



Predicting the Bioavailability of Phosphorus in Soil Amended with Phosphate Rocks Using Isotopic Exchange Kinetics

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Abstract

Investigations on plant responses to applications of various forms and rates of P fertilizers usually involve glasshouse and/or field experiments. This traditional procedure assumes that whatever the soil-fertilizer-plant system, increase in total P uptake by plant between no P treatment (control) and fertilizer treatment equals the plant P uptake from fertilizer. This study uses the isotopic exchange technique in the laboratory to predict bioavailability of P fertilizers without the need to conduct glasshouse or field experiment. Serdang series soil (Typic Paleudult) was incubated with 7 sources of P fertilizers comprising of triple superphosphate (TSP) and phosphate rocks from North Carolina (NCPR), Algeria (APR), Tunisia (TPR), Jordan (JPR), Christmas Island (CIPR) and China (CPR) at the rates of 0, 2, 4, 6 and 8 g kg⁻¹ soil with 20 % moisture content at room temperature in three replications. The soils were sampled at 1, 3, 6 and 9 months after incubation and isotopically exchangeable P determined by method of Fardeau and Jappe (1976). Intensity, quantity and capacity factors of soil P were calculated and the residual availability of these fertilizers were predicted.

Phosphorus in solution was highest in TSP treated soil for all treatments. Among the phosphate rocks, NCPR at rate 8g kg⁻¹ soil gave the highest value while, CPR at rate 2 gave the lowest value. Thus showing that these PRs have different reactivity in this soil, where NCPR, APR, TPR and JPR were the reactive PR, while CIPR and CPR were the unreactive ones. The isotopically exchangeable P at one minute (E_1) in the soil sampled at 9 months after incubation was found to correlate very well with plant P uptake by oil palm seedlings grown under the same condition. Calculations made on the percentage of P derived from these fertilizers up to a period of more than one year after application showed that the reactive PRs to have more residual P made available to plants than the unreactive PR.

Introduction

Phosphorus is an essential nutrient element in crop production , and its deficiency can be a major factor in declining crop production in many acidic agriculture soils in developing countries(Chien, 1995; Chien and Menon, 1993).

In recent years, sharp increases in the price of raw materials for the manufacture of water soluble of P fertilizers, increased transport and application costs, and depressed agricultural commodity prices have raised interest in the use of phosphate rocks (PRs) as source of P fertilizer. Direct application of PR to soils may be an alternative, due of the possible high residual effect of PR. Thus it is considered best to use PR for the purpose of permanently improving the P status of soils.

Conventional method of evaluating and investigating P availability involves glasshouse or field trials to assess biological responses to an application of various forms of P fertilizers. For each P fertilizer, a large range in relative agronomic efficiency (RAE) values has been reported for pot and field experiment by direct application of PR. This traditional procedure assumes that whatever the soil-fertilizer-plant system, increases in total plant uptake between no P treatment and fertilized treatment equals the plant P uptake from fertilizer.

The isotopic exchange method can be used to predict the phosphorus bioavailability of fertilizers and hence for evaluating the agronomic effectiveness of P fertilizers without the need for conducting field or glasshouse experiments. It also

has an advantage over the chemical extractants because it does not disturb the soil components and there is an identity between the isotopically exchangeable P and the phosphate absorbed by plants (Morel and Fardeau, 1991).

In addition, to estimate the availability of soil P, it is necessary to consider intensity, quantity and capacity factors which can be assessed using isotopic exchange kinetics in the laboratory (Morel and Fardeau, 1991). Intensity factor (I) is the P concentration in solution of the soil-water suspension (C_p). Quantity factor (Q), is the quantity of all phosphate ions in soil solution. At time 1 minute, E_1 -value, is the amount of P in the soil-water suspension which is isotopically exchangeable during the first minute of exchange. Capacity factor describes the ability of the soil to maintain the intensity factor constant when P is added to or removed from the soil (the value of isotopically exchangeable P at 1 minute (E_1) divided by C_p (E_1/C_p)).

Besides that, available soil P can be divided into five pools using the E value method. The pools containing phosphate ions that will be released to the soil solution instantaneously in the central compartment is called isotopically exchangeable P at one minute (E_1) and will equilibrate with other pools, namely A, B, C, and D. *Pool A* is the amount of P which is exchangeable with P in soil solution from one minute to one day. *Pool B* is the amount of P which is exchangeable with P in soil solution from one day to three months. *Pool C* is the amount of P which is exchangeable with P in soil solution from three months to one year. *Pool D* is the

amount of P which is exchangeable with P in soil solution in more than one year

Thus the objectives of this experiment were :

- To assess the immediate and residual availability of P from P fertilizers added
- To evaluate the relative agronomic efficiency (RAE) of P fertilizers.
- To calculate P derived from fertilizer (%Pdff) in soil solution using the E value approach.

Materials and Methods

Six phosphate rocks (PRs) varying widely in reactivity and source were evaluated using Triple superphosphate (TSP) as comparison. The sources of PR used were from Christmas Island, North Carolina (USA), Jordan, China, Tunisia and Algeria. The soil used for this experiment was from the Serdang series (Typic Paleudult) collected from the UPM farm.

The chemical characteristics of the PRs were determined by digesting the PR samples in concentrated HNO_3 + HCl mixture. Two g of each P fertilizer was added in a beaker containing 4 ml HNO_3 , 4 ml HCl and 50 ml of distilled water. The mixture was heated to boil for about 30 minutes, cooled and filtered. The filtrate was collected and analysed. The moisture content was determined by drying 2 g PR in an oven at 105°C for two hours. The particle size of the PRs was determined by passing 100 g samples through sieves of mesh 80 (< 0.1875 mm), and the percentage of that passed was then calculated (SIRIM, 1995).

One kg soil was mixed with the P fertilizers (2, 4, 6, and 8 g P/kg soil) and incubated in plastic containers at 20 % moisture content and at room temperature. A control with no P treatment was included. Each treatment was replicated three times. The soil was sampled at 1, 3, 6, and 9 months after incubation. The isotopically exchangeable P at one minute (E_1) was determined in each case using the E value method (Fardeau and Jappe, 1976). The soil samples were air dried and ground to pass through 2 mm sieve for the E_1 determination.

A similar set of treatments were made using 15 kg soil where 3-months old uniform oil palm seedlings were planted and maintained for 9 months, after which the plants were harvested, dried and analysed for total P content.

Determination of isotopically exchangeable phosphorus (E value)

The determination of isotopically exchangeable phosphorus was carried out by shaking 10 g of soil with 99 ml distilled water overnight in a polyethylene bottle to obtain the steady-state soil-solution system. One ml of ^{32}P with a radioactivity (R) of about 2 MBq/10 gram soil, was added to the soil and mixed well with a magnetic stirrer at 200 rpm.

