underground water, rivers and streams within agricultural land has been attributed to loss of P from non-point sources within the agricultural land due probably to over application of P fertilisers, losses of P through drainage and erosion [4].

In any wetland soil, where the pH is likely to be low as a result of the reducing condition prevailing in such situation, the P fixing capacity of the soil will determine primarily the availability of P to crop (like rice) growing under such condition. This will also directly affect the quantity of P that will be required for optimum performance of the crop and also to minimize P losses to the surrounding water bodies. Likewise, in areas where the wetland undergoes repeated cycles of drying and wetting (seasonal), the P chemistry in the soil is also affected in like manner [5]. Therefore, if this hypothetical situation is true, then it will be highly essential to know the P sorption characteristics of such soils in the wet and dry conditions before an appropriate P fertiliser regime can be recommended for such soils.

In most part of the developing world, all year round cropping of wetland is a common practice especially in areas where irrigation facilities are not available for supplemental water application during the dry season (Fadama farming). The Fadama is usually cultivated both during the wet and dry season either for rice or vegetables. The chemistry of the Fadama soil under the wet condition could be different from the dry condition [6]. This redox process could affect the pH of the soil as well as the activities of oxides of aluminium and iron thus affecting the P-sorption capacity of the soil. As such, studies of this nature will be of immense benefit in developing P fertiliser recommendation for the crop farmers who cultivate wetland soils. The objective is to determine the effects of soil moisture condition on the P-sorption characteristics in some wetland soils in Abeokuta.

2. MATERIALS AND METHODS

The research was conducted on wetland soils of the Federal University of Agriculture Abeokuta Experimental Station. The soils of the wetland were being used for rice and leafy vegetables such as amaranths production.

Two alternating soil drainage conditions were examined which where the wet and dry conditions. Soil samples for the wet condition were taken during the rainy season and maintained under a wet condition till chemical analyses. On the other hand, soil samples for the dry condition were taken during the dry season and the samples were maintained dry till chemical analyses. In each of the drainage condition, samples were taken at 0-30 and 30-60 cm soil depths, representing the surface and subsurface soils respectively. Four different locations representing the entire wetland of the experimental station were sampled. Ten different concentrations of phosphorus were used as treatments. The soil samples used for the dry condition were air-dried before chemical analyses while samples for the wet condition were analysed without prior testing using a gravimetric method to get the equivalent amount of the dry weight in the wet weight.

2.1 Chemical Analyses of Soils

Soil pH was measured by the glass electrode method on 1:2 soil: water suspensions. Total soil organic carbon was determined using acid dichromate wet-oxidation procedure of Walkey and Black method as described by [7]. Total Nitrogen was determined by micro Kjeldahl digestion method as described by [8]. Cation exchange capacity (CEC) and exchangeable bases (i.e. Ca, Mg, K, and Na) were measured using 1 M ammonium acetate (NH4OAc) at pH 7 [9]. Effective CEC (ECEC) was calculated by summing the extractable Ca, Mg, K, Na in NH4OAc at pH 7 and A1 and H in 1 M KC1 [10]. Base saturation percentage (BS%) was expressed by the percentage of the sum of the Ca, Mg, K, and Na in 1 M NH4OAc at pH 7 to ECEC [11]. The amount of exchangeable A1 and H was determined based on the Yuan's method [12].

2.2 P-sorption Study

Five (5) grammes of each of the soil sample was weighed into a 50 cm test tube in 10 replicates. Twenty millilitres (20 ml) of different P concentrations (0, 2, 4, 8, 10, 25, 50, 75, 100 and 125 mg/L) was added to the replicates. This experimental set up was done in triplicates. The experiment was a 2 x 10 factorial laid out in a completely randomised design (CRD) in three replicates. Two (2) wetland conditions (wet and dry) and 10 levels of P concentrations. A drop of toluene was added to each test tube to avoid microbial growth during the period of the experiment. The test tubes were well covered, arranged on suitable racks and shaken on a reciprocal shaker for 1hour on the first day and 30minutes for the next 5days. At the end of the 6^{th} day, the solution was filtered using Whatman No.41 filter paper and the P-concentration in the residue or filtrate were determined by the Molybdate blue method [13], using spectrophotometer at 882 nm.

