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Phosphate Adsorption Capacity and Organic Matter Effect on Dynamics of P Availability in Upland Ultisol and Lowland Inceptisol

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ABSTRACT

Ultisols and Inceptisols were used to investigate the adsorption-desorption capacity of P and the effect of organic matter on the dynamics of P availability in tropical acid soils. The experiment consisted of two sub-experiments. Sub-experiment I was to study the adsorption-desorption capacity of Ultisols, Fresh-water lowland Inceptisols, and tidal-swamp Inceptisols. Therefore, surface soils (0 to 30 cm) of each tested soil were treated with 0, 10, 20, 30, 40, 60, 80, 100, 120, 140, 170, and 200 mg P kg⁻¹ of soil. Sub-experiment II was to study the effects of organic matter application (0, 5, 10, and 15 Mg ha⁻¹) on the dynamics of available P following 60d incubation under room temperature. P fertilizer application significantly affected water soluble-P (WSP) ($p < 0.01$) and soil available P-Bray and Kurtz No. 1 (BKP) ($p < 0.01$) in the three tested soils. The different response of both WSP and BKP confirmed that the soils tested in the current experiment had different soil P buffering capacity in the order of Tidal-lowland Inceptisol > Upland Ultisol > fresh-water Lowland Inceptisol. OM application increased the BKP in all tested soils as compared to the control. Differences in pattern of soil available P dynamics over time were detected between upland soil and two lowland soils used in the current experiment.

Keywords: Adsorption-desorption, Inceptisols, organic matter, Ultisols

INTRODUCTION

Phosphorus (P) retention capacity, a measurement of the ability of soil to retain P, is an important factor to control the releasing P from soil complexes. It is often determined in the laboratory by equilibrating soil with a range of P concentrations for a set period of time. The amount of P sorbed is estimated as the difference between the amount of P added and P remaining in soil solution at equilibrium. The data obtained are then fitted into different adsorption models and various indices of P adsorption capacity are determined (Barrow 1978; Chien and Clayton 1980; Kinniburgh 1986). Various soil properties have been reported to be closely related to the P retention capacity of soils. Such properties include the extractable iron (Fe) and aluminum (Al) oxides (Toor *et al.* 1997; Freese *et al.* 1992), clay content (Johnston *et al.* 1991; Toor *et al.* 1997), organic C (Daly *et al.* 2001), pH (Barrow 1984), calcium carbonate (Bertrand *et al.*

2003), and sand content (Yuan and Lucas 1982; Leclerc *et al.* 2001).

P deficiency as well as Al and Fe toxicity are mostly found in acid soils in the tropics, such as Ultisol in upland areas and Inceptisol in lowland areas (Ismail *et al.* 1993; Soedarjo and Habte 1993). Chemically, upland Ultisols and lowland Inceptisols have different characteristics. Upland Ultisols contain high Al solubility (Miller 1983; Kadir *et al.* 2001; 2002; 2003); while lowland Inceptisols contain high Fe solubility (Marsi 1996). Different levels of Al and Fe solubility among these soils will give different reaction to P (Evangelou, 1998).

Application of P fertilizers to acid soils are a common practice to ensure plant growth and productivity. However, more than 80% of the added P becomes immobile and unavailable for plant uptake because strong phosphate retention is easily induced in soils which are rich in crystalline and amorphous oxides and hydroxides of Fe and Al (De Datta 1981; Holford 1997; Mehadi and Taylor 1988; Rajan and Watkinson 1976; Rodríguez and Fraga 1999). Then, if P is continuously applied to the soil in excess of crop requirement, P will generally build up in the soil. A study by Marsi *et al.* (1999) in

acid Ultisols and sulphate soils of South Sumatra, Indonesia using rock phosphate, TSP and SP-36 indicated that residual P increased as the rate of P application increased, regardless of the P sources.

Lime is commonly used to improve conditions of acid soils for plant growth. Liming increases soil pH, decreases concentrations of active Al and Fe level and increases the supply of P and other nutrients. An alternative approach other than liming is the application of organic matter to increase P availability and reduce Al and Fe toxicity. The interactions between high contents of organic matter input into soil and the availability of soil P have been demonstrated for various crops under no-till or minimum-till conditions (McDowell and McGregor 1984; Langdale *et al.* 1985). Similarly, the accumulation of crop residues from previous cropping at the soil surface has been shown to increase the soil test value for P (Sharpley and Smith 1989). Observations of this nature have also been made on changes in the availability of soil P after the application of liquid manures to soil (Sharpley *et al.* 1984).