About 15 ml of the mixture was taken at 1, 10, 40 and 100 minutes, and immediately filtered through 0.025 μm pore-size filter to obtain a clear solution. Radioactivity (r_t) remaining in the soil solution at each time (t) was measured by

liquid scintillation counter (LSC). The same solution was also used for determination of phosphate ions in the soil solution (C_p).

Determination of phosphorus in the soil solution (C_p)

Malachite green with phosphomolybdate under acidic conditions was used to measure inorganic orthophosphate in nanomolar range of phosphate because P concentration in soil solution was very low.

The C_p was determined by adding 0.2 ml of reagent A (1.75 % (w/v) ammonium heptamolybdate.4H₂O in 6.3N H₂SO₄). The solution was allowed to stand for 10 minutes before adding 0.2 ml of reagent C (polyvinyl alcohol). The absorbance was read at 610 nm after allowing the solution to stand for about 30 minutes.

Determination of P status and P kinetics parameters.

Soil P status parameters

The intensity, quantity and capacity factors in the soil were calculated as follows :

$$\text{Intensity factor (I) is } C_p \text{ mg P } \Gamma^{-1} \quad (1)$$

$$\text{Quantity factor at 1 min (E}_1\text{)} = 10 C_p / (r_1/R) \text{ mg kg}^{-1} \text{ soil} \quad (2)$$

$$\text{Capacity factor at 1 min } E_1/C_p = 10 (R/r_1) \text{ kg}^{-1} \text{ soil} \quad (3)$$

Where C_p is P concentration in soil solution, E_1 is the amount of P in soil which isotopically exchangeable during the first minute of exchange, r_1 is the radioactivity remaining in soil solution at the time $t=1$ min, and R is the initial radioactivity in the soil solution at the time $t=0$ min.

Kinetics parameters

The decrease in radioactivity remaining in soil solution with isotopic exchange time can be described by the following equation (Fardeau et al, 1988)

$$r_t/R = (r_1/R)t^{-n} + 10C_p/P_M \quad (4)$$

where r_t is the radioactivity remaining in soil solution at each time t , r_1 is the radioactivity remaining in solution after one minute of isotopic exchange, n the kinetic parameter of the isotopic exchange and P_M is total P in the soil. The last term in equation (4), $10 C_p/P_M$, can be negligible between 1 and 10000 min. Therefore equation (4) can be transformed to the following equation :

$$\log (r_t/R) = \log r_1/R - n \log t \quad (5)$$

Slope " n " in equation (4) can be calculated by the least square method. If there are only two sampling times, t_1 and t_2 , the slope n can be obtained as follows:

$$n = - (rt_2 - \log rt_1) / (\log t_2 - \log t_1) \quad (5a)$$

If t_2 is ten times larger than t_1 , for instance $t_1 = 1$ min and $t_2 = 10$ min then :

$$n = - \log (rt_2/rt_1) \quad (5b)$$

Assuming that, at any time, the specific radioactivity of phosphate ions in solution is equal to the ions in the soil-solution system, the quantity E_t , isotopically exchangeable soil phosphorus, can be deduced as follows :

$$r_t/M = R/E_t \quad (6)$$

Where M is the quantity of phosphate ions in solution, since 10 g of soil are suspended in 100 ml of water, then $M=10C_p$. M and E_t are expressed in mg P kg⁻¹ soil and C_p in mg P l⁻¹. Combining (4) and (6), the following equation is derived :

$$E_t = M(R/r_t)t^n = E_1t^n \quad (7)$$

Therefore, the characterization of isotopic exchangeable phosphate ions between soil and solution, requires at least the determination of three parameters, namely : r_1/R , n and M . Equation (7) indicates that the estimate of the total available soil phosphate is a function of time, thus its value is clearly dependent on the time chosen for measurement.

The quantity, E_t (mg P kg⁻¹ soil), of isotopically exchanged P at time t is calculated assuming that ; ³¹PO₄ and ³²PO₄ ions have the same fate in the system and whatever the time t , the specific activity of phosphate ions in the soil solution is identical to that of the isotopically exchanged phosphate ions in the whole system.

Pool A is the amount of P which is exchangeable with P in soil solution from one minute to one day. **Pool B** is the amount of P which is exchangeable with P in soil solution from one day to three months. **Pool C** is the amount of P which is exchangeable with P in soil solution from three months to one year. **Pool D** is the

amount of P which is exchangeable with P in soil solution in more than one year.

These can then be calculated thus :

$$\text{Pool A} = E_{1 \text{ day}} - E_{1 \text{ min}} \quad (8)$$

$$\text{Pool B} = E_{3 \text{ months}} - E_{1 \text{ day}} \quad (9)$$

$$\text{Pool C} = E_{1 \text{ year}} - E_{3 \text{ months}} \quad (10)$$

$$\text{Pool D} = E_{\text{eq}} - E_{3 \text{ months}} \quad (11)$$

where $E_{\text{eq}} = P_m = \text{total P in the soil}$

Calculation of P derived from fertilizer (% Pdff) in the soil solution

For the determination of Pdff % required at least two treatments ; the soil without fertilizer and the same soil with fertilizer. Let SA_f and SA_o be the specific activities of phosphorus in soil solution with and without fertilizer, respectively, while Et_f and Et_o are the E value at a given time with and without fertilizer respectively. Pdff% in soil solution can be calculated as follows :

$$\text{Pdff}\% = 100 (1 - SA_f/SA_o) = 100 (Et_f - Et_o) / Et_f$$

Determination of relative agronomic effectiveness

The relative agronomic effectiveness (RAE) is the agronomic evaluation of each PR in comparison with a standard P source (TSP) as shown below :

$$\text{RAE} = \text{response to PR} / \text{response to standard P fertilizer (TSP)}$$

Where response to PR is calculated in terms of isotopically exchangeable P (E value) for each PR.

Analysis of Data

Statistical Analysis Package (SAS), version 6.0 for windows was used to analyse the data (Anova, DMRT and correlation coefficient).

Results and Discussion

The chemical composition of the PRs used are shown in Table 1. The P content from the various PRs ranges from 13.11 % in APR to 14.29 % in CIPR. TSP has the highest P content of 20.16 %. However Chien (1995) reported that the total P content is not an indication of chemical reactivity or agronomic effectiveness of PR. The particle size (% passing through in mesh 80) of the PRs used is also shown in Table 1. It could be seen that the particle sizes of the PRs vary widely and range from 46.45 % in NCPR to 99.71 % in APR. APR has the finest particles, wherein 99.71% of particles was below 0.1875 mm.