The amount of P sorbed was calculated as the difference between the amount of P added and that remaining in solution [14]. The linear form of the Langmuir adsorption equation was adopted for the adsorption isotherm.

$$C/Q = 1/kS_{max} + C/S_{max}$$

Where C is the equilibrium P concentration (mg L^{-1}), Q is the total amount of P sorbed (mg kg^{-1}), k is a constant related to the binding energy (L mg^{-1}), and S_{max} is the adsorption maximum (mg kg^{-1}).

Other Langmuir parameters were determined from the regression equation obtained by plotting C/Q on the Y-axis and C on the X- axis. The slope of the graph is $1/S_{max}$ while the intercept of the line on Y-axis is $1/kS_{max}$. The adsorption maximum is the reciprocal of the slope while k is obtained by dividing the slope by the intercept (as slope/intercept).

The maximum P-buffering capacity (PBC) was calculated by multiplying sorption coefficients Smax and k [15]. Standard P requirement of soil (SPR) was determined as the amount of P sorbed at a solution P concentration of 0.2 mg P L^{-1}[14]. This was achieved by substituting 0.2 mg P L^{-1} for C in the linear Langmuir equation $Q = (k*C*S_{max})/(1+kC)$.

The data was analyzed using Genstat package 9^{th} Edition. Significant means were compared at 5 % probability level.

3. RESULTS AND DISCUSSION

3.1 The Physical and Chemical Characteristics of the Wetland Soils

Table 1 present the physical and chemical properties of the selected locations of the wetland soils. Location BZB had 3 diagnostic horizons namely: Ap, A2 and A3 of overall 49 cm soil depth. The textural class ranged from loamy sand at the upper horizons to sandy loam in the lower horizons. The A2 is higher in gravel (silica) content than other horizons. The soil pH ranged from 6.9 to 7.30 with high and fairly constant percent base saturation (99.03 - 99.20). The organic carbon and available P are very low while the exchangeable cations are fairly moderate with also a moderate effective cation exchange capacity across the 3 horizons.

Location bamboo, four diagnostic horizons namely: Ap, B1, B2 and B3 were identified. The soil depth was 81 cm and the textural class ranged from loamy sand to sandy loam with 39 % gravel (silica) content at the B3. The soil is slightly acidic (6.4 – 6.8). The soil organic carbon is relatively high at the Ap horizon with a steady decline down the profile. The B2 is richer in available P than other horizons. Among other cations, magnesium is significantly higher at B1 with a higher ECEC values than other horizons. Generally, the subsoil was found to be richer than the topsoil. This could be due to the eluviation of the top soil and the subsequent accumulation of nutrient rich materials in the subsoil. The % base saturation was in the order of 98 % across the horizons.

Table 1. Soil Physical and chemical characteristics of the representative sites of the wetland