In greenhouse experiments in a sand culture, Tan and Binger (1986) showed that in the absence of humic acid, growth of maize decreased linearly with increasing Al additions. However, addition of humic acid at 100 to 300 mg kg⁻¹ greatly improved plant growth and ameliorated the negative effect of increasing Al concentrations. The possible mechanisms for the amelioration of Al and Fe toxicity by the addition of organic residues to soil were an increase in soil pH by decomposition of organic matter, a complexation of Al and Fe in soil solution by soluble organic matter, and a reduction of exchangeable Al and Fe due to complexation of solid-phase organic matter (Haynes and Mokolobate 2001). In addition, organic matter might also contain significant amounts of inorganic P, which was readily available to plants (Wong and Swift 2003). Results from these various studies had shown increasing in both organically and inorganically bound of soil phosphorus. Therefore, the present research was undertaken to study P adsorption-desorption capacity of acid soils. In addition, the effect of organic matter on the dynamics of P availability in Ultisols and Inceptisols was also examined.

MATERIALS AND METHODS

Soil Sampling

Soils used in current experiment were collected from three locations representing three different

acid soils widely found in South Sumatra. The first location represented upland soil, while the other two represented lowland soils (fresh-water lowland soil and tidal lowland soil). At each location, five disturbed soil samples were taken up to a depth of 30 cm by a shovel, which were then composited into one soil sample per location. The upland soil sample representing Order of Ultisols was collected from Sembawa Village, Banyuasin District. The Ultisols was characterized by a high acidity (pH 4.60), a very low content of available P (2.95 µg g⁻¹ of soil), a low content of organic C (15.3 g kg⁻¹), a moderate content of exchangeable Al and Fe (2.45 and 0.02 cmol (+) kg⁻¹, consecutively), a high content of Al-P (71.25 µg g⁻¹ of soil) and a very high content of Fe-P (306.17 µg g⁻¹ of soil). The two lowland soils (fresh-water lowland soil and tidal lowland soil) belonged to Inceptisols. The fresh-water lowland Inceptisol was collected from Agro Techno Park, Gelumbang, Muara Enim District. This fresh-water lowland Inceptisols was characterized by a high acidity (pH 4.85), a moderate content of available P (10.15 µg g⁻¹ of soil), a high content of organic C (33.4 g kg⁻¹), a very low content of exchangeable Al (0.97 cmol (+) kg⁻¹) but a high content of exchangeable Fe (0.14 cmol (+) kg⁻¹) and a low content of Al-P (12.75 µg g⁻¹ of soil) but a very high content of Fe-P (262.46 µg g⁻¹ of soil). The tidal-lowland Inceptisol sample was collected from Telang II Village, Banyuasin District. This soil was characterized by a high acidity (pH 4.69), a high content of available P (18.41 µg g⁻¹ of soil), a very high content of organic C (76.5 g kg⁻¹), a moderate content of exchangeable Al (3.29 cmol (+) kg⁻¹) but a very high content of exchangeable Fe (0.21 cmol (+) kg⁻¹) and a moderate content of Al-P (41.25 µg g⁻¹ of soil) but a very high content of Fe-P (378.49 µg g⁻¹ of soil).

Experimental Design

Overall experiment consisted of two sub-experiments. Sub-experiment 1 was done to study P fixing capacity of each soil. Sub-experiment 2 was to investigate the dynamics of soil available P during the incubation period due to the application of organic matter.