Soil P Status Parameter

Intensity factor (I) is the P concentration in the solution of the soil-water suspension (Cp), quantity factor (Q) (E-value) is the amount of P which is isotopically exchangeable, and then capacity factor (Cf) describes the ability of soil

to maintain the intensity factor constant when P is added to or removed from the soil (the value of isotopically exchangeable P divided by C_p (E value/ C_p)). Table 2 shows that the P concentration in the solution of the soil-water suspension (C_p) at 1 minute amongst the PRs is very low ranging from $0.16 \mu\text{gP g}^{-1}$ soil for soil treated with CPR at rate 2 to $1.50 \mu\text{gP g}^{-1}$ for soil treated with NCPR at rate 8. The C_p value for TSP was the highest for all rates while the C_p value of control was the lowest. This indicates that the ability of each PR to release P into the soil solution is different. The differences in PR physical, chemical and mineralogical properties affect their reactivity and dissolution to release P into the soil solution (Chien, 1995; Sale and Mokwunye, 1993).

Based on the C_p values, the results showed that NCPR, TPR, JPR and APR are more reactive than CIPR and CPR. The soluble P fertilizer (TSP) was not compared due to the high C_p value obtained. Increasing the rate of P application increased the concentration of phosphate ions in the solution for all treatments. The C_p values for reactive PR was always higher than the low unreactive sources. Generally the C_p values increased with rate of P application in the soil.

The r_1/R value is the radioactivity that remained in the solution after 1 minute of isotopic exchange over the total radioactivity added. Table 2 shows that the r_1/R in all PR varied from 0.04 to 0.08 and there are no significant differences among the treatments. Fardeau and Jappe (1978) reported that high P fixing soils generally have an r_1/R value < 0.2 and soils having $r_1/R > 0.4$ do not fix much P.

Tran et al, (1988) also reported that based on the analysis of the P sorption capacities of 58 Canadian soils, $r_1/R < 0.22$ indicated that the soil has a high fixing capacity. In addition Salcedo et al (1991) and Morel and Fardeau (1989) stated that the E value method was a good index to estimate soil P fixing capacity. The values from this study were below 0.2 for all PR treated soil, these were very low and indicated that Serdang soil fix much of the added P.

The high P-fixing capacity of the soil was related to their high clay content (Frossard et.al, 1994). A kinetic parameter (n value) which indicate the decrease of the radioactivity remaining in the solution over time ($\log r/R$ vs $\log t$) is presented in Table 3. The n value varied widely but generally there is no significant difference among the sources and rates of application.

The quantity of phosphate isotopically exchangeable within 1 minute (E_1 minute) was calculated from the corresponding values of C_p and r_1/R using the equation, $E_1 = 10 C_p/(r_1/R)$ (Table 2). The E_1 value was highest in NCPR, and the more reactive PRs (NCPR, JPR, APR and TPR) generally have E_1 values higher than the low reactive PRs (CIPR and CPR). The E_1 increased with C_p value, and tend to increase also with rate application of PR in the soil. The E_1 value is a good approximation of the quantity of free phosphate ions in the solution system available without chemical transformation to plant (Tran et al, 1988 and Salcedo et al 1991).

The exchangeable values at 3, 6 and 9 months after PR application were calculated using equation $E(t) = 10 C_p [R/r(1)]t^n$ (Morel and Fardeau, 1991) and presented in Table 3.

Capacity factor describes the ability of soil to maintain the intensity factor constant when P is added to or removed from the soil (the value of isotopically exchangeable P at 1 minute (E_1) divided by C_p (E_1/C_p)) (Table 2). In general the capacity factor increased with decreasing C_p and E value. There was no significant difference for the treatments in terms of the capacity factor value with the exception of the control (soil alone).

Pool A is the amount of P which is exchangeable with P in soil solution from one minute to one day. Pool B the amount of P which is exchangeable with P in soil solution from one day to three months. Pool C the amount of P which is exchangeable with P in soil solution from three months to one year. Pool D is the amount of P which is exchangeable with P in soil solution in more than one year. These were calculated and presented in Table 4. The pools estimate the immediate as well as the residual P availability in the soil.

In general Table 4 shows that NCPR is the best source to provide immediate and residual P in the soil, CIPR is slow to release P and has the lowest immediate or residual P availability. Conversely, TSP is superior in providing P immediately, but residual P availability is low. Chan (1981) reported that the residual effect of PR was found to be significant and gave good results in acid soils at least for two

to four years. There is no relationship between the rate of application of PR and the P pools size.

The expected percentage of P derived from fertilizer (Pdff) in 1 minute, 1 day, 3 months and 1 year are presented in Table 5. In general, Pdff values increase with E value and rate of P application. The ranking of PRs based on Pdff are:

TSP > NCPR > TPR > APR = JPR > CPR > CIPR

The exchangeable values at 1 minute, C_p , r_t/R , Pdff and capacity factor at 9 months after PR application were calculated and presented in tables 6. In general, the patterns of variation for all parameters at 9 months after PR application were the same as E_1 values after 1 month application of PR

Relationships between Plant P uptake and E value

The E_1 value after 9 months of PR applications gave good correlation with plant P uptake as shown in Figure 1. It is seen that E values increase with plant P uptake. This indicated that the E value can be used to predict the effectiveness of PR without the need for conducting field or green house experiment.

However Salcedo (1991) and Wolf et al (1986) reported that the E value has been shown to over estimate the soil available P because of over estimation of ^{31}P concentration in the soil. On the other hand, Kato et. al (1995) found that E_1 value

almost agreed with the plant P uptake and is a good indicator of available P in the soil.

Furthermore, Kato et al (1995) stated that although E_1 values over estimate plant available P, the E_1 value was could be a good index to compare the P availability of the soil.

Relative Agronomic Effectiveness

The expected relative agronomic effectiveness after 9 months of PR applications are presented in Table 7. The RAE (%) increase with the rate of application . Overall, Table 7 showed that the ranking of RAE (%) is in agreement with Pdf, which was :

$$\text{NCPR} > \text{TPR} > \text{APR} = \text{JPR} > \text{CPR} > \text{CIPR}$$

Correlation Between the Isotopically Exchangeable P and P Uptake by Oil Palm Seedling After 9 Month of PR application.

The coefficients of correlation between P uptake and E value at 1, 40 and 100 minutes are presented in Table 8. The E value at 1 minute gave the highest correlation with plant uptake. Cp at 1 minute also gave the highest correlation compared to Cp values obtained after 40 and 100 minutes, and there is a good correlation between E value and Cp for all times.

