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

Received 02 January 2017/ accepted 01 May 2017

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 give 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

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 yang diextrak 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 mengekstraksi P dari konstituen tanah yang diextraksi oleh larutan Bray P-1 dan paling sedikit adalah larutan Olsen, keduanya pada perlakuan tanah + batuan fosfat + kompos dimana jumlah P yang diekstraksi menggunakan larutan Mehlich-1 adalah yang tertinggi kemudian diextraksi 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 diextraksi larutan Bray P-1 dan yang paling rendah adalah dengan menggunakan larutan Olsen.

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

J Trop Soils, Vol. 22, No. 2, 2017: 67-76
ISSN 0852-257X
INTRODUCTION

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 phosphate rock comes from rocks containing mineral apatite that contains quite high amount of 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 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,

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 (Ziadì 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 (Ziadì 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 NaHCO₃ 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 matter 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 NH₄F + 0.025 M HCl), Mehlich-1 (0.05 M HCl + 0.0124 M H₂SO₄), and Olsen (0.5 M NaHCO₃ 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 B₁ (100% soil), B₂(100% phosphate rock), B₃ (100% compost), B₄(75% soil + 25% phosphate rocks), B₅ (50% soil + 25% phosphate rock + 25% organic material). The amount of P extracted in the equilibrium condition of all treatments (B₁, B₂, B₃, B₄, and B₅) 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).

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

\[ \frac{dP}{dt} = kP^n \]  
\[ \text{in which } P \text{ is the fraction of P in the colloid } \left( \frac{P_t}{P_o} \right) \text{ and } n \text{ is the order of the reaction, and } t \text{ is time (days), } P_o \text{ is the extracted P at time } t, \text{ and } k \text{ is the rate constant. For the pseudo first order kinetics:} \]

\[ \frac{dP}{dt} = kP \]  
\[ \frac{dP}{P} = kdt \]

by integration of equation (4) then,

\[ \ln P_t - \ln P_o = kt \]

rearranged

\[ \ln P_t = \ln P_o - kt \]

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-

J Trop Soils, Vol. 22, No. 2, 2017: 67-76
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$_2$O$_5$) and 3.14% (P$_2$O$_5$), 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. 25.98 mg kg$^{-1}$). Similarly, the amount of P extracted from the same soil by Mehlich-1 solution in equilibrium condition (i.e. 4.64 mg kg$^{-1}$) is about eight times less than that in kinetics condition (i.e. 33.93 mg 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, 100% organic material) and the amounts of P extracted were lower in equilibrium condition compared to kinetics condition.

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

| Chemical properties                        | Value       | Criteria* |
|-------------------------------------------|-------------|-----------|
| pH H$_2$O                                 | 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$_2$O$_5$ of soil by25% HCl (mg kg$^{-1}$)| 197.64      | low       |
| P$_2$O$_5$ of phosphate rock by25% HCl(%)  | 25.87       | High      |
| P$_2$O$_5$ of organic by25% HCl(%)         | 3.14        | High      |

*(Soil Research Institute 2005).*

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

\[ X-P_0 \rightarrow X-P_t + P_i K_{seq} \]  \hspace{1cm} (7)

In which P_i is not removed from the soil reactor, then:

\[ K_{seq} = (X-P_t)/(P_i) \]  \hspace{1cm} (8)

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

\[ X-P_0 \rightarrow X-P_t \rightarrow P_i \]  \hspace{1cm} (9)

In which P_i (9) is removed from the soil reactor and the extracted solution is renewed and therefore, the P_i 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 PO_4 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 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 (0.05) | t-Table (0.01) |
|-------------------|---------------------|-------------------------------|--------------|---------------|---------------|
|                   |                     | Equilibrium vs Kinetics       |              |               |               |
| Soil              | Bray P-1            | 2.84                          | 25.98        | 7.85*         | 6.31          |
|                   | Mehlich-1           | 4.64                          | 33.93        | 11.89*        | 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**       |               |
| Compost           | 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.
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 $M \ HCl + 0.0125 M \ H_2SO_4$) that are highly acidic (Mehlich 1972); Bray P-1 solution consists of 0.025 $M \ HCl + 0.03 M \ NH_4F$ in which the $F^-$ ion will be as powerful as $H_2PO_4^-$ 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, Mehlich-1 and Olsen solutions as a function of time](image)

---

### 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 vs Bray P-1 | 74.85** | 94.23** | 6.31 | 12.71 |
| Bray P-1 vs Olsen | 51.70** | 3.01** |         |
| Mehlich-1 vs Olsen | 71.73** | 136.10** |         |

*ns* = not significantly different * *= significantly different at 5% significance level; ** *= significantly different at 1% significance level
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 $ln [P]$, 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 $ln [P]$, 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](image-url)  
Figure 3. $ln [P]$, as a function of time on the pseudo first-order reaction of P desorption from soil.  
---: 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.