Sub-experiment 1 was aimed to study adsorption-desorption capacity. The effects of soil type and P addition on P adsorption-desorption were determined in a batch technique. Triplicates of 25-g dry-oven soil samples were weighed into preweighed 250-ml erlenmeyers. To each of these erlenmeyers was added 0 ml, 2.5 ml, 5 ml, 7.5 ml, 10 ml, 15 ml, 20 ml, 25 ml, 30 ml, 35 ml, 42.5 ml or 50 ml of 100 mg P L⁻¹ solution to represent P

treatments of 0, 10, 20, 30, 40, 60, 80, 100, 120, 140, 170 or 200 mg P kg⁻¹ soil. Then, aquadest was added to make the volume of solution to be 100 ml. After shaking for 72 hours continuously at 200 rpm, the pH of soil suspension was measured and the soil suspensions were transferred into preweighed 100-ml centrifuge tubes and centrifuged at 2,500 rpm for 40 minutes. The clear supernatants were filtered using Whatman paper No. 42 and the supernatants were collected into 250-ml erlenmeyers for determining of solution phase-P. The centrifuge tubes were weighed to quantify the entrapped solution. The soils were used to determine available P and Fixed P. Soil available P was determined by Bray I method. Soil fixed P was fractionated into Al-P, Fe-P and Ca-P according to Chang and Jackson Method (1957) modified by Hedley *et al.* (1982), Tiessen and Moir (1993), Sallade and Sims (1997) and Litaor *et al.* (2004). Consecutive extraction methods for Al-P (ratio soil to 0.5 N NH₄F solution was 1 : 150 and shaken for 17 hours) and Fe-P (ratio soil to 1.0 N NaOH solution was 1 : 150 and shaken for 17 hours) were applied to determine soil Al-P and Fe-P fractions. Soil P was measured by spectrophotometer at a 660 nm wavelength.

Sub-experiment II was intended to study the effects of organic matter application (0, 5, 10, and 15 Mg ha⁻¹) on the dynamics of soil available P in three different acid soils (upland Ultisol, fresh-water lowland Inceptisol and tidal lowland Inceptisol). The experiment was arranged in a completely randomized design in 3 replicates. Triplicates of 500 g dry-oven soil samples weighed into 1-L plastic containers. The soils were equilibrated with P by adding 21.25 mg, 12.25 mg and 14.25 mg P for upland Ultisol, tidal lowland Inceptisol and fresh-water lowland Inceptisol, respectively. The amount

of P added was calculated from adsorption-desorption equilibrium point resulted from sub-experiment 1. The soil and P fertilizer were mixed homogeneously, incubated for 7 days, air-dried, and sieved prior to organic matter application. To each container was added an organic matter at the rate equivalent to 0, 5, 10, and 15 Mg ha⁻¹, and mixed homogeneously. The soil-organic matter mixtures were incubated for 60 days at a room temperature. Soil moisture content was maintained at a field capacity during incubation.

Measurements

Measurements for sub-experiment 1 were made on the supernatant P, soil available (P Bray and Kurtz no. 1 (BKP) and water-soluble P (WSP)) and fixed P (Al-P and Fe-P) at the end of experiment. Meanwhile, measurements for sub-experiment 2 were made on the available P and fixed P (Al-P and Fe-P) immediately after organic matter application, 7, 15, 30, and 60 days after incubation.

Statistical Analysis

Data were analyzed statistically using General Linear model (GLM) of Costat Version 2.0. Relationships among variables were analyzed using a regression and a correlation analysis.

RESULTS AND DISCUSSION

Soil Characteristics

Three acid soils tested in the current study had a wide range of chemical properties. Soil pH ranged from 4.60 to 4.85, OC from 15.3 to 76.5 g kg⁻¹, exchangeable Al from 0.97 to 3.29 cmol (+) kg⁻¹, exchangeable Fe from 0.02 to 0.21 cmol (+) kg⁻¹,

Table 1. Some characteristics of soil tested in the current experiment.

Soil Characteristics	Unit	Upland Ultisols	Fresh-Water Lowland Inceptisols	Tidal Lowland Inceptisols
pH H ₂ O	-	4.60 (a)	4.85 (a)	4.69 (a)
Organic C	g kg ⁻¹	15.3 (l)	33.4 (h)	76.5 (vh)
BKP	µg g ⁻¹	2.95 (vl)	10.15 (m)	18.41 (vh)
CEC	cmol(+) kg ⁻¹	16.31 (m)	14.14 (l)	15.23 (m)
Exchangeable Al	Cmol (+) kg ⁻¹	2.45 (m)	0.97 (vl)	3.29 (m)
Exchangeable Fe	Cmol (+) kg ⁻¹	0.02 (m)	0.14 (h)	0.21 (vh)
Sand	%	31.11	41.30	63.14
Silt	%	44.49	23.46	23.14
Clay	%	24.40	35.24	13.72
Al-P	µg g ⁻¹	71.25	12.75	41.25
Fe-P	µg g ⁻¹	306.17	262.46	378.49