Location	Horizon	Depth	Sand	Silt	Clay	Gravel	pH_w	pH_K	OC	Avail-P	TEA	Ca^{2+}	Mg^{2+}	K^+	Na^+	ECEC	Bsat
		(cm)	←		%	→			(%)	mg kg^{-1}	←		Cmol kg^{-1}			→	(%)
BZB	Ap	0 – 22	87.00	2.00	11.00	10.27	7.30	5.70	1.98	0.31	0.10	2.00	10.00	0.20	0.13	12.43	99.20
BZB	A2	22 – 36	81.60	7.00	11.40	35.07	6.90	5.50	0.48	0.72	0.10	2.40	7.60	0.10	0.11	10.31	99.03
BZB	A3	36 – 49	79.20	3.80	17.00	21.17	7.10	5.35	0.40	0.00	0.10	2.80	9.20	0.10	0.13	12.33	99.19
Bamboo	Ap	0 – 12	77.60	8.40	14.00	19.07	6.50	4.75	2.55	0.55	0.10	2.80	5.20	0.17	0.15	8.42	98.81
Bamboo	B1	12 – 32	68.00	15.40	16.60	7.4	6.40	5.15	0.83	0.00	0.10	1.60	16.40	0.11	0.22	18.43	99.46
Bamboo	B2	32 – 59	72.00	12.00	16.00	11.27	6.50	4.70	0.04	1.05	0.10	2.40	13.60	0.09	0.24	16.43	99.39
Bamboo	B3	59 – 81	83.00	3.40	13.60	38.6	6.80	5.25	0.22	0.92	0.10	4.00	8.00	0.08	0.35	12.52	99.20
BFH	Ap	0 – 35	64.60	21.40	14.00	8.07	6.30	4.75	1.49	0.54	0.10	3.60	0.40	0.13	0.17	4.41	97.73
BFH	B1	35 – 62	80.00	8.40	11.60	7.83	6.50	5.85	0.35	0.15	0.10	3.20	11.20	0.12	0.15	14.77	99.32
BFH	B2	62 – 100	88.60	0.80	10.60	8.87	6.80	5.50	0.18	0.36	0.10	4.40	8.80	0.09	0.15	13.54	99.26
FDLI	Ap	0 – 33	84.00	5.40	10.60	4.2	6.60	4.70	0.70	1.35	0.10	1.60	20.40	0.08	0.11	22.29	99.55
FDLI	B1	33 – 67	85.00	5.40	9.60	8.43	6.90	5.15	0.31	0.77	0.10	2.00	3.20	0.05	0.17	5.52	98.19
FDLI	B2	67 – 98	76.60	15.40	8.00	27.83	6.40	5.25	0.26	0.01	0.10	4.00	8.00	0.21	0.26	12.57	99.20
FDLI	B3	98 – 140	58.00	2.40	39.60	43.27	6.10	3.85	0.31	0.49	1.70	1.20	12.80	0.21	0.15	16.06	89.42
FDLI	C	140 – 180	50.60	5.80	43.60	18.67	5.60	5.25	0.26	0.16	0.10	2.80	3.20	0.09	0.15	6.34	98.42

OC =organic carbon, TEA =total exchangeable acidity, ECEC =effective cation exchange capacity, Bsat =Base saturation

The Table 1 also indicate that the textural class of location BFH ranges from sandy loam at the Ap to loamy sand at the B1 and B2 horizons. Gravel content was relatively lower compared to BZB and Bamboo sites. The soil was slightly acidic to near neutral with low exchangeable acidity. Calcium is slightly higher while the other exchangeable cations were relatively lower compared with BZB and Bamboo. The effective cation exchange capacity was very low at the Ap horizon while this was high at B1 and B2 horizons. The intensive and continuous growing of vegetables with very little external inputs could lead to the degradation of topsoil; and this could account for the observed trends.

At location FDLLI (FADAMA at TREFAD), the soil ranges from sand to sandy clay in the subsoil. Five diagnostic horizons were identified down to the C horizon (Table 1). There was a gradual increase in gravel content from Ap to B3 and a subsequent lower gravel content at the C horizon. The soil is slightly acidic to near neutral and follows within the suitable range of crop production. The soil organic carbon was very low while the exchangeable cations were also low in most of the horizons with the exception of magnesium at the Ap horizon; subsequently leading to very high ECEC value at the latter. Previous research showed that FADAMA soils are very rich in plant nutrients such as the exchangeable cations [16]. As expected there were very low nutrients in the C horizon and those horizons close to it.

Comparatively, the FDLI had higher exchangeable cations at the topsoil while all the other sites tend to have higher cations at the subsoil. The soil texture fluctuates between loamy sand and sandy loam while the pH was neutral to slightly alkaline. The organic carbon was generally low with the exception bamboo at the Ap horizon which had a considerably high value. The percent base saturation was fairly constant with an average of 98%.

