Agr. Nat. Resour. 56 (2022) 85–94

AGRICULTURE AND
NATURAL RESOURCES

Journal homepage: http://anres.kasetsart.org

Research article

Effect of co-application of phosphate rock with organic wastes on P fractions in a tropical loamy sand soil

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Article Info

Article history:
Received 30 July 2021
Revised 6 December 2021
Accepted 20 December 2021
Available online 9 February 2022

Keywords:
Acid soil,
Inorganic P,
Organic P,
Soil P pool,
Wastes from starch industry

Abstract

Importance of the work: Phosphate rock (PR) can be used as P fertilizer in acidic soils, but its effectiveness via direct soil application is low. Organic materials could improve its solubility and alter the soil P fractionation related to the P-supply capacity to plants.
Objectives: This study was conducted under controlled laboratory conditions to determine the effect of cassava peel (CP) and cassava starch waste (CSW) on inorganic (Pi) and organic (Po) fractions in a PR-applied loamy sand.
Materials & Methods: Amounts of 6.25 t/ha and 12.5 t/ha of each waste were added to separate soil samples treated with 50 kg P2O5/ha of PR, with no added PR or wastes as the control.
Results: The PR contained 20.3% P2O5 with most of the P dissolved in 2% formic acid accounting for 22.25% of total P2O5 and when added to the soil, it significantly increased Pi (18.8±1.13–20.1±2.30 mg/kg) more than Po (4.92±0.58–6.61±0.71 mg/kg) contents. Phosphorus quickly transformed to more stable Pi pools after PR application (27.0–36.6% of total P), likely leading to insufficient P for the plant. Both rates of CP and CSW promoted similar PR solubility, resulting in a significant increase in all P fractions (Pi, 23.1±1.27–31.7±0.33 mg/kg; Po, 15.9.1±2.06–7.41±0.59 mg/kg). The labile Pi and Po contents were the highest at 14 and 56 d, respectively; hence, P solubilized from the more stable Po fractions could replenish labile Po.
Main finding: Although most P occurred in the moderately labile fraction, the labile Pi at day 112 still showed an increasing trend, especially for the PR + CP treatment with 12.5 t/ha waste.

Introduction

Phosphorus (P) is among the most common nutrients constraining crop production on highly weathered acidic soils that dominate the tropics, including Thailand, where the limited P availability to crops of these soils is attributed to the abundance of Fe and Al that strongly sorbs P, coupled with the inherently low soil P content, especially in sandy soils (Sanchez and Uhera, 1980). Therefore, chemical P fertilizer is necessary for crop production; however, more than almost 70% of P added to the soil is converted into complexes and is susceptible to loss by leaching (Tarkalson and Leytem, 2009; Nest et al., 2014); hence phosphate rock (PR) can be considered as

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https://doi.org/10.34044/j.anres.2021.56.1.08

an alternative to chemical P fertilizers. The other interest in the use of PR relates to its effects in liming acidic soils, while the other elements in PR, particularly calcium (Ca), can improve soil chemical and physical characteristics and contribute to plant nutrition (Chien et al., 2011). However, PR is well known for its very low solubility (Chien, 1993) that obstruct its use as a P fertilizer, resulting in concerns being often expressed on the effectiveness of PR for direct application to soils (Sikora, 2002; Chien et al., 2011).

The co-application of PR with organic materials, compost (Waigwa et al., 2003), animal manure (Mahimairaja et al., 1995; Agyarko et al., 2016; Agyin-Birikorang et al., 2007) and crop residues (Oladeji et al., 2006) has been reported to increase the solubility of PR because the amounts of organic acids produced during the composting of the organic materials can acidify and dissolve the PR (Mahimairaja et al., 1995; Waigwa et al., 2003; Saleque et al., 2004; Menezes-Blackburn et al., 2016). The content of P solubility of PR varies with the type of organic material and the rate of decomposition (Mahimairaja et al., 1995; Oladeji et al., 2006). Incorporating organic materials can be a low cost means to enhance the effectiveness of the low reactivity PR, but the P availability in soil could be altered (Linquist et al., 1997; Waigwa et al., 2003; Chien et al., 2011). The phosphorus pool in the soil is dynamic; hence, different types of P fractions differ notably in mobility, bioavailability, and chemical behavior, resulting in one fraction of P being transformed into another under certain conditions (Hedley et al., 1982; Sharpley, 1995; Linquist et al., 1997). In addition, they differ in their rates of P release (Chien, 1993; Chien et al., 2011) and so it is necessary to separate them into different biologically meaningful pools. Consequently, the contents of different P fractions could indicate distinct bioavailability to crops. Nonetheless, there is currently insufficient information on the co-effects of PR with organic material inputs regarding their impact on the soil P fractionation of various forms of inorganic and organic P.