The coefficients of correlation between P status parameters and pool parameters of isotopically exchangeable P are presented in Table 9. The E values were highly correlated with water soluble P (Cp), pool A and pool D.

Conclusions

The isotopic exchange method can be used to predict the phosphorus bioavailability of fertilizers and thus for evaluating the agronomic effectiveness of P fertilizers without the need for conducting field or glasshouse experiments. It also has an advantage over the chemical extractants because it does not disturb the soil components and there is a similarity between the isotopically exchangeable P and the phosphate absorbed by plants. The isotopic exchange technique provides the most complete analysis of soil available phosphate, it can assess the immediate and residual availability of P. It can also be used in the determination of relative agronomic efficiency (RAE) of P fertilizers and also the calculation of P derived from fertilizer (%Pdff). The E value was also a good index to estimate soil P fixing capacity. This study showed that the ability of PR to provide P in the soil depends on their reactivity, and a constant result was obtained among all the parameters. In general, the ranking of PR reactivity in this study is as follows :

$$\text{NCPR} > \text{TPR} > \text{APR} = \text{JPR} > \text{CPR} > \text{CIPR}.$$

This study also identified a good correlation between P uptake with E values at 1 minute and P in the soil-water suspension (Cp)

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Table 1. The composition of the PRs used

P sources	Item (%)							
	P	P ₂ O ₅	CaO	CaO/P ₂ O ₅	Fe ₂ O ₃	Al ₂ O ₃	Mesh 80 (< 0.1875 mm)	Moisture
TSP	20.16	46.24	19.32	0.42	0.79	3.21	-	5.82
NCPR	13.47	30.90	45.03	1.46	0.28	0.89	46.45	2.28
APR	13.11	30.07	46.54	1.55	0.09	0.79	99.71	1.41
TPR	13.21	30.31	45.01	1.48	0.08	0.58	52.64	2.43
JPR	13.79	31.63	40.81	1.29	0.67	2.63	78.68	1.72
CIPR	14.29	32.78	34.15	1.04	6.31	17.07	86.33	0.91
CPR	13.93	31.95	42.27	1.32	0.24	0.89	95.09	2.44

Table 2: Soil Phosphorus Status Parameters at 1 minute 1 Month after PR Application

Treatment	Rate (g Pkg ⁻¹ soil)	Cp (µgPml ⁻¹)		r1/R		E 1 Minute (µgPg ⁻¹)		Capacity Factor (mlg ⁻¹)	
		mean	sd	mean	sd	mean	sd	mean	sd
TSP	2	89.94 ±	2.05	0.53 ±	0.37	3621.05 ±	4164.01	40.61 ±	47.05
TSP	4	99.98 ±	5.18	0.46 ±	0.36	4195.74 ±	4368.42	40.69 ±	40.56
TSP	6	183.96 ±	41.51	0.54 ±	0.39	6037.42 ±	5671.31	38.03 ±	42.63
TSP	8	240.39 ±	5.95	0.51 ±	0.37	8837.85 ±	9075.57	37.05 ±	38.54
NCPR	2	0.75 ±	0.25 b	0.08 ±	0.01 a	97.89 ±	30.52 cdef	132.62 ±	21.36 b
NCPR	4	1.14 ±	0.12 a	0.07 ±	0.02 a	177.57 ±	50.35 a	157.53 ±	47.81 b
NCPR	6	1.31 ±	0.24 a	0.07 ±	0.02 a	187.74 ±	16.93 abc	148.00 ±	36.93 b
NCPR	8	1.50 ±	0.09 a	0.07 ±	0.04 a	235.83 ±	89.97 ab	159.56 ±	66.50 b
APR	2	0.24 ±	0.01 gh	0.06 ±	0.04 a	47.76 ±	29.52 fg	198.25 ±	113.34 b
APR	4	0.27 ±	0.03 bcdefg	0.05 ±	0.01 a	54.43 ±	10.28 efg	199.97 ±	24.34 b
APR	6	0.38 ±	0.10 fgh	0.05 ±	0.01 a	84.44 ±	6.82 efg	229.15 ±	54.20 b
APR	8	0.41 ±	0.10 efgh	0.07 ±	0.02 a	63.49 ±	20.78 fg	158.01 ±	49.49 b
TPR	2	0.34 ±	0.10 defgh	0.06 ±	0.00 a	54.99 ±	15.02 efg	160.56 ±	12.07 b
TPR	4	0.40 ±	0.19 bcdef	0.07 ±	0.04 a	62.94 ±	11.97 defg	160.56 ±	109.11 b
TPR	6	0.47 ±	0.12 bcdefg	0.07 ±	0.05 a	81.53 ±	44.17 efg	186.44 ±	105.12 b
TPR	8	0.74 ±	0.15 bcdef	0.07 ±	0.04 a	81.53 ±	34.26 defg	176.82 ±	69.51 b
JPR	2	0.74 ±	0.12 efgh	0.07 ±	0.00 a	114.74 ±	22.21 efg	163.04 ±	7.60 b
JPR	4	0.25 ±	0.10 fgh	0.06 ±	0.01 a	44.19 ±	18.48 fg	177.29 ±	47.23 b
JPR	6	0.27 ±	0.04 bcdefg	0.06 ±	0.02 a	47.21 ±	37.81 defg	174.68 ±	70.27 b
JPR	8	0.48 ±	0.17 bc	0.05 ±	0.06 a	101.03 ±	65.67 bcde	209.61 ±	120.07 b
CIPR	2	0.77 ±	0.09 defgh	0.07 ±	0.03 a	136.80 ±	0.83 efg	192.33 ±	68.63 b
CIPR	4	0.20 ±	0.10 efgh	0.07 ±	0.01 a	27.39 ±	14.08 fg	155.96 ±	32.57 b
CIPR	6	0.25 ±	0.08 bcdefg	0.06 ±	0.02 a	42.30 ±	27.61 efg	170.74 ±	56.16 b
CIPR	8	0.36 ±	0.10 bcde	0.05 ±	0.03 a	70.43 ±	47.04 cdef	192.95 ±	82.17 b
CPR	2	0.44 ±	0.05 gh	0.07 ±	0.01 a	72.63 ±	21.99 efg	159.60 ±	70.24 b
CPR	4	0.16 ±	0.07 efgh	0.04 ±	0.03 a	40.44 ±	28.85 defg	242.38 ±	89.51 b
CPR	6	0.19 ±	0.24 bcd	0.05 ±	0.01 a	47.78 ±	73.42 abcd	226.51 ±	57.04 b
CPR	8	0.39 ±	0.23 bcdefg	0.04 ±	0.00 a	100.94 ±	66.80 defg	248.57 ±	15.09 ab
Control	0	0.33 ±	0.00 h	0.04 ±	0.01 a	93.12 ±	4.49 g	275.91 ±	191.79 a
		0.02 ±		0.03 ±		9.09 ±		394.54 ±	

Note: Values follow by the same letters in the same column are not significantly different at 5% level as determined by DMRT. Means for TSP were not compared due to its high value.