3.2 Phosphorus Sorption Characteristics of the Wetland Soils

All the adsorption isotherms had the characteristic L- shape curves (Figs. 1, 3, 5 and 7). The L curve isotherm is characterized by an initial slope that does not increase with the characteristics of the adsorptives in the soil solution. This type of isotherm is the resultant effect of high relative affinity of the soil particles for the adsorbate at low surface coverage coupled with a decreasing amount of adsorbate increases both in the wet and dry condition.

As a result of the characteristics of the adsorption curves, the linear model of Langmuir adsorption isotherm was adopted for describing the P-sorption characteristics of the soils (Figs. 2, 4, 6 and 8). The coefficient of determination (R^2) ranged from 0.9779- 0.9947 for the wet samples (Table 1) and 0.9428- 0.9895 for the dry samples (Table 3). The sorption maxima (S_{max}) of the wet condition (rainy season) were very low and ranged from 17.094 – 39.216 mg kg^{-1} (Table 2). Likewise, the sorption maxima of the dry soil condition (dry season) were very high and ranged from 37.736- 138.889 mg kg^{-1} (Table 2). Also, the specific phosphorus requirement of the soils (SPR at 0.2 mg P L^{-1}) ranged from 0.151 – 0.511 for the wet samples (Table 2) and 0.399 – 1.120 for the dry soils (Table 3). The soils apparently have low buffering capacity for P (MPBC) as the MPBC of the soils ranged from 0.816 – 2.99 for wet soil and 2.000 – 5.680 for dry soil condition.

Table 2. Phosphorus sorption parameters of soils during the wet season

Sample location	Depth	Slope	Intercept	R^2	S_{max} (mg kg^{-1})	k (L^{-1})	PBC	SPR (mgPL^{-1})
Bamboo	0-30	0.049	1.2241	0.98343	20.408	0.04	0.816	0.151
Bamboo	30-60	0.0585	1.0331	0.9779	17.094	0.057	0.974	0.193
BFH	0-30	0.0473	0.3816	0.9933	21.142	0.124	2.622	0.511
BFH	30-60	0.0336	0.5675	0.9901	29.762	0.059	1.756	0.347
FDL I	0-30	0.0264	0.8487	0.9813	37.879	0.031	1.174	0.233
FDL I	30-60	0.0418	0.659	0.9904	23.923	0.063	1.507	0.298
FDL II	0-30	0.0375	0.6049	0.9917	26.667	0.062	1.653	0.327
FDL II	30-60	0.0324	0.6055	0.9947	30.864	0.054	1.667	0.329

S_{max} =Adsorption maxima, k =binding energy, PBC =phosphorus buffering capacity, SPR =standard phosphorus

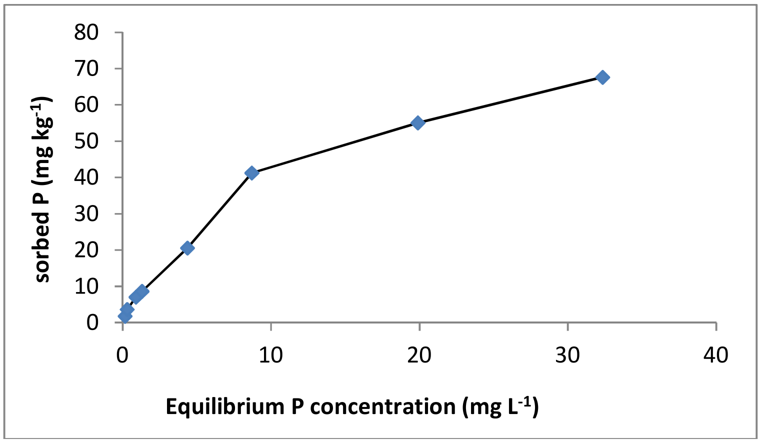

Fig. 1. P sorption curve for bambo (Dry condition)