Note: a = acid; vl = very low, l = low, m = moderate, h = high, vh = very high

Bray and Kurtz no. 1 soil P test (BKP) from 2.95 to 18.41 $\mu\text{g g}^{-1}$, Al-P from 12.75 to 71.25 $\mu\text{g g}^{-1}$, and Fe-P from 262.46 to 378.49 $\mu\text{g g}^{-1}$ (Table 1). Such differences were important factors in determining whether P in the soil would be adsorbed by soil components or readily available for plant uptake (Toor *et al.* 1997; Freese *et al.* 1992; Johnston *et al.* 1991; Toor *et al.* 1997; Daly *et al.* 2001; Barrow 1984; Bertrand *et al.* 2003; Yuan and Lucas 1982; Leclerc *et al.* 2001). However, careful precautions are needed in interpreting correlation relationships between P retention capacity and soil properties because of the inter-correlations among soil properties (as explained by Bertrand *et al.* 2003). Thus, a strong correlation of a soil property with P retention capacity may not necessarily imply the direct influence of the soil property on P retention capacity of the soil, but may be due to the indirect influence of some other soil properties. Inherent collinearity among the independent variables used to model P retention capacity may prevent obtaining a regression model of desired accuracy (Walker 2004, Kutner *et al.* 2004). This was supported by Zhang *et al.* (2005) who reported that the significant correlation observed between P sorption capacity and clay content was due to the significant indirect influences of Al_{ox} and Fe_{ox} .

Soil Available P

P fertilizer application significantly affected WSP ($p < 0.01$) and BKP ($p < 0.01$) in the three tested soils. Both WSP and BKP in the three soils were correlated with the amount of applied P (Figure 1). Furthermore, every unit increase of applied P (mg P kg^{-1} soil) resulted in an increase of concentration of WSP as much as 0.017 mg P L^{-1} ($p = 0.020$), 0.023 mg L^{-1} ($p < 0.001$) and 0.006 mg L^{-1} ($p = 0.003$) for Upland Ultisol, Fresh-water Lowland Inceptisol, and Tidal lowland Inceptisol, consecutively (Figure 1a). Similarly, every unit of applied P (mg P kg^{-1} soil) increased BKP as much as 0.196 mg P kg^{-1} ($p = 0.003$), 0.233 mg P kg^{-1} ($p < 0.001$) and 0.107 mg P kg^{-1} ($p < 0.001$) for upland Ultisol, fresh-water lowland Inceptisol, and tidal lowland Inceptisol, respectively (Figure 1b). The increase in soil WSP and BKP concentrations were due to the lowest P fertilizer application for Tidal-lowland Inceptisols. This indicated that Tidal-lowland Inceptisols had the greatest P adsorption capacity among the three tested soils. On the other hand, although Upland Ultisols and Fresh-water Lowland Inceptisols showed a similar pattern of increases in WSP and BKP, Fresh-water Lowland Inceptisols showed a higher increase in WSP and BKP (Figure 1). The different response of both

WSP and BKP of the three tested soils confirmed that the soils used in current experiment had different soil P buffering capacity. The order of buffering capacity of the soils to available P is Tidal-lowland Inceptisol > Upland Ultisol > fresh-water Lowland Inceptisol.

Phosphorus Sorption

A consistent pattern for the effect of P fertilizer application on the amount of P fixed by the three soils was found in the current study, as illustrated in Figure 2. Significant correlations ($p < 0.05$) were observed between the amount of fixed P and the amount of applied P. Maximum P adsorption was not reached in current experiment likely due to the fact that the highest rate of P application in current experiment (200 mg P kg^{-1}) was still much lower than the maximum capacity of P retention by the soils. Earlier findings by Setyawan (1995) and Budianta and Vanderleen (1995) reported that the maximum P adsorptions were 3,191 mg P kg^{-1} and 1,034 mg kg^{-1} for South Sumatra Cambisol and Ultisol, respectively.