Table 3: Isotopically Exchangeable P at One Minute (E1) 1 Month after PR Application

Treatment	rate (g P/kg soil)	n		E 1 minute		E 1 day		E 3 month		E 6 month		9 month		E 1 year	
		mean	sd	mean	sd	mean	sd	mean	sd	mean	sd	mean	sd	Mean	sd
TSP	2	-0.07 ±	0.063	3621 ±	4164	4790 ±	3828	6094 ±	3514	6359 ±	3505	6524 ±	3512	6646 ±	3523
TSP	4	-0.013 ±	0.011	4195 ±	4368	4380 ±	4262	4506 ±	4186	4526 ±	4174	4538 ±	4166	4547 ±	4161
TSP	6	-0.026 ±	0.029	6037 ±	5671	6805 ±	5346	7437 ±	5178	7547 ±	5162	7614 ±	5154	7662 ±	5149
TSP	8	-0.043 ±	0.036	8837 ±	9075	10864 ±	8928	12642 ±	8839	12965 ±	8847	13160 ±	8856	13302 ±	8865
NCPR	2	-0.134 ±	0.043 ab	97 ±	30 def	270 ±	116 abcd	523 ±	305 bc	581 ±	353 bc	617 ±	384 bc	645 ±	408 bc
NCPR	4	-0.059 ±	0.048 ab	177 ±	50 abc	278 ±	91 abcd	382 ±	186 bc	402 ±	207 bc	414 ±	221 bc	423 ±	231 bc
NCPR	6	-0.064 ±	0.053 ab	187 ±	16 ab	315 ±	131 abc	455 ±	293 bc	483 ±	327 bc	500 ±	348 bc	513 ±	364 bc
NCPR	8	-0.064 ±	0.017 ab	89 ±	89 a	138 ±	138 ab	188 ±	188 bc	198 ±	198 bc	204 ±	204 bc	208 ±	208 bc
APR	2	-0.041 ±	0.092 ab	235 ±	29 efg	320 ±	3 def	390 ±	70 bc	402 ±	87 bc	409 ±	99 bc	414 ±	108 bc
APR	4	-0.107 ±	0.000 a	47 ±	10 efg	91 ±	11 ef	158 ±	12 bc	173 ±	12 bc	183 ±	13 bc	191 ±	13 bc
APR	6	-0.019 ±	0.052 ab	54 ±	6 defg	62 ±	67 bcdef	67 ±	156 bc	68 ±	175 bc	69 ±	188 bc	69 ±	197 bc
APR	8	-0.076 ±	0.031 ab	84 ±	20 defg	156 ±	40 cdef	239 ±	85 bc	256 ±	96 bc	267 ±	103 bc	275 ±	108 bc
TPR	2	-0.101 ±	0.064 ab	63 ±	15 efg	132 ±	107 bcdef	211 ±	311 bc	228 ±	363 bc	238 ±	398 bc	245 ±	424 bc
TPR	4	-0.133 ±	0.156 ab	54 ±	11 defg	160 ±	141 abcde	334 ±	475 ab	376 ±	566 ab	403 ±	626 ab	424 ±	673 ab
TPR	6	-0.138 ±	0.087 ab	62 ±	44 defg	216 ±	49 bcdef	571 ±	95 bc	667 ±	110 bc	523 ±	120 bc	713 ±	128 bc
TPR	8	-0.093 ±	0.049 ab	81 ±	34 cde	144 ±	145 abcde	228 ±	304 bc	246 ±	339 bc	258 ±	361 bc	267 ±	377 bc
JPR	2	-0.087 ±	0.038 ab	114 ±	22 efg	240 ±	61 def	392 ±	141 bc	424 ±	162 bc	444 ±	175 bc	458 ±	185 bc
JPR	4	-0.132 ±	0.048 ab	44 ±	18 efg	116 ±	44 ef	219 ±	81 bc	241 ±	88 bc	256 ±	93 bc	267 ±	96 bc
JPR	6	-0.049 ±	0.075 a	47 ±	37 def	72 ±	105 bcdef	98 ±	191 bc	103 ±	208 bc	106 ±	219 bc	108 ±	226 bc
JPR	8	-0.031 ±	0.112 b	101 ±	65 bcd	141 ±	93 ab	191 ±	76 a	201 ±	176 ab	207 ±	126 ab	211 ±	129 ab
CIPR	2	-0.161 ±	0.031 ab	136 ±	0 fg	300 ±	14 ef	390 ±	36 bc	400 ±	41 bc	510 ±	45 bc	712 ±	47 bc
CIPR	4	-0.107 ±	0.039 ab	27 ±	14 efg	60 ±	21 ef	100 ±	33 bc	109 ±	35 bc	114 ±	37 bc	118 ±	38 bc
CIPR	6	-0.107 ±	0.049 ab	42 ±	27 defg	57 ±	52 def	71 ±	90 bc	74 ±	97 bc	75 ±	102 bc	76 ±	105 bc
CIPR	8	-0.043 ±	0.047 ab	70 ±	47 defg	111 ±	72 bcdef	153 ±	114 bc	161 ±	127 bc	166 ±	136 bc	169 ±	143 bc
CPR	2	-0.062 ±	0.075 ab	72 ±	21 efg	169 ±	56 def	297 ±	159 bc	325 ±	185 bc	342 ±	202 bc	356 ±	215 bc
CPR	4	-0.125 ±	0.059 ab	40 ±	28 efg	91 ±	64 def	170 ±	120 bc	189 ±	132 bc	201 ±	139 bc	210 ±	145 bc
CPR	6	-0.107 ±	0.020 ab	47 ±	73 def	222 ±	133 bcde	390 ±	199 bc	426 ±	212 bc	448 ±	220 bc	465 ±	226 bc
CPR	8	-0.090 ±	0.039 ab	100 ±	66 def	194 ±	217 abcde	292 ±	436 bc	312 ±	484 bc	324 ±	515 bc	332 ±	538 bc
Control	0	-0.088 ±	0.032 ab	93 ±	4 g	11 ±	4 f	13 ±	5 c	14 ±	5 c	14 ±	5 c	14 ±	5 c
		-0.100 ±		9 ±		11 ±		13 ±		14 ±		14 ±		14 ±	
		-0.040 ±		9 ±		11 ±		13 ±		14 ±		14 ±		14 ±	

Note: Values follow by the same letters in the same column are not significantly different at 5% level as determined by DMRT. Means for TSP were not compared due to its high value.