In the process that produces cassava starch from fresh cassava tuber leaves, substantial industrial wastes are generated such as tails and stalk, cassava peel, and cassava starch waste; in northeast Thailand, it has been estimated that about 10 million t of wastes is produced by the starch manufacturing industry annually (Office of Agricultural Economics, 2020; Thai Tapioca Starch Association, 2021). Using these wastes in agricultural soils, especially in areas where other soil amendments such as animal manures are scarce, could be a reasonable way to reduce the cost of waste disposal and could promote the dissolution of the chemicals in the PR. Recognizing the importance of organic wastes in creating a favorable environment for P solubilization from PR, the current incubation study was initiated to determine the extent of P solubilization from PR through mixing with different rates of cassava starch waste and cassava peel, based on an assessment of the P fractions of different plant availability in a sandy loam soil. The understanding of organic and inorganic P proportions in this soil would provide a proper long-term P fertilizer management, which in turn could help farmers growing cassava to reduce the cost of this fertilizer in cassava cultivation. The information gained could be useful in making decisions on how to improve soil P availability by applying PR as a P fertilizer for crop production.

Materials and Methods

Soil sample

The study was conducted as an incubation experiment using the surface soil horizon (0–30 cm) of a Dan Khot Thod soil series, Dk (Ustic Quartzipsamments), collected from a cassava field (47P; 763332 E, 1678984 N) in Nakhon Ratchasima province, northeast Thailand. This soil type is commonly used for field crop production, especially for cassava throughout the region where it occupies 0.37% of the total area (Duangpatra, 1988). The initial properties of the surface soil (0–30 cm) were: loamy sand texture (895 g/kg sand, 37 silt g/kg, 68 g/kg clay); strongly acidic (pH 4.95 in water); cation exchange capacity, 1.5 cmol_c/kg; organic matter (Walkley and Black method), 15.07 g/kg; available P (Bray II extraction), 4.58 mg/kg; NH_4OAc-exchangeable K, 34.8 mg/kg; Ca, 224 mg/kg; and Mg, 13.4 mg/kg. In addition, the soil had a very low total P (HNO_3-$HClO_4$ acid digestion) content of 30.8 mg/kg, indicating a very low reserve of P which could eventually be available to plants.

Phosphate rock sample

The phosphate rock sample (PR) was sampled from ore sources in Kamphaeng Phet province, Thailand where it occurs as pockets and cavity fillings in limestone caves containing P_2O_5 in the range 18–27% (Japakasetr, 1982). This PR had a total P content of 20.2% P_2O_5 but had low reactivity since its solubility in all standard extractants (Association of Official Analytical Chemists, 1975) was only 35.6% of total P_2O_5 (Fig. 1). Much of the P was dissolved in 2% formic acid, being twice as great as that in 2% citric acid and four times that in neutral ammonium citrate and Petermann alkaline ammonium citrate. Nevertheless, soluble P in the deionized water extractant was the lowest (only 0.06% of total P_2O_5). Hence, there would be insufficient P available for plants if the studied PR were to be used directly as P fertilizer.

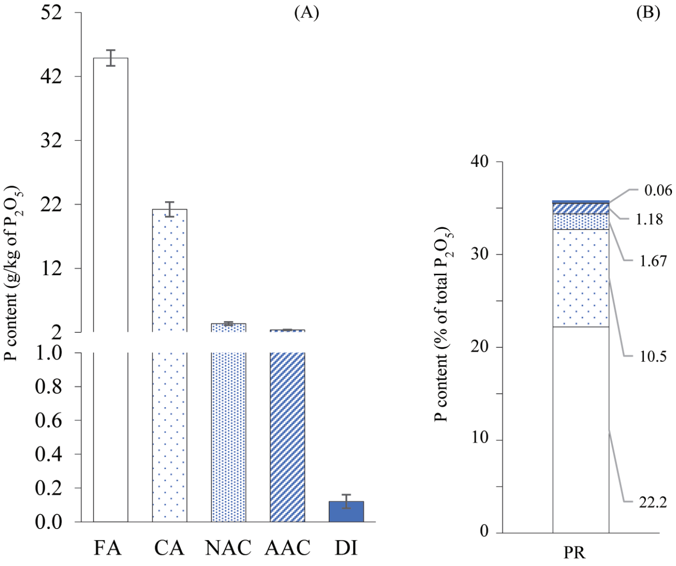

Fig. 1 Solubility of phosphate rock (PR) in different standard extractants-2% formic acid (FA), 2% citric acid (CA), neutral ammonium citrate (NAC), Petermann alkaline ammonium citrate (ACC), deionized water (DI)-expressed as: (A) P content; (B) percentage of total P_2O_5, where error bars indicate ± SD