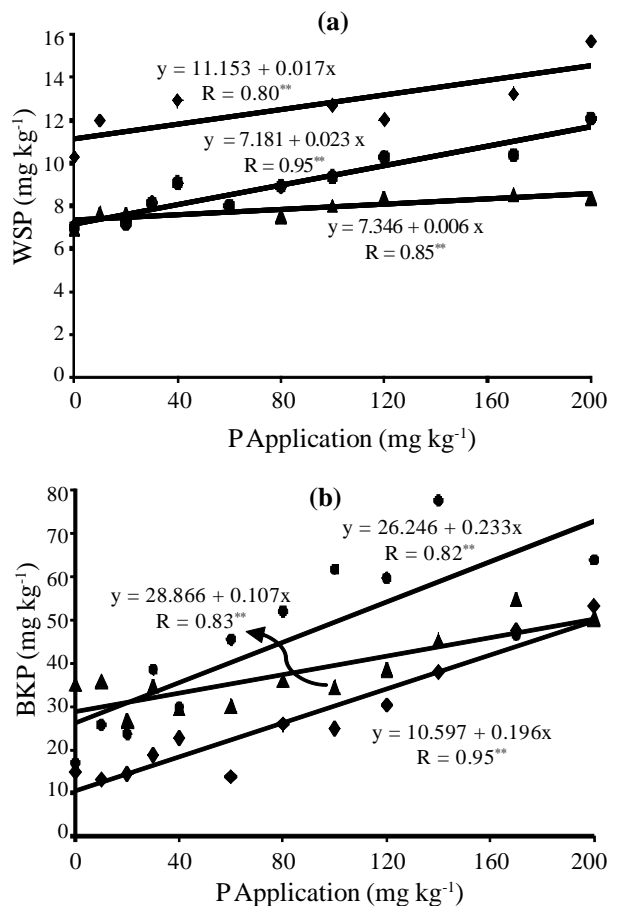


Figure 1. Relationship between P application (a) WSP and (b) BKP. \blacklozenge = Upland Ultisols, \bullet = Fresh-water Inceptisols, and \blacktriangle = Tidal lowland Inceptisols

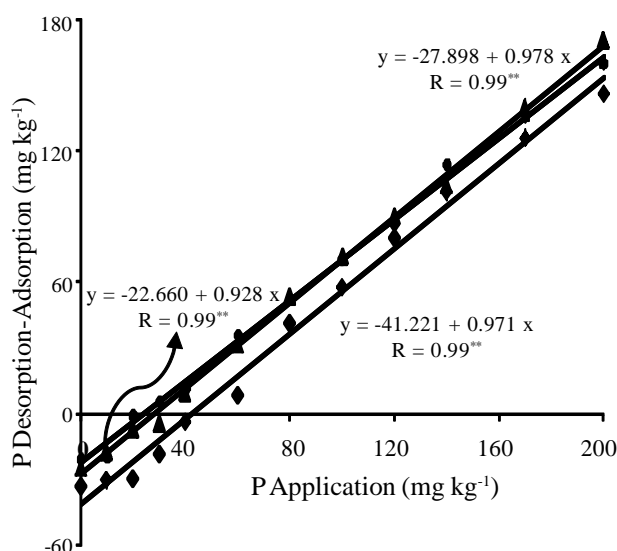


Figure 2. Relationship between P sorption-desorption equilibrium and P application. ♦ = Upland Ultisols, ● = Fresh-water Inceptisols, and ▲ = Tidal lowland Inceptisols

Results in Figure 2 showed that desorption-adsorption equilibrium points were achieved when 42.5 mg P kg⁻¹, 24.5 mg P kg⁻¹, and 28.5 mg P kg⁻¹ were applied to Upland Ultisol, Fresh-water lowland Inceptisol and Tidal-lowland Inceptisol, respectively. If the rate of P application was lower than that of equilibrium point, desorption of P would take place, and vice versa. Similar to the P availability, P adsorption ability of soil represented tidal lowland Inceptisol is the highest followed by those of upland Ultisol and fresh-water lowland Inceptisol as shown by the slopes of regression lines.