Table 4: Size of P Pools in The Soil 1 Month after PR Application

Treatment	Rate(gP/k gsoil)	First Pool (A)		Second Pool (B)		Third Pool (C)		Last Pool (D)	
		Mean	sd	Mean	sd	Mean	sd	Mean	sd
TSP	2	1170 ±	784	1303 ±	1291	552 ±	619	3576 ±	3523
TSP	4	184 ±	120	126 ±	84	40 ±	27	15598 ±	4161
TSP	6	768 ±	91	631 ±	819	225 ±	302	22405 ±	5149
TSP	8	2027 ±	1477	1778 ±	1644	659 ±	670	26688 ±	8865
NCPR	2	173 ±	98 ab	253 ±	195 b	121 ±	105 b	14503 ±	408 op
NCPR	4	101 ±	83 bc	103 ±	107 b	41 ±	47 b	29574 ±	231 k
NCPR	6	127 ±	126 abc	140 ±	161 b	58 ±	71 b	44332 ±	364 g
NCPR	8	85 ±	62 bc	69 ±	57 b	24 ±	21 b	59580 ±	208 c
APR	2	44 ±	31 bc	66 ±	67 b	33 ±	37 b	15364 ±	108 n
APR	4	48 ±	1 bc	70 ±	1 b	34 ±	0 b	30741 ±	13 j
APR	6	71 ±	62 bc	83 ±	89 b	35 ±	41 b	45791 ±	197 f
APR	8	68 ±	31 bc	79 ±	49 b	33 ±	23 b	61076 ±	108 a
TPR	2	105 ±	97 bc	174 ±	204 b	89 ±	112 b	15012 ±	424 on
TPR	4	153 ±	153 abc	355 ±	334 ab	208 ±	197 ab	29793 ±	673 k
TPR	6	62 ±	45 bc	83 ±	74 b	39 ±	39 b	45442 ±	128 k
TPR	8	125 ±	112 abc	152 ±	159 b	66 ±	73 b	60388 ±	377 b
JPR	2	72 ±	46 bc	102 ±	85 b	48 ±	44 b	14539 ±	185 op
JPR	4	24 ±	33 bc	26 ±	37 b	10 ±	15 b	29206 ±	96 k
JPR	6	40 ±	87 bc	49 ±	87 b	20 ±	35 b	43610 ±	226 h
JPR	8	166 ±	55 a	380 ±	70 a	359 ±	485a	56986 ±	1244 d
CIPR	2	33 ±	13 bc	40 ±	220 b	17 ±	10 b	14176 ±	47 p
CIPR	4	15 ±	15 bc	13 ±	13 b	5 ±	5 b	28213 ±	38 m
CIPR	6	40 ±	39 bc	42 ±	41 b	16 ±	16 b	42115 ±	105 i
CIPR	8	96 ±	36 bc	127 ±	66 b	58 ±	37 b	55923 ±	143 e
CPR	2	51 ±	53 bc	79 ±	105 b	39 ±	56 b	14449 ±	215 op
CPR	4	42 ±	45 bc	51 ±	59 b	22 ±	26 b	28855 ±	145 l
CPR	6	93 ±	63 bc	98 ±	70 b	39 ±	29 b	43046 ±	226 h
CPR	8	129 ±	151 abc	167 ±	218 b	75 ±	102 b	57272 ±	538 d
Control	0	2.62 ±	2 c	2.26 ±	2 b	0.83 ±	1 b	285.20 ±	6 q

Note: Values follow by the same letters in the same column are not significantly different at 5% level as determined by DMRT. Means for TSP were not compared due to its high value.

Table 5: Expected P derived from Fertilizer (% Pdf) in the Soil Solution 1 Month after PR Application

Treatment	Rate (gP/kg soil)	% Pdf 1 min		% Pdf 1 day		% Pdf 3 month		% Pdf 1 year	
		Mean	sd	Mean	sd	Mean	sd	Mean	sd
TSP	2	99.47 ±	0.53	99.64 ±	0.31	99.70 ±	0.22	99.72 ±	0.20
TSP	4	99.52 ±	0.57	99.53 ±	0.46	99.52 ±	0.38	99.52 ±	0.36
TSP	6	99.72 ±	0.32	99.72 ±	0.27	99.72 ±	0.24	99.72 ±	0.23
TSP	8	99.79 ±	0.24	99.82 ±	0.18	99.84 ±	0.15	99.84 ±	0.14
NCPR	2	91.11 ±	1.94 ab	95.57 ±	0.43 a	97.03 ±	0.81 ab	97.36 ±	0.88 a
NCPR	4	95.00 ±	1.70 a	95.11 ±	3.23 ab	94.93 ±	4.46 ab	94.84 ±	4.88 a
NCPR	6	95.13 ±	2.32 ab	96.14 ±	1.38 a	96.33 ±	1.82 ab	96.35 ±	1.97 a
NCPR	8	95.64 ±	2.62 ab	95.62 ±	3.19 a	95.48 ±	3.71 ab	95.41 ±	3.88 a
APR	2	78.33 ±	10.84 abcd	87.05 ±	5.13 abcdefg	88.91 ±	8.02 abcd	89.14 ±	9.13 abc
APR	4	83.35 ±	8.30 d	81.50 ±	5.25 efg	79.85 ±	4.47 d	79.25 ±	4.64 c
APR	6	89.21 ±	5.09 abcd	90.75 ±	6.17 abcde	91.01 ±	8.00 abcd	91.00 ±	8.64 abc
APR	8	83.95 ±	9.19 abc	90.17 ±	5.96 abcde	92.36 ±	5.35 abc	92.88 ±	5.20 ab
TPR	2	83.87 ±	5.94 ab	91.33 ±	4.77 abcde	93.98 ±	3.95 ab	94.61 ±	3.71 a
TPR	4	84.50 ±	9.19 abc	92.82 ±	4.06 abc	92.61 ±	9.31 abc	92.08 ±	11.06 abc
TPR	6	84.31 ±	13.00 abc	92.82 ±	5.18 abcde	92.61 ±	4.51 abc	92.08 ±	4.56 ab
TRP	8	84.31 ±	4.91 ab	90.69 ±	6.12 abc	92.71 ±	7.53 ab	93.16 ±	7.99 ab
JPR	2	91.26 ±	6.50 abc	92.74 ±	2.58 abcdef	93.02 ±	3.38 abc	93.03 ±	3.47 abc
JPR	4	78.38 ±	3.73 c d	89.10 ±	6.46 defg	92.32 ±	11.99 cd	93.04 ±	13.73 bc
JPR	6	81.07 ±	6.02 abcd	81.68 ±	6.86 abcdef	80.30 ±	8.34 abcd	79.63 ±	8.99 abc
JPR	8	89.88 ±	6.20 a	89.40 ±	0.75 a	87.85 ±	0.62 a	87.14 ±	0.64 a
CIPR	2	91.59 ±	15.90 bcd	97.14 ±	9.07 fg	98.30 ±	6.39 bcd	98.52 ±	5.74 abc
CIPR	4	67.04 ±	6.10 d	80.03 ±	7.34 g	85.34 ±	8.12 d	86.67 ±	8.36 c
CIPR	6	79.02 ±	2.26 abcd	79.18 ±	4.66 abcdefg	79.24 ±	8.65 abcd	79.26 ±	9.97 abc
CIPR	8	87.34 ±	4.95 ab	88.79 ±	5.32 abc	88.52 ±	4.96 ab	88.27 ±	4.81 a
CPR	2	86.53 ±	10.35 abcd	92.02 ±	4.73 bcdefg	94.06 ±	7.65 abcd	94.55 ±	8.29 abc
CPR	4	75.66 ±	8.51 abcd	85.37 ±	6.12 cdefg	87.44 ±	9.42 abcd	87.81 ±	10.60 abc
CPR	6	77.84 ±	5.00 abc	84.35 ±	5.30 abcde	85.90 ±	5.24 abc	86.11 ±	5.20 ab
CPR	8	88.75 ±	6.29 ab	91.56 ±	6.06 abc	92.85 ±	5.67 ab	93.20 ±	5.52 ab
Control	0	88.60 ±	0.00	91.74 ±	0.00	92.95 ±	0.00	93.26 ±	0.00
		0.00 ±		0.00 ±		0.00 ±		0.00 ±	