**REFERENCES**

Arai Y and DL Sparks. 2007. Phosphate reaction dynamics in soils and soil minerals: a multiscale approach. *Adv Agron* 94: 135-179.

Babana AH and H Antoun. 2006. Effect of Tilemsi phosphate rock-solubilizing microorganism on phosphorus uptake and yield of field-grown wheat (*Triticum aestivum* L.) in Mali. *Plant Soil* 287: 51-58.

Bray RH and LT Kurtz. 1945. Determination of total organic and available forms of phosphate in soils. *Soil Sci* 59:39-45.
De Araújo L, E Sampaio and M De Araújo. 2015. Phosphorus desorption from Fe and Al oxides mediated by soil microorganisms. Commun Soil Sci Plant Anal 46: 633-640.

Devau N, E Le Cadre, P Hinsinger and FGérard. 2010. A mechanistic model for understanding root-induced chemical changes controlling phosphorus availability. Ann Bot (Lond) 105: 1183-1197.

Evangelou VP. 1998. Environmental Soil and Water Chemistry: Principle and Application, John Wiley & Sons Inc. New York, 564 p.

Gartley KL, JT Sims, CT Olsen and P Chu. 2002. Comparison of soil test extractants used in mid-Atlantic United States. Commun Soil Sci Plant Anal 33: 873-895.

Gorgin N, M Fekri and L Sadegh. 2011. Impact of organic-matter application on phosphorus-desorption kinetics in two agricultural soils in Southeastern Iran. Commun Soil Sci Plant Anal 42: 514-527.

Kooppans GF, WJ Chardon, P de Willigen and WH van Riemsdijk. 2004. Phosphorus desorption dynamics in soil and the link to a dynamic concept of bioavailability. J Environ Qual 33:1393-1402.

Kweon G, E Lund, C Maxton, W Lee and D Mengel. 2015. Comparison of soil phosphorus measurements. T Am Soc Agric Biol Eng 58: 405-414.

Lindsay WL, PLGVlek and SHChien. 1989. Phosphate minerals. In: JB Dixon and SB Weed (eds). Minerals in Soil Environment, 2nd Ed. Soil Science Society of America, Madison, WI, pp. 1089-1130.

Lookman R, D Freese, R Merckx, K Vlassak and WH van Riemsdijk. 1995. Long-term kinetics of phosphate release from soil. Environ Sci Technol 29:1569-1575.

Lookman R, K Jansen, R Merckx and K Vlassak. 1996. Relationship between soil properties and phosphate saturation parameters a transect study in northern Belgium. Geoderma 69: 265-274.

Lumbanraja J. 1995. Sorption behavior of phosphorus in acid soil of Ultisols: Effects of phosphorus sources and urea. J Pen Pengb Wil Lahan Kering 15:1-17 (in Indonesian).

Lumbanraja J, T Tadano, M Ninaki, K Oya, T Yoshida, M Utomo and AD Sitorus. 1982. Nutritional limitation factors for rice and corn growth on Podsolic Soils in Lampung Province. In: Y Asada (ed). Cooperation Research between DGHE and JSPS. Ehime University, Japan, pp.118-124.

Lumbanraja J, T Tadano, M Ninaki, K Oya, T Yoshida, M Utomo and AD Sitorus. 1982. The effect of nitrogen, phosphorus, and potassium fertilizers on cassava growth on “Bandarjaya Podsolic Soil” and “Gedung Meneng Latosol Soil”. In: Y Asada (ed) Cooperation Research between DGHE and JSPS. Ehime University, Japan, pp.112-122.

Lumbanraja J and M Utomo. 1996. Phosphorus availability for rice and P-sorption behavior in soil affected by P-source and N-fertilizer in an acid soil of Sumatera. IVth International Symposium on Plant-Soil Interactions at Low pH. Brazil, March 17-24.

Lumbanraja J, M Utomo and B Sitio. 1995. Sorption characteristics of soil phosphorus in the three different tillages and nitrogen fertilization in the experimental plot of a long-term experiment plots (in Indonesian). In M Utomo, IH Utomo, FX Susilo, J Lumbanraja (eds) Proceedings of the Fifth National Seminar of Conservation Tillage. Bandar Lampung Indonesia pp. 69-77.

Lumbanraja J, S Djuniwati and M Murad. 1994. The influence of particle size and the type of iron concretions and compost on the availability of phosphorus in the clay fraction of an Ultisols and an Alfisols (in Indonesian). J Pen Pengb Wil Lahan Kering 14:12-27.