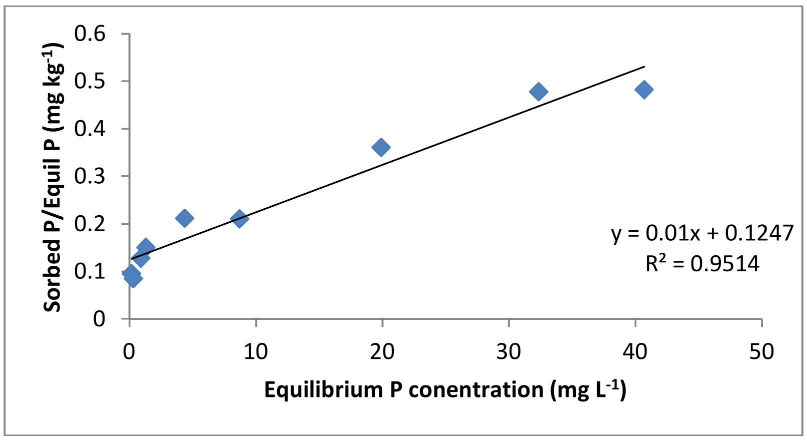

Fig. 2. Langmuir II P sorption isotherm for bamboo (Dry)

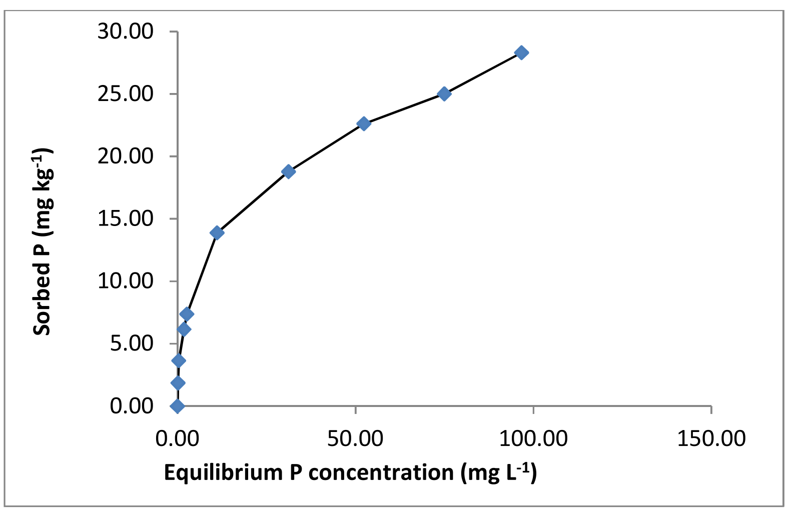

Fig. 3. P sorption curve for FDL I (Dry condition)

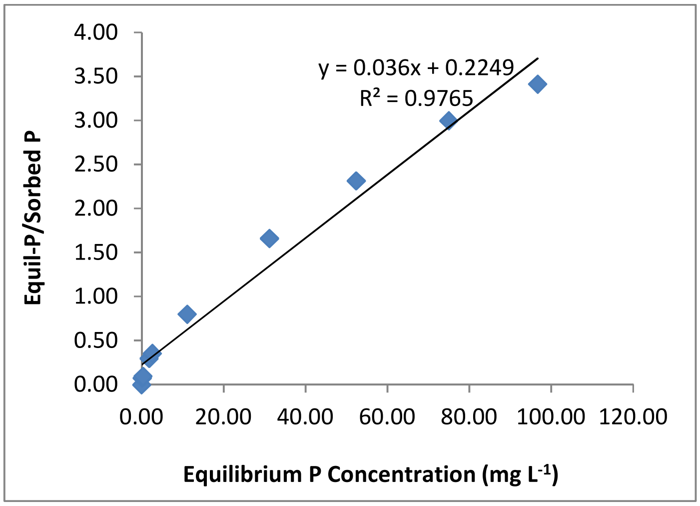

Fig. 4. Langmuir II P sorption isotherm (Dry condition)