Note: Values follow by the same letters in the same column are not significantly different at 5% level as determined by DMRT. Means for TSP were not compared due to its high value.

Table 6: Experimental Parameters of Isotopically Exchangeable P at 9 months after PR Application

Treatment	Rate (g P/kg soil)	Cp (μgPml^{-1})		r_1/R		E 1 minute (μgPg^{-1})		pdf 1 min. (%)		Capacity Factor (ml/g)	
		Mean	sd	Mean	sd	Mean	sd	Mean	sd	Mean	sd
TSP	2	177.98 ±	1.46	0.311 ±	0.019	5736.56 ±	392.75	99.58 ±	0.16	32.22 ±	1.95
TSP	4	241.13 ±	7.39	0.405 ±	0.018	5957.03 ±	369.89	99.60 ±	0.16	24.70 ±	1.07
TSP	6	429.79 ±	9.73	0.383 ±	0.013	11225.97 ±	474.55	99.79 ±	0.09	26.12 ±	0.88
TSP	8	460.69 ±	18.43	0.402 ±	0.018	11479.29 ±	518.96	99.79 ±	0.09	24.93 ±	1.08
NCPR	2	0.67 ±	0.09 c	0.048 ±	0.003 ab	139.65 ±	25.68 ef	81.96 ±	9.57 abcde	207.83 ±	11.11 g
NCPR	4	0.81 ±	0.13 ab	0.047 ±	0.001 abc	171.78 ±	26.67 de	86.24 ±	4.92 abcd	212.98 ±	4.36 g
NCPR	6	0.83 ±	0.11 ab	0.039 ±	0.003 c	210.95 ±	15.60 cd	88.74 ±	4.31 abc	256.38 ±	18.65 g
NCPR	8	0.90 ±	0.08 a	0.041 ±	0.041 bc	216.07 ±	18.51 c	88.99 ±	4.26 abc	241.33 ±	11.45 g
APR	2	0.17 ±	0.05 ghi	0.031 ±	0.009 d	58.96 ±	20.83 ijk	59.95 ±	6.67 gh	345.49 ±	117.64 fg
APR	4	0.20 ±	0.06 fgh	0.020 ±	0.002 ef	94.50 ±	22.75 ghi	75.11 ±	7.77 abcdef	491.07 ±	38.92 efg
APR	6	0.24 ±	0.05 efg	0.017 ±	0.002 efg	138.01 ±	21.04 ef	82.50 ±	7.36 abcde	580.85 ±	52.71 def
APR	8	0.33 ±	0.04 de	0.021 ±	0.002 e	154.92 ±	24.64 ef	84.76 ±	5.40 abcd	469.06 ±	34.44 efg
TPR	2	0.33 ±	0.01 hijk	0.021 ±	0.001 fgh	154.92 ±	19.76 ghi	84.76 ±	14.73 bcdefg	469.06 ±	104.01 abcd
TPR	4	0.11 ±	0.01 ghij	0.012 ±	0.000 fgh	92.08 ±	7.03 fgh	72.11 ±	8.90 abcdef	851.75 ±	32.72 abcd
TPR	6	0.14 ±	0.04 ghij	0.012 ±	0.001 h	114.87 ±	56.26 de	79.06 ±	7.40 abcd	819.09 ±	107.03 a
TPR	8	0.15 ±	0.01 ef	0.009 ±	0.002 gh	173.60 ±	56.58 b	85.58 ±	2.73 ab	1134.06 ±	171.31 abc
JPR	2	0.28 ±	0.09 fg	0.011 ±	0.014 a	260.28 ±	21.23 ijk	91.00 ±	6.07 hi	914.04 ±	70.32 g
JPR	4	0.23 ±	0.05 d	0.050 ±	0.002 abc	48.82 ±	6.94 ghi	50.16 ±	11.88 bcdefg	211.70 ±	9.10 g
JPR	6	0.42 ±	0.06 d	0.047 ±	0.001 d	89.57 ±	14.44 efg	72.98 ±	5.89 abcde	215.20 ±	11.24 fg
JPR	8	0.42 ±	0.05 bc	0.031 ±	0.000 de	133.51 ±	21.69 a	82.45 ±	2.76 a	322.50 ±	6.58 efg
CIPR	2	0.75 ±	0.02 jk	0.024 ±	0.009 efg	312.95 ±	22.35 jk	92.46 ±	25.26 hi	417.49 ±	505.18 bcd
CIPR	4	0.06 ±	0.01 jk	0.018 ±	0.009 efg	40.07 ±	26.28 ijk	35.21 ±	10.70 hi	718.92 ±	458.61 bcd
CIPR	6	0.07 ±	0.01 ijk	0.016 ±	0.002 gh	52.08 ±	10.88 hijk	51.51 ±	12.74 efg	800.71 ±	155.35 abc
CIPR	8	0.07 ±	0.01 hijk	0.011 ±	0.005 efg	68.58 ±	14.23 hij	65.58 ±	7.16 cdefg	940.33 ±	179.47 cde
CPR	2	0.12 ±	0.02 ijk	0.016 ±	0.002 fgh	78.10 ±	21.95 ijk	70.46 ±	1.57 fgh	681.62 ±	145.30 abcd
CPR	4	0.07 ±	0.01 ijk	0.012 ±	0.001 gh	60.46 ±	13.98 hij	61.03 ±	14.92 defgh	868.99 ±	90.63 abc
CPR	6	0.08 ±	0.01 ijk	0.011 ±	0.000 gh	74.61 ±	12.60 hi	67.46 ±	11.05 bcdefg	921.08 ±	42.57 ab
CPR	8	0.09 ±	0.01 hijk	0.010 ±	0.001 fgh	87.28 ±	15.86 ghi	72.71 ±	10.68 abcdef	1020.87 ±	79.47 abcd
Control	0	0.11 ±	0.01 k	0.012 ±	0.006 efg	92.06 ±	9.20 k	74.05 ±	0.00 j	847.67 ±	243.15 bcde
		0.03 ±		0.016 ±		23.74 ±		0.00 ±		706.79 ±	