Lynch JP. 2011. Root phenes for enhanced soil exploration and phosphorus acquisition: tools for future crops. Plant Physiol156:1041-1049.

Maguire RO and JT Sims. 2002. Soil testing to predict phosphorus leaching. J Environ Qual31:1601-1609.

Mehlich A. 1972. Uniformity of expressing soil test results. A case for calculating results on a volume basis. CommunSoil Sci Plant Anal: 417-424.

Meetei WH, HS Athokpam, RKK Singh, L Watham, N Chongtham, KN Devi, NB Singh, KL Singh and NJ Singh. 2015. Evaluation of some soil test methods in acid soils for available phosphorus for soybean in Imphal East Distric, Manipur, India. Afr J Agric Res 10:767-771.

Morel C, N Ziadi and A Messiga. 2014. Modeling of phosphorus dynamics in contrasting agroecosystems using long-term field experiments. Can J Soil Sci 94:377-387.

Murphy J and JP Riley. 1962. A modified single solution method for the determination of phosphate in natural waters. Anal Chimica Acta27:31-36.

Nafiu A. 2009. Effects of soil properties on the kinetics of desorption of phosphate from Alfisols by anion-exchange resins. J Plant Nutr Soil Sci 172:101-107.

OelkersEH and E Valsami-Jones. 2008. Phosphate mineral reactivity and global Sustainability. Elements 4: 83-87.

Olsen SR, CV Cole, FS Watanabe and LA Dean. 1954. Estimation of available phosphorus in soils by extraction with sodium bicarbonate. Cir. No. 939 USDA Washington, DC p. 19.

Pavlaticov A and NA Polyzopoulos. 1988. The role of diffusion in the kinetics of phosphate desorption: the relevance of the Elovich equation. Eur J Soil Sci 39: 425-436.

Rouachan H, AB Arpat and Y Poirier. 2010. Regulation of phosphorus starvation responses in plants: signaling players and cross-talks. Mol Plant 3: 288-299.

Schachtman DP, RJ Reid and SM Ayling. 1998. Phosphorus uptake by plants: from soil to cell. Plant Physiol 116: 447-453.

Schoumans OF. 2013. Description of the phosphorus sorption and desorption processes in lowland peaty clay soils. Soil Sci 178: 291-300.

Singh BR, T Krogstad, YS Shivay, BG Shivakumar and M Bakkegard. 2005. Phosphorus fractionation and sorption in P-enriched soils of Norway. Nutr Cycl Agroecosyst 73: 245-256.
Soil Research Institute. 2005. Technical Guidelines for Chemical Analysis of Soil, Plant, Water, and Fertilizer. Soil Research Institute. Bogor. 136 p.
Sparks DL. 1989. Kinetics of Soil Chemical Processes. Academic Press. INC. 210 p.
Tiesen H and JO Moir. 2008. Characterization of Available P by Sequential Extraction. In: MR Carter and EG Gregorich (eds). Soil Sampling and Methods of Analysis. 2nd Edition. Canadian Society of Soil Sciences, pp. 293-306
Thom WO and M Utomo. 1991. Laboratory Management and Soil and Plant Analysis Methods. University of Lampung. 85 pp (in Indonesian).
Tipping E, S Benham and JF Boyle. 2014. Atmospheric deposition of phosphorus to land and freshwater. Environ Sci: Processes & Impacts 16:1608-1617.
Torrent J and A Delgado. 2001. Using phosphorus concentration in the soil solution to predict phosphorus desorption to water. J Environ Qual 30:1829-1835.
Van der Zee SEATM and WH van Riemsdijk. 1986. Sorption kinetics and transport of phosphate in sandy soil. Geoderma 38:293-309.
Van der Zee SEATM and WH van Riemsdijk. 1988. Model for long-term phosphate reaction kinetics in soil. J Environ Qual 17:35-41.
Vetterlein D, C Bergmann and RF Hüttl. 1999. Phosphorus availability in different types of open-cast mine spoil and the potential impact of organic matter application. Plant Soil 213: 189-194.
Wahida A, A Fahmi and A Jamberi. 2007. Effect of phosphate rock fertilizer from Morocco on the rice growth in land acid sulfate. J Trop Soil 12: 85-90 (in Indonesian).
Wolf AM and DE Baker. 1985. Comparison of soil test phosphorus by Olsen, Bray-P1, Mehlich-1, and Mehlich-3 methods. Commun Soil Sci Plant Anal 16: 467-484.
Ziadi N, RR Simard, TS Tran and G Allard. 2001. Soil-available phosphorus as evaluated by desorption techniques and chemical extractions. Can J Soil Sci 81:167-174.