Organic wastes

Two types of organic waste from the starch manufacturing industry—cassava starch waste (CSW) and cassava peel (CP)—were collected from Ratchasima Green Energy Co., Ltd., Nakhon Ratchasima province, Thailand. The wastes contained very high organic carbon contents and consisted of several plant nutrients dominated by K, Ca and N (Table 1).

Incubation experiment

An incubation experiment was conducted involving the P fractions solubilized from PR using different organic wastes in the laboratory of the Department of Soil Sciences, Faculty of Agriculture, Kasetsart University, Bangkok, Thailand during September–December 2019. The soil sample was air-dried and all roots and organic debris were removed before the soil was gently crushed to pass through a 2 mm sieve. The PR samples and organic wastes were air-dried; then, the former was ground through a 100-mesh sieve while the latter were hand-crushed to less than 0.5 mm particle size before use. Amounts of PR equivalent to 50 kg P_2O_5/ha—the recommended rate for cassava grown in light-textured soil with low fertility (Sittibusaya, 1996)—were thoroughly mixed with soil samples at a moisture content of 60% field capacity (FC) and stored at 27°C for 5 d in plastic buckets with tight-fitting lids. Then, each waste (CSW or CP) was applied at 6.25 t/ha or 12.5 t/ha, where the latter is the generally recommended rate for

Table 1 Properties and elemental composition of cassava peel (CP), cassava starch wastes (CSW) and phosphate rock (PR) used in experiment

Property	CP	CSW	PR
$pH_{(H_2O,\ 1:5)}$	6.72	7.82	7.31
Electrical conductivity$_{(H_2O,\ 1:5)}$ (dS/m)	1.35	0.41	0.12
CEC[1] ($cmol_c$/kg)	55.5	12.5	8.25
CCE[2] (%)	nd	nd	35.1
Organic carbon[3] (g/kg)	75.0	348	4.94
Total N[4] (g/kg)	5.04	3.22	0.98
Other element[5]			
P (g/kg)	0.25	0.35	88.3
K (g/kg)	3.95	4.33	0.64
Ca (g/kg)	2.27	2.26	90.0
Mg (g/kg)	0.30	0.44	0.35
Zn (mg/kg)	1.42	1.58	196.4
Fe (mg/kg)	91.0	944.1	1934.8
Cu (mg/kg)	0.21	0.52	65.5
Mn (mg/kg)	5.63	20.48	620

[1]CEC = cation exchange capacity based on 1M NH_4OAc at pH 7.0; [2]CCE = calcium carbonate equivalent with endpoint at pH 5.0; [3]Walkley and Black method; [4]H_2SO_4-Na_2SO_4-Se digestion mixture; [5]HNO_3-$HClO_4$ acid digestion; nd = not determined

organic amendments to field crops in Thailand (Department of Agriculture, 2005), with the following acronyms used for the four different treatments: $CSW_{6.25}$, $CSW_{12.5}$, $CP_{6.25}$, and $CP_{12.5}$. Soil without PR or organic wastes was also included as the control. Each treatment was replicated three times and arranged in a completely randomized design.

Samples of the PR-treated soils were thoroughly mixed with the desired amounts of CSW or CP; then, along with the control soil, all samples were incubated in glass bottles at 27°C and closed with parafilm in which three holes were made with a pin to allow gaseous exchange with the atmosphere. At each measurement time of 0 d, 3 d, 7 d, 14 d, 28 d, 56 d and 112 d after incubation (DAI) with wastes, samples were taken to determine the contents of the chemical P fractionations. The samples of day 0 incubation were analyzed immediately after mixing the soil and wastes. The incubation bottles were re-randomized and evenly mixed at the end of each of the specified incubation period. In addition, the incubation bottles were aerated by opening the parafilm every 3 d throughout the incubation period to prevent the development of anