Phosphorus Extraction from Soil Constituents Using Bray P-1, Mehlich-1 and Olsen Solutions

Jamalam Lumbanraja, Sri Mulyani, Muhajir Utomo and Sarno

Department of Soil Science Faculty of Agriculture University of Lampung, Jln. Prof. Soemantri Brodjonegoro, No. 1, Bandar Lampung 35145, Indonesia, e-mail: j.lumbanraja53@gmail.com, jamalam.lumbanraja@fp.unila.ac.id

ABSTRACT

The extraction methods using Bray P-1, Mehlich-1, and Olsen solutions are the most frequently used in equilibrium condition to estimate the available P in the soil constituents. However, each method can gives some different values that may not describe the availability of soil P. Therefore, it is necessary to conduct a laboratory experiment to compare the three solutions in equilibrium and kinetics conditions for P release from soil colloids as a basic data for the future related to plant productions. The objective of this study was to compare the amounts of P release in equilibrium and kinetics conditions using Bray P-1, Mehlich-1, and Olsen solutions and the rate constants (k) of P release from soil colloids using the three solutions of five soil constituents or treatments: (1) Soil (100% soil), (2) P-rock (100% phosphate rock), (3) compost (100% chicken manure compost), (4) soil + P-rock (75% soil + 25% phosphate rock), and (5) soil + P-rock + compost (50% soil + 25% phosphate rock + 25% chicken manure compost). Each extraction for each treatment was conducted in triplicate. The results indicate that the amounts of extracted P employing equilibrium condition in all treatments are significantly lower compared to those employing kinetics condition. The results also show that Mehlich-1 solution is the most powerful solution to extract P from soil constituents followed by Bray P-1 solution and Olsen solution, except that in the soil + phosphate rock + compost treatment in which the amount of P extracted using Mehlich-1 solution is the highest then followed by that of P extracted by Olsen solution and Bray P-1 solution both in equilibrium and kinetic conditions. The highest rate constants (k) of the reaction in all treatments were found in the extractions using Mehlich-1 solution for desorbed P followed by that of using Bray P-1 solution and Olsen solution.

Keywords: Compost, equilibrium, kinetics, P extraction solutions, phosphate rock, soil

ABSTRAK

Metode ekstraksi Bray P-1, Mehlich-1, dan Olsen adalah yang paling sering digunakan dalam kondisi kesetimbangan untuk memperkirakan fosfor (P) yang ada dalam konstituen tanah. Namun masing-masing metode tersebut dapat memberikan nilai berbeda yang mungkin tidak menggambarkan ketersediaan P dalam tanah. Oleh karena itu, perlu dilakukan percobaan laboratorium untuk membandingkan ketiga larutan dalam kondisi kesetimbangan dengan kinetika untuk pelepasan P dari koloid tanah sebagai data dasar untuk masa datang terkait dengan produksi tanaman. Tujuan penelitian ini adalah untuk membandingkan jumlah P terekstrak dalam kondisi ekuilibrium dan kinetika dengan menggunakan larutan pengekstrak Bray P-1, Mehlich-1, dan Olsen dan konstanta kecepatan (k) pelepasan P dari koloid tanah dengan menggunakan tiga larutan dengan perlakuan: (1) Tanah (100% tanah), (2) P-rock (100% batuan fosfat), (3) kompos (100% kompos kotoran ayam), (4) tanah + P-rock (50% tanah + 25% batuan fosfat + 25% kompos kotoran ayam) yang diekstraksi dalam tiga ulangan. Hasil penelitian menunjukkan bahwa jumlah P yang diekstraksi dalam kondisi ekuilibrium pada semua perlakuan secara nyata lebih rendah dibandingkan dengan menggunakan kinetika. Hasil penelitian juga menunjukkan bahwa larutan Mehlich-1 adalah yang paling banyak mengekstrak P dari konstituen tanah yang diikuti oleh larutan Bray P-1 dan paling sedikit adalah larutan Olsen, kecuali pada perlakuan tanah + batuan fosfat + kompos dimana jumlah P yang diekstraksi menggunakan larutan Mehlich-1 adalah yang tertinggi kemudian diikuti oleh P yang diekstraksi dengan larutan Olsen dan yang terendah adalah larutan Bray P-1 baik dalam kondisi kesetimbangan maupun kinetika. Konstanta kecepatan (*k*) tertinggi dalam semua perlakuan ditemukan dengan menggunakan larutan Mehlich-1 untuk ekstraksi P diikuti larutan Bray P-1 dan yang paling rendah adalah dengan menggunakan larutan Olsen.

Kata kunci: kompos, ekuilibrium, kinetika, larutan ekstraksi P, batuan fosfat, tanah

INTRODUCTON

Phosphorus (P) deficiency is one of the limiting factors to support the soil productivity in a humid tropical region in which the soil parent materials have undergone further weathering and leaching (Lumbanraja 1995; Lumbanraja *et al.* 1982; Oelkers and Valsami-Jones, 2008). The low pH of the soils can be an indication of high P retention by oxide of iron (Fe) and aluminum (Al), resulting in lower P availability to plants (Lumbanraja *et al.* 1981; Lumbanraja *et al.* 1994; Arai and Sparks 2007; De Araújo *et al.* 2015). The works have been done to improve the availability of P in soils, such as adding phosphate rock and manufacturing phosphate and organic fertilizers (Lumbanraja and Utomo 1996; Lumbanraja *et al.* 1995; Vetterlein *et al.* 1999; Lindsay *et al.* 1989; Gorgin *et al.* 2011). Natural phosphate rock is the primary raw material used in the manufacture of phosphate fertilizers. Natural phosphate rock comes from rocks containing mineral apatite that contains quite high amount of P_2O_5 (Lindsay *et al.* 1989; Wahida *et al.* 2007). On the other hand, prediction of the amount of P_2O_5 in soil, organic materials and phosphate rocks in general depends on the extraction methods employed using different kinds of extractant solutions (Gartley *et al.* 2002; Kweon *et al.* 2015) .

Prediction of the availability of P in soil for any kinds of cultivated plants has to use appropriate methods of soil analysis. Phosphate availability is usually measured as a function of chemical equilibrium that is controlled by solubility and rate limited process (Sparks 1989; Lindsay *et al.* 1989; Arai and Sparks 2007; Kweon *et al.* 2015). Most methods used for the determination of available P attempt to quantify soluble P using different extractant solutions, but few of them related to P supply rates that are relevant to plant uptake (Ziadi *et al.* 2001; Lynch 2011; Meetei *et al.* 2015). Test methods for soil constituents including organic and phosphate rocks do not measure the amount of available P to a certain crop, but extract a portion of P from the soil constituents that is related to plant available P (Devau 2010; Lynch 2011; Rouached *et al.* 2010; Babana and Antoun 2006; Kweon *et al.* 2015). The amount of P extracted using different kinds of methods has to be related to variety of crop production, but the correlation will not always be transferable between crops and soils (Morel *et al.* 2014; Sing *et al*. 2005; Lumbanraja and Utomo 1996). It is because the immediately available P pool is constantly replenished through dissolution or desorption of less available P and through the mineralization of P in soil constituents such as weathering of soil and phosphate rocks and decomposition of organic matter (Ziadi *et al.* 2001) and the available P for plant is strongly time dependent (van der Zee *et al.* 1988; van der Zee *et al.* 1986; Vetterlein *et al.* 1999).

There are several methods that are often used in the determination of soil P, namely Bray P-1, Mehlich-1, and Olsen. The most commonly used methods are the alkaline bicarbonate method (Olsen *et al.* 1954; Wolf and Baker 1985) and the acid ammonium fluoride extraction (Bray and Kurtz 1945; Wolf and Baker 1985) with various modifications. The bicarbonate method using $NaHCO_3$ solution buffered at pH 8.5 (Olsen *et al.* 1954; Wolf and Baker 1985) has been used successfully in a wide range of acid to alkaline soils, especially in alkaline soils, while the acid ammonium fluoride extraction (Bray and Kurtz 1945) has been widely used on acid and neutral soils. Both methods are purely chemical soil tests that cannot be interpreted to plant function (Wolf and Baker 1985; Tiessen and Moir 2008). Various soil samples are commonly used for P extraction using Mehlich-1 method, expressing an excellent method to test the versatility of soil P extractant (Mehlich 1972). Mehlich-1 worked well in predicting plant- available P in acidic coastal plain soil (pH less than 6.5) with low cation exchange capacity (CEC < 10 cmol kg^{-1}) and low organic mater content (< 5%, however, Mehlich-1 was not always adequate in predicting plant-available P in soils with high pH and CEC and significant accumulations of iron and aluminum such as in tropical Ultisols. Mehlich-1 method, which is suitable applied on acidic soils, can extract P in the form of Al-P, Fe-P and Ca-P (Meetei *et al.* 2015).

Phosphorus extraction methods usually take place in an equilibrium state to determine the available P for plant uptake. However, the equilibrium reaction is found less corresponding to availability of P for plant uptake (Meetei *et al.* 2015). The amount of P being desorbed from the colloid of soil constituents or phosphate rocks in the equilibrium reaction will be limited by the P concentration in the solution (pseudo solubility product - Ksp). Meanwhile, the "true" reaction of P release into soil solution is an open reaction in which the reaction product of P loses through plant uptake or leaching in the soil systems (Koopmans *et al.* 2004; Maguire and Sims 2002; van der Zee *et al.* 1988; Torrent and Delgado 2001; Tipping *et al.* 2014). The desorbed P from soil colloids in the field soil systems will not be limited by the Ksp such as in the equilibrium condition but rather the released P will be absorbed by plant roots or reacted into a different form (Tiesen and and Moir 2008; Sparks

1989; Schoumans 2013). Therefore, the kinetics approaches will be more reliable to express the availability of P in the soil reaction in describing the availability of P for plants (Lookman *et al.* 1995; Lookman *et al.* 1996; Lynch 2011; Nafiu 2009; van der Zee *et al.* 1986). The kinetics P can describe P release from soil colloids or phosphate rocks continuously using Bray P-1, Mehlich-1, and Olsen solutions. In the kinetics reaction, the cumulative product of P, which is extracted from the soil reactor, is expected to be higher than that in the equilibrium reaction. The purposes of the study were (1) to compare the amount of phosphate extracted by Bray P-1, Mehlich-1 and Olsen solutions in equilibrium and kinetics conditions, and (2) to compare the rate constants (kinetics) of P release using Bray P-1, Mehlich-1 and Olsen solutions in determining extractable P in a soil sample, compost and phosphate rock.

MATERIALS AND METHODS

The soil constituents used in this study were phosphate rock from Egypt, organic material (*i.e.* compost from chicken egg production) and a soil sample taken from the Experimental Station of University of Lampung in Natar, South Lampung District. The extractants used for determining the available P were Bray 1 (0.03 M NH_4F + 0.025 M HCl), Mehlich-1 (0.05 M HCl + 0.0124 M H_2SO_4), and Olsen (0.5 M $NaHCO_3$ buffered at pH 8.5) solutions (Bray and Kurtz 1945; Mehlich 1972; Olsen *et al.* 1954). The P desorption reaction was conducted using a sequential extraction using batch techniques (Sparks 1989; Tiessen and Moir 2008) for the samples in the treatments of B_1 (100% soil), B_2 (100% phosphate rock), B_3 (100% compost), B_4 (75% soil + 25% phosphate rocks), B_5 (50% soil + 25% phosphate rock + 25% organic material). The amount of P extracted in the equilibrium condition of all treatments (B_1, B_2, B_3, B_4, and B_5) were determined using Bray P-1, Mehlich-1 and Olsen solutions (Bray and Kurtz 1945; Mehlich 1972; Olsen *et al.* 1954). On the other hand, the amount of P extracted in kinetics condition was determined using a sequential extraction (Tiessen and Moir 2008) followed by the cumulative extraction of day 1 + day 2 + day 4 + day 8 + day 16 + day 32 + day 64. About 1.5 g of samples was weighed in triplicate and then placed into a bottle, then 15 ml of P extractant solutions (Bray P-1, Mehlich-1, and Olsen) was added to the respective bottle. The suspensions were shaken using a shaker with the speed of 500 rpm for 30 minutes. The soil constituent suspensions were centrifuged at a speed of 5000

rpm for 10 minutes, then filtered using a filter paper to separate the solids and the clear solutions. The solids were subsequently extracted back using fresh extractant solutions of Bray P-1, Mehlich-1 and Olsen, respectively. The clear solution from each sequential extraction was used to determine the concentration of P by using a spectrophotometer at a wavelength of 720 nm (Murphy and Riley 1962; Thom and Utomo 1991).