Note: Values follow by the same letters in the same column are not significantly different at 5% level as determined by DMRT. Means for TSP were not compared due to its high value.

**Table 7: Relative Agronomic Effectiveness of Various PRs
9 Months After PR Application**

Treatment	Relative Agronomic Effectiveness (%)					
	Rate of application (g kg ⁻¹ soil)					
	2	4	6	8	mean	ranking
NCPR	82.30	86.59	88.93	89.17	86.75	1
TPR	72.41	79.38	85.77	91.19	82.18	2
APR	60.20	75.42	82.67	84.94	75.81	3
JPR	50.37	73.27	82.63	92.65	74.73	4
CPR	61.29	67.73	72.86	74.20	69.02	5
CIPR	35.36	51.72	65.72	70.61	55.85	6

Table 8: Correlation Coefficient between Isotopically Exchangeable P Values and P Uptake by Oil Palm Seedling 9 month after PR Application

1 Minute				
Parameters	(r/R)	Cp	E 1 min.	Cf
Cp	0.352***			
E 1 min.	-0.131	0.830***		
Cf	-0.844***	-0.346***	0.037	
P Uptake	0.138	0.750***	0.880***	-0.243

40 Minutes				
Parameters	(r/R)	Cp	E 1 min.	Cf
Cp	0.390***			
E 1 min.	-0.099	0.815***		
Cf	-0.864***	-0.349***	0.086	
P Uptake	0.264	0.623***	0.675***	-0.325***

100 Minutes				
Parameters	(r/R)	Cp	E 1 min.	Cf
Cp	0.295			
E 1 min.	-0.183	0.833***		
Cf	-0.863***	-0.247		
P Uptake	0.107	0.537***	0.197	
			0.607***	-0.130

- Note : *** denotes 99% of confidence limit

Table 9: Correlation Coefficient among Status and Kinetic Parameters of Isotopically Exchange P

Parameters	(r/R)	Cp	E 1 min.	Cf	Pool A	Pool B	Pool C
Cp	0.352***						
E 1 min.	-0.131	0.830***					
Cf	-0.844***	-0.347***	-0.843***				
Pool A	0.256	0.386***	0.357***	-0.194			
Pool B	0.390***	0.240	0.115	-0.251	0.903***		
Pool C	0.418***	0.194	0.042	-0.257	0.828***	0.988***	
Pool D	0.131	0.449***	0.490***	-0.160	0.241	0.144	0.119

Note : *** denotes 99% of confidence limit

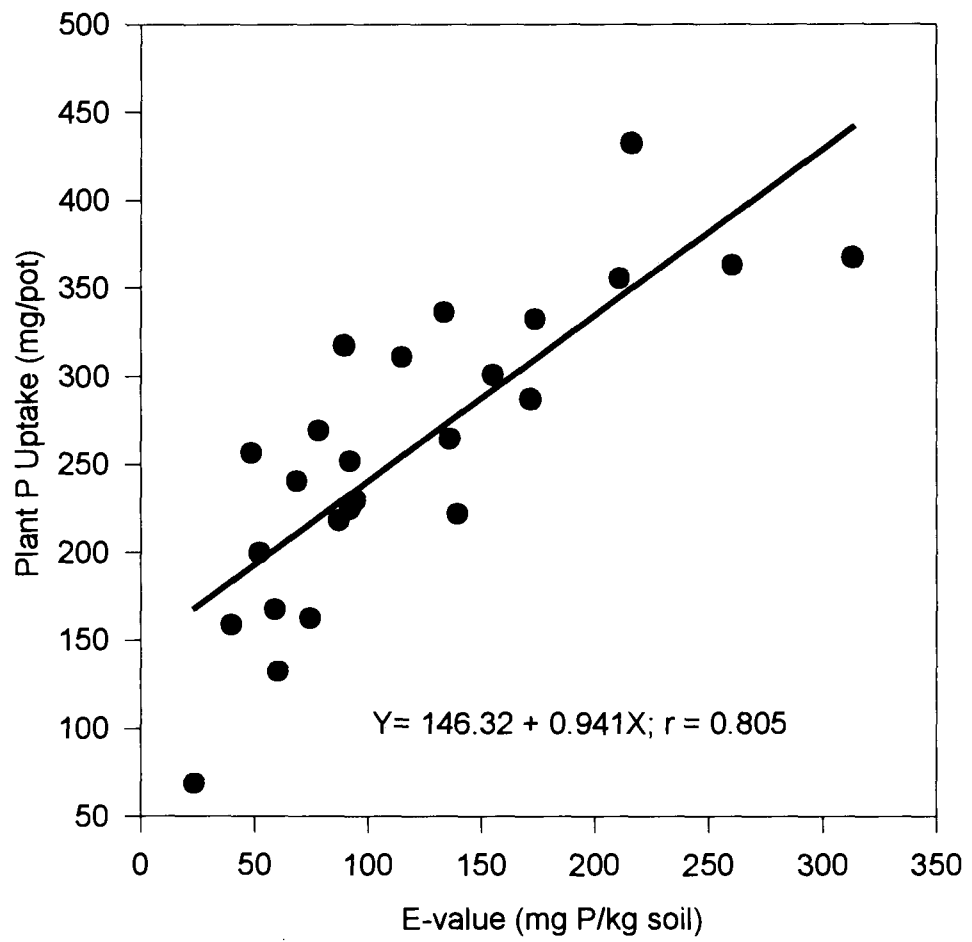


Figure 1: Relationships between plant P uptake and E-value