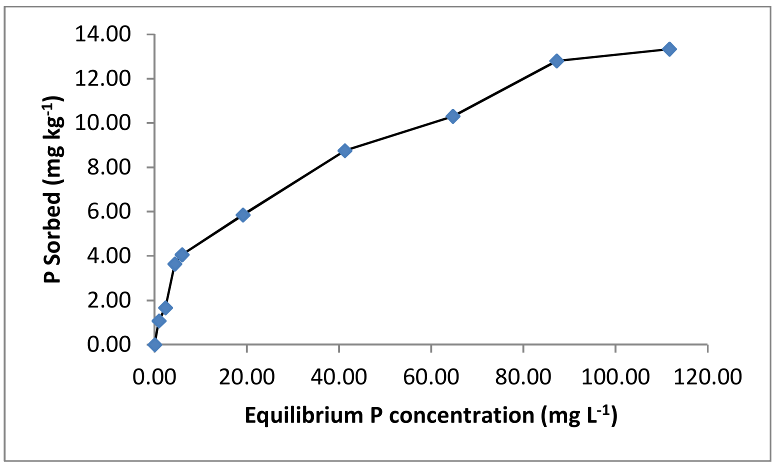

Fig. 5. P sorption curve for Bamboo (Wet)

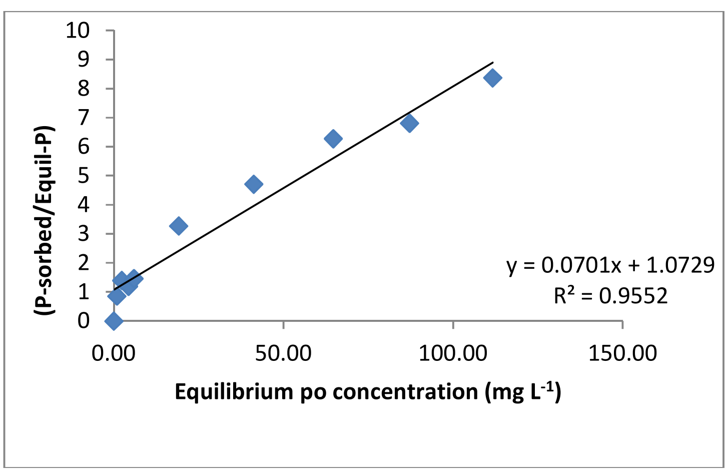

Fig. 6. Langmuir II P sorption isotherm for Bamboo (Wet)

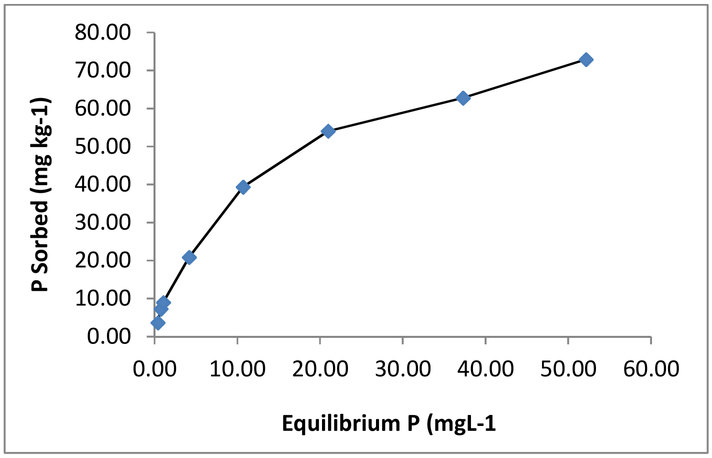

Fig. 7. P sorption curve for FDL I (Wet condition)