The data were tabulated and interpreted based on the results in equilibrium and kinetics conditions. The following kinetics equations that describe the P release rate of the reactants (soil, phosphate rock and organic material) according to pseudo first order kinetics equation (Sparks 1989).

$$X\text{-}P_o \text{ à } X\text{-}P_t \text{ à } P_t \quad . . . . (1)$$

in which $X\text{-}P_o$ is the fraction of P at zero time, $X\text{-}P_t$ is the fraction of P in the colloid at time t, and P_t is the accumulation of P fraction removed from the soil reactor at time t.

$$dP/dt = \underline{k}P^n . . . . (2)$$

in which P is the fraction of P in the colloid ((P_o - P_{ex})/ P_o) and n is the order of the reaction, and t is time (days), P_{ex} is the extracted P at time t, and k is the rate constant. For the pseudo first order kinetics:

$$dP/dt = \underline{k}P . . . . (3)$$

$$dP/P = \underline{k}dt . . . . (4)$$

by integration of equation (4) then,

$$\ln P_o - \ln P_t = \underline{k}t . . . . (5)$$

rearranged

$$\ln P_t = \ln P_o - \underline{k}t . . . . (6)$$

When *ln* P_t is plotted as a function of *t* (day), it is a linear equation to create the kinetics figure of pseudofirst order to determine the rate constant *k*.

RESULTS AND DISCUSSION

The chemical properties of soil sample, P content in the phosphate rock, and P content in the organic material are presented in Table 1. The soil (Ultisol) from the Experimental Station of the University of Lampung in Natar has low fertility status as indicated by low pH (acid soil), low P-potential, very low available-P and exchangeable-

Table 1. Chemical properties of Ultisol from Natar, P content in the phosphate rock
and P content in the organic matterial used in the study.

Chemical properties	Value	Criteria*
pH H_2O	5.05	Acid
pH KCl	4.82	Acid
Total-N (%)	0.06	Very low
Available-P(Bray P-1) (mg kg^{-1})	2.66	Very low
Exchangeable-K (cmol kg^{-1})	0.24	Low
Total-C (%)	0.43	Very low
CEC (cmol kg^{-1})	5.73	Low
P_2O_5 of soil by 25% HCl (mg kg^{-1})	197.64	low
P_2O_5 of phosphate rock by 25% HCl(%)	25.87	High
P_2O_5 of organic by 25% HCl(%)	3.14	High

*(Soil Research Institute 2005).

K, and very low total nitrogen and total-C. The low content of the nutrients in the soil is probably due to the soil has undergone further weathering and most of organic materials in the soil have been lost due to leaching processes and intensive decomposition. The potential P contents of the phosphate rock and organic material extracted using 25% HCl are considered as high, *i.e.* 25.87% (P_2O_5) and 3.14% (P_2O_5), respectively.

Comparison of the Amounts of Extracted P in Equilibrium and Kinetics Conditions

The cumulative curve of P concentrations extracted from soil sample using different extractant solutions of Bray P-1, Mehlich-1, and Olsen is presented in Figure 1, and the cumulative P concentrations determined using the three solutions in equilibrium and kinetics conditions (sequential extraction) are presented in Table 2. The cumulative extracted P from soil increases as a function of extraction time (days) (Figure 1). It showed that the Mehlich-1 solution extracts the highest amount of P, followed by Bray P-1 and Olsen solutions. The amount of P extracted from the soil by Bray P-1 solution in equilibrium condition (*i.e.* 2.84 mg kg^{-1}) is about nine times less than that of in kinetics condition (*i.e.* 25.98mg kg^{-1}). Similarly, the amount of P extracted from the same soil by Mehlich-1 solution in equilibrium condition (*i.e.* 4.64m g kg^{-1}) is about eight times less than that in kinetics condition (*i.e.* 33.93mg kg^{-1}) and the amount of P extracted by Olsen solution in equilibrium condition (*i.e.* 1.65 mg kg^{-1}) is about 14 time less than that in kinetics condition (*i.e.* 21.70 mg kg^{-1}).

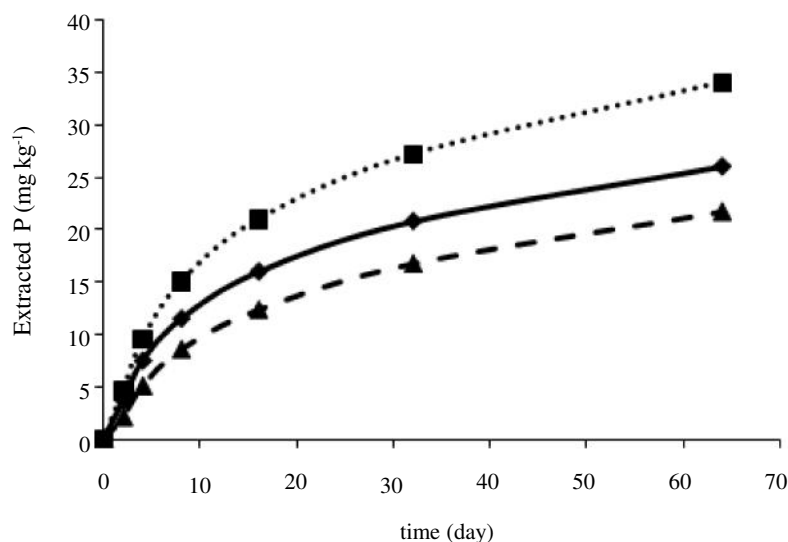Similar trends as those in the soil sample were found for all other treatments (100% phosphate rock,

Figure 1. Cumulative extracted P from soil as a function of time (t) using Bray P-1, Melich-1 and Olsen
⬥ : Bray, ▪ : Mehlich, ▲ : Olsen.

Table 2. Comparison of the amounts of P in each treatment extracted using Bray P-1, Mehlich-1, and Olsen solutions in equilibrium and kinetics conditions.

Treatment	Extractant Solution	Extracted P (mg kg^{-1})			t-calculated	t-Table	
		Equilibrium	vs	Kinetics		(0.05)	(0.01)
Soil	Bray P-1	2.84		25.98	7.85*		
	Mehlich-1	4.64		33.93	11.89*	6.31	12.71
	Olsen	1.55		21.70	11.58*		
P-rock	Bray P-1	18.94		236.19	14.55**		
	Mehlich-1	6,408.28		49,970.73	23.85**		
	Olsen	9.28		96.61	16.21**		
Compost	Bray P-1	2,979.21		6,467.87	7.98*		
	Mehlich-1	3,612.20		29,155.17	17.14**		
	Olsen	1,880.67		6,959.33	8.14*		
Soil+P-rock	Bray P-1	23.29		235.84	8.37*		
	Mehlich-1	4,822.87		61,176.83	54.42**		
	Olsen	3.18		47.28	17.48**		
Soil+P-rock+ Compost	Bray P-1	34.82		356.60	14.76**		
	Mehlich-1	5,622.88		49,978.46	33.82**		
	Olsen	63.91		487.65	13.81**		

*= significantly different at 5% significance level; **= significantly different at 1% significance level.

100% compost, 75% soil + 25% phosphate rock and 50% soil + 25% phosphate rock + 25% compost) (Table 2). The amounts of extracted P employing equilibrium condition in all treatments are significantly lower compared to that in kinetics condition. Especially, the amounts of extracted P employing equilibrium condition in the presence of phosphate rock are highly significantly (** significant at 1%) lower compared to that in the kinetics condition, except that in the mixture of soil and phosphate rock of the extraction of Bray P-1 solution in which the difference on the amount of extracted P is significant (* significant at 5%).

It also indicated that the amount of extractable P in each treatment extracted by Bray P-1, Mehlich-1, and Olsen solutions in equilibrium condition is approximately 10 times lower than that of extracted P in the kinetics condition. The reason for these results can be explained as the following reactions (7) and (9):

$$X-P_o à X-P_t + P_t K_{seq}. \quad \ldots \ldots \ldots \quad (7)$$
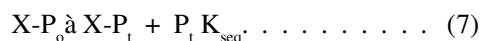
In which P_t is not removed from the soil reactor, then:

$$K_{seq} = (X-P_t)(P_t) \quad \ldots \ldots \ldots \ldots \ldots \quad (8)$$

In the equilibrium condition (7), the product of extracted P_t in the solution controls the equilibrium constant of "extractability product" (K_{seq}) and therefore when the P_t product in the solution meets the K_{seq} (8), then the P from colloids will not be removed any more or the reaction stops (equilibrium), while in kinetics, the following reaction takes place (9):

$$X-P_o à X-P_t à P_t \quad \ldots \ldots \ldots \ldots \ldots .(9)$$
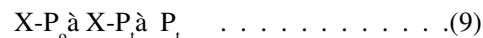
In which P_t (9) is removed from the soil reactor and the extracted solution is renewed and therefore, the P_t product in the solution can not control the K_{seq} (8), then the P from colloids ($X-P_t$) can be removed or extracted continuously or the reaction can still continue until asymptotically close to the quantity of potential P (referring to Figure 1 and Table 1, especially the quantity of P_2O_5 extracted by 25% HCl that is considered as potential extractable P) that can be extracted from the colloids.

Comparison of the Amounts of Extracted P Employing Bray P-1, Mehlich-1 and Olsen Solutions in Equilibrium and Kinetics Conditions

The results showed that Mehlich-1 solution is the most powerful solution to extract P from the soil constituents followed by Bray P-1 solution and Olsen solution, except that in the soil + phosphate rock + compost treatment in which the amount of P extracted using Mehlich-1 solution is the highest

Table 3. Comparison of extracted P employing Bray P-1, Mehlich-1, and Olsen solutions in equilibrium and kinetics conditions.

Extractant solution	t-calculated of extracted P		t-table	
	Equilibrium	Kinetics	0.05	0.01
Mehlich-1 vsBray P-1	74.85**	94.23**	6.31	12.71
Bray P-1 vs Olsen	51.70**	3.01[ns]		
Mehlich-1 vs Olsen	71.73**	136.10**		

ns= not significantly different *= significantly different at 5% significance level; **= significantly different at 1% significance level

followed by that in the Olsen solution and Bray P-1 solution both in equilibrium kinetics conditions (Table 2). The results in Table 3 also showed that the amounts of P extracted using Mehlich-1 solution are highly significantly (** significant at 1%) higher compared to that of using Bray P-1 and Olsen solutions both in equilibrium and kinetics conditions. In addition, the amounts of P extracted using Bray P-1 solution are highly significantly (** significant at 1%) higher compared to that of using Olsen solutions in equilibrium condition, but the amounts of P extracted using Bray P-1 and Olsen are not significantly different in the kinetics condition. One of the reasons could be related to the acidity of the solutions. Mehlich-1 solution consists of two acid solutions (0.05 M HCl + 0.0125 M H$_2$SO$_4$) that are highly acidic (Mehlich 1972); Bray P-1 solution consists of 0.025 M HCl + 0.03 M NH$_4$F in which the F$^-$ ion will be as powerful as H$_2$PO$_4^-$ and HPO$_4^{2-}$ for anion exchange (Bray and Kurtz, 1945); while Olsen solution consists of 0.5 M NaHCO$_3$ buffered at pH 8.5, which is more appropriate for calcareous soils (Olsen *et al.* 1954). The non significant difference between the amounts of P extracted using Bray P-1 and Olsen solutions in kinetics condition is not clear. The trends of the amounts of P extracted

using the two solutions are not consistent. For example, the amounts of P extracted using Bray P-1 solution are higher compared to that of Olsen solution in the treatments of (1) soil, (2) phosphate rock and (3) soil + phosphate rock. On the other hand, the amounts of P extracted using Olsen solution are higher compared to that of Bray P-1 solution in the treatments of (1) compost and (2) soil + phosphate rock + compost. The interesting result is that the amounts of P extracted using Olsen solution are consistently higher compared to that of using Bray P-1 in the treatment of soil + phosphate rock + compost both in equilibrium and kinetics conditions.

Kinetics of P Release from Soil Constituents Employing Bray P-1, Mehlich-1, and Olsen Solutions

Figure 2 indicates the fraction of P remained in the colloids at time *t*, showing the lines of linear curves started from the steeper (higher) slopes at the beginning of the reactions followed by the lower asymptotic slopes at the later reactions. In kinetics reaction, P in soil solution as the product of P release is removed from the soil reactor, the rate of the P release from colloids will be determined by the
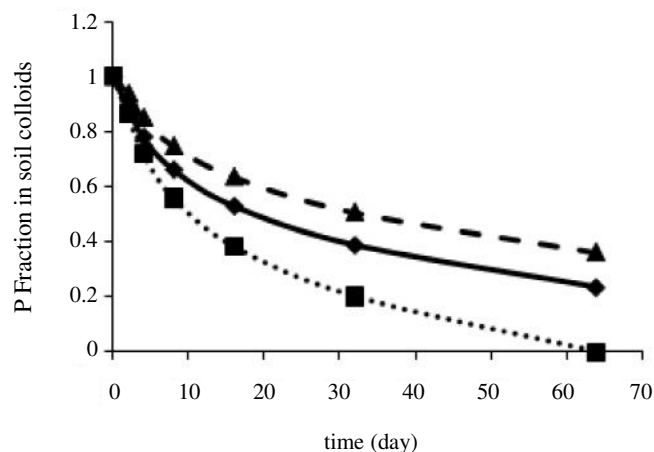

Figure 2. P-fraction in soil extracted using Bray P-1, Melich-1 and Olsen solutions as a function of time
———◆———: Bray, ∙∙∙■∙∙∙: Mehlich, ━▲━ : Olsen.

Table 4. Linear equations of P kinetics in each treatment determined using Bray P-1, Mehlich-1 and Olsen
    solutions.

Treatment	Extractant Solution	Linier equation	k	r^2
Soil	Bray P-1	y = -0.0264x – 0.143	-0.0264	0.961
	Mehlich-1	y = -0.0472x – 0.138	-0.0472	0.986
	Olsen	y = -0.0196x – 0.087	-0.0196	0.959
P-rock	Bray P-1	y = -0.0174x – 0.001	-0.0174	0.913
	Mehlich -1	y = -0.0486x – 0.159	-0.0486	0.985
	Olsen	y = -0.0125x – 0.001	-0.0125	0.931
Compost	Bray P-1	y = -0.0052x – 0.095	-0.0052	0.695
	Mehlich -1	y = -0.0725x – 0.267	-0.0725	0.976
	Olsen	y = -0.0054x – 0.081	-0.0054	0.827
Soil + P-rock	Bray P-1	y = -0.0285x – 0.001	-0.0285	0.923
	Mehlich -1	y = -0.0487x – 0.158	-0.0487	0.986
	Olsen	y = -0.0215x – 0.001	-0.0215	0.911
Soil + P-rock+ Compost	Bray P-1	y = -0.0101x – 0.001	-0.0101	0.914
	Mehlich -1	y = -0.0477x – 0.150	-0.0477	0.988
	Olsen	y = -0.0082x – 0.002	-0.0082	0.901

Note: k = rate constant of P; r^2 = coefficient determination; y= ln P_t ; x= time t (day)

concentration of P in the colloids and the energy involved such as acidity and ionic strength of particular solution to dissolve or extract P from the soil colloids (Wolf and Baker 1985; Tiessen and Moir 2008; Sparks 1989).

The data in Table 4 are the pseudo first order of the reaction employing the linear equation of $lnP_t = lnP_o - kt$ (6), in which the concentration of P_t is expressed in the fraction of P in soil colloids as a function of time t (day) and the slope k represents the rate constant of the reaction (Nafiu 2009; Lookman *et al*. 1995; Sparks 1989). Figure 3 represents the *ln [P]*$_t$ as a function of time in the pseudo first-order reaction of P desorption from soil,

Figure 4 represents that from phosphate rock and Figure 5 represents that from compost.