Phosphate adsorption capacity of soil was influenced by soil characteristics such as type and content of clay, exchangeable Al and Fe contents, organic matter content and soil pH (Evangelou 1998). Although there was not enough information to correlate characteristics of soils tested in the current experiment, earlier findings had shown that various soil properties, such as extractable Fe and Al oxides (Toor *et al.* 1997; Freese *et al.* 1992), clay content (Johnston *et al.* 1991; Toor *et al.* 1997), organic C (Daly *et al.* 2001), pH (Barrow 1984), calcium carbonate (Bertrand *et al.* 2003), and sand content (Yuan and Lucas 1982; Leclerc *et al.* 2001) have been reported to be closely related to the P retention capacity of soils.

Bertrand *et al.* (2003), however, stressed the need for caution in interpreting correlation relationships between P retention capacity and soil properties because of the inter-correlations among soil properties. Thus, a strong correlation of a soil property with P retention capacity may not necessarily imply the direct influence of the soil property on P retention capacity of the soil, but may be due to the indirect influence of some other soil properties. Inherent collinearity among the independent variables used to model P retention capacity may prevent obtaining a regression model of desired accuracy (Walker 2004, Kutner *et al.* 2004). This was supported by Zhang *et al.* (2005) who reported that the significant correlation observed between P sorption capacity and clay content was due to the significant indirect influences of Al_{ox} and Fe_{ox}. As such, simple correlation analysis may not be sufficient in evaluating the direct influence of soil properties on P retention capacity.

Tabel 2. Dynamics of BKP in tested soils.

Soil	OM --(Mg ha ⁻¹)--	BKP at				
		0d	7d	15d	30d	60d
		----- (mg kg ⁻¹) -----				
Ultisol	0	5.70	11.50	3.45	6.15	3.75
	5	5.70	31.65	3.30	6.75	6.60
	10	5.70	18.75	4.20	6.30	5.10
	15	5.70	14.10	2.70	8.10	9.60
Fresh-water lowland Inceptisols	0	14.25	4.05	5.25	10.05	6.45
	5	14.25	5.85	4.05	10.65	8.25
	10	14.25	4.80	6.60	13.80	12.00
	15	14.25	6.15	6.30	13.50	17.10
Tidal-swamp Inceptisols	0	20.55	6.30	5.25	18.15	10.80
	5	20.55	15.90	8.10	17.40	11.70
	10	20.55	9.90	9.30	17.85	11.25
	15	20.55	10.95	9.60	16.05	13.35

Effect of Organic Matter on Dynamics of Soil Available P

Table 2 presents the availability of P during the experiment. Data on 0d was the available P (BKP) at the start of the experiment. OM application increased the BKP in all tested soils as compared to the control and application of OM at 5 Mg ha⁻¹ appeared to be the most suitable to correct P availability in Ultisols and Tidal lowland

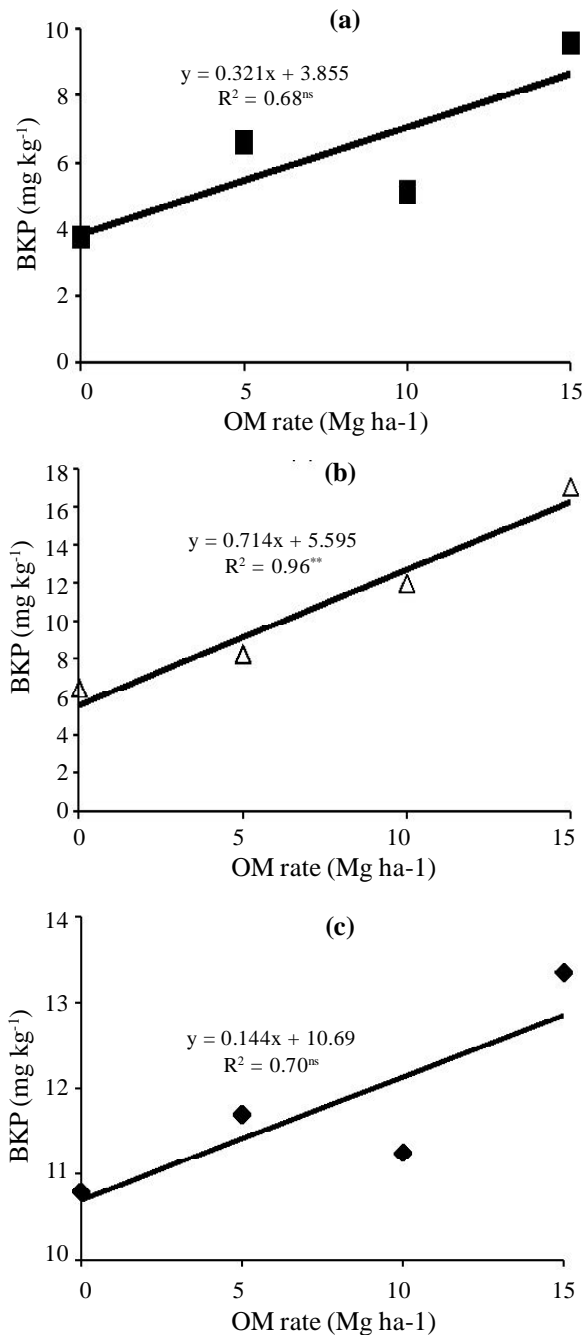


Figure 3. Relationship between OM application and BKP at 60d in Ultisols (a), fresh-water Inceptisols (b), and tidal-swamp Inceptisols (c).

Inceptisols and 10 Mg ha⁻¹ for that of fresh-water lowland Inceptisol.

To evaluate the relative effectiveness of OM to increase BKP, the BKP was regressed on the rate of OM applied for each soil. Examples of the data at 60d of incubation are shown Figure 3. This figure showed that available P of all tested soils increased as OM application increased. However, a significant ($p=0.02$) relationship was observed only on fresh-water lowland Inceptisols (Figure 3b).

The increase in the availability of P could be attributed to the chemical and biochemical processes involved. The humic acids might have helped in solubilizing P from insoluble to soluble form resulting in its increase. The benefits of addition of organic matter to the soils might be due to the anion replacement or competition between humate from added OM and phosphate ions on adsorbing surfaces which in turn would have increased the P availability. Dormar and Chang (1995) and Hao *et al.* (2003) indicated that fulvic acids and intermediate products of organic matter decomposition had played a significant role in mobilizing fairly soluble phosphates. The reason attributed was phosphate ions were expected to interact with humic acid more through its phenolic and hydroxyl groups which might have changed the behaviour of P. In addition, humus would form protective coating over sesquioxides and thereby reducing the fixation of any phosphate, which made them available in the soil (David *et al.* 1994).

The increase in available P might also be due to the mineralisation of soil organic P as well as humic acid (Dormar and Chang 1995; Hao *et al.* 2003). The results obtained in the current experiment confirmed this fact (Table 2 and Figure 3). Therefore, maintenance of soil organic matter is very essential for the successful maintenance of P availability in acid soils because soil organic matter (SOM) and soil organic P are important to fertility of tropical acid soils, both as a source of P and potentially as a buffer against P fixation by clay minerals (Tiessen *et al.* 1994; Afif *et al.* 1995; Guggenberger *et al.* 1996).

The BKP in the three tested soils was fluctuating over time at all OM addition levels (Table 2). However, differences in pattern of soil available P dynamics over time were detected between upland soil and two lowland soils used in the current experiment. The BKP of upland Ultisol initially (from 0 to 7d of incubation period) increased but drastically decreased from 7 to 15d, and little change thereafter. Meanwhile, available P of fresh-water and tidal lowland Inceptisols decreased at early incubation period (from 0 to 7 or

15d), then increased at 30d of incubation and slightly changed thereafter. The different pattern was likely due to differences in soil characteristics involved in adsorption and desorption of soil P among the three soils, such as content of Al and Fe, soil pH. The fact that BKP showed only small change or was stable by the end of incubation (from 30 to 60d) was due to the formation of more stable P and less soluble Fe-P and Al-P complexes.

CONCLUSIONS

Base on the results of this current experiment, it can be concluded that: phosphate adsorption capacity of tidal lowland Inceptisol > Upland Ultisol > fresh-water Lowland Inceptisol.

OM application increased the BKP in all tested soils as compared to the control. The application of OM at 5 Mg ha⁻¹ appeared to be the most suitable to correct P availability in Ultisols and Tidal lowland Inceptisol and 10 Mg ha⁻¹ for that of fresh-water lowland Inceptisol.

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