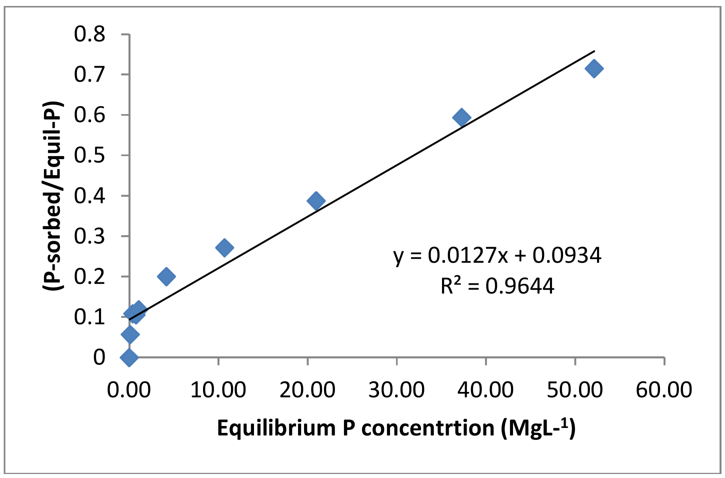

Fig. 8. Langmuir II P sorption isotherm for FDL I(Wet)

Table 3. Phosphorus sorption parameters of soils during the dry season

Sample location	Depth	Slope	Intercept	R2	S max (mg kg-1)	k (L-1)	PBC	SPR (mgpL-1)
Bamboo	0-30	0.0075	0.261	0.9789	133.33	0.029	3.867	0.769
Bamboo	30-60	0.0115	0.3928	0.9726	86.957	0.029	2.522	0.501
BFH	0-30	0.0124	0.3018	0.9668	80.645	0.041	3.307	0.656
BFH	30-60	0.0123	0.3057	0.9757	81.301	0.04	3.252	0.645
FDL I	0-30	0.0072	0.1939	0.9516	138.889	0.037	5.139	1.021
FDL I	30-60	0.0125	0.1766	0.9820	80	0.071	5.68	1.120
FDL II	0-30	0.0083	0.2117	0.98	120.482	0.039	4.699	0.932
FDL II	30-60	0.004	0.5127	0.9428	250	0.008	2.000	0.399

S_{max} =Adsorption maxima, k =binding energy, PBC =phosphorus buffering capacity, SPR =standard phosphorus

According to [17] anaerobic soils released more P to soil solution low in soluble P and sorbed more P from solution high in soluble P than did aerobic soils. The difference in behavior of P under aerobic and anaerobic soil conditions was attributed to the change brought about in ferric oxyhydroxide by soil reduction. The transformation of ferric oxyhydroxide ($Fe(OH)_3$) to ferrous hydroxide ($Fe(OH)_2$) in a biologically active waterlogged soil apparently results in more sorption sites on reduction, which may explain greater P sorption under reduced conditions. Similarly, [18] observed that soils enriched with amorphous and poorly crystalline forms of iron (a dominant form of iron oxides in wetland) act as an excellent reservoir for P by adsorbing excessive P in aerobic sediment zones and releasing it upon burial under anaerobic soil conditions. Thus, P requirement during the rainy season is lesser than the amount required during the dry season. Care is therefore warranted during the wet season to prevent over application which can cause eutrophification and other ecological menace.

4. CONCLUSION

Soil moisture condition has a significant impact on phosphorus sorption characteristics. Soil drainage condition helps in modulating the pattern of phosphorus release in the soil. The P-sorption capacity of a wetland soil was higher during the dry season than in the wet rainy season due to the inherently low phosphorus content and anaerobic transformation of ferric hydroxide. This suggests that more phosphorus is available in the soil solution during wet season than the dry season and this might be beneficial to crop production. Management of paddies, therefore, requires different strategic nutrient management approaches at different cropping cycles to ensure sustainable food production. This should thus be taken into considerations in fertiliser management programmes not only for increased food production but also for environmental sustainability.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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