The equations of the *ln [P]*$_t$ as a function of time and the rate constants that are represented by the slopes of the linear equations for all treatments are presented in Table 4. The highest rate constants (*k*) of the reactions in all treatments are found in the extractions using Mehlich-1 solution for desorbed P followed by that of using Bray P-1 solution and that of using Olsen solution. The reasons for this finding could be due to the Mehlich-1 solution is the most powerful solution to release P from colloids since Mehlich-1 solution is the strongest acidic solution compared to that of Bray P-1 and Olsen
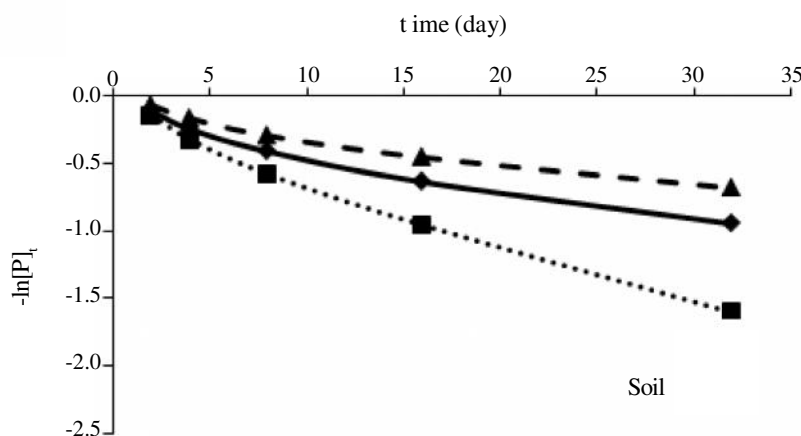
Figure 3. *ln [P]*$_t$ as a function of time on the pseudo first-order reaction of P desorption from soil. ◆: Bray, ■: Mehlich, ▲ : Olsen.
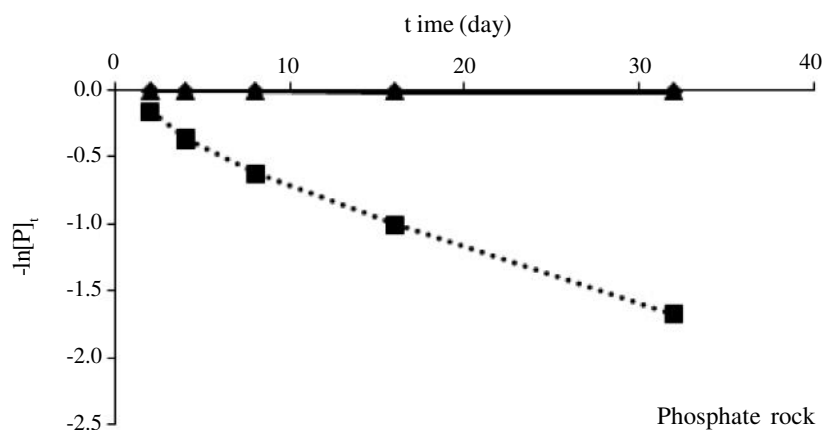
Figure 4. *ln [P]$_t$* as a function of time on the pseudo first-order reaction of P desorption from phosphate rock. ◆——: Bray, ···■···: Mehlich, —▲—: Olsen.
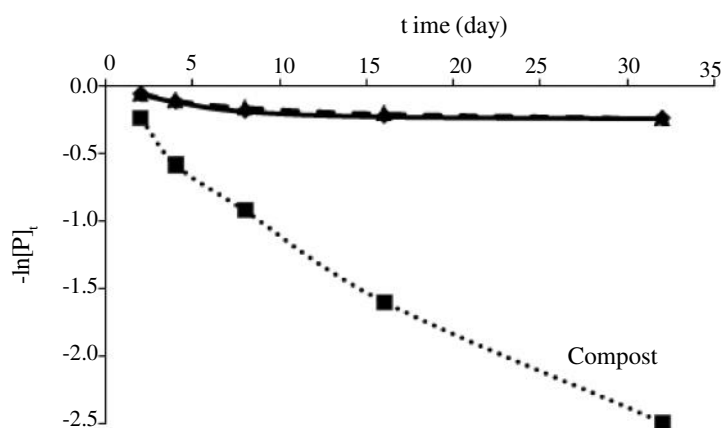

Figure 5. *ln [P]$_t$* as a function of time on the pseudo first-order reaction of P desorption from compost. ◆——: Bray, ···■···: Mehlich, —▲— : Olsen.

solutions, therefore, Mehlich-1 solution has more power to extract P from Al-P, Fe-P, and Ca-P from soil colloids, and the Mehlich-1 extraction is more suitable for acid soils (pH <6.5) with CEC less than 10 cmol kg^{-1} and organic matter content less than 5% (Wolf and Baker 1995). Mehlich-1 solution also has the highest ionic strength [I] compared to Bray P-1 and Olsen solutions (Evangelou 1998).

CONCLUSIONS

The amounts of extracted P employing equilibrium condition in all treatments are significantly lower compared to that in kinetics condition. The results also showed that Mehlich-1 solution is the most powerful solution to extract P followed by Bray P-1 solution and Olsen solution, except that in the soil + phosphate rock + compost treatment in which the amount of P extracted using Mehlich-1 solution is the highest followed by Olsen solution and Bray P-

1 solution both in equilibrium and kinetics conditions. The highest rate constants (*k*) of the reaction in all treatments were found in the extractions using Melich-1 solution for desorbed P followed by that of using Bray P-1 solution and Olsen solution. Further researches are expected to study the relationships of these findings to any kinds of crop productions in the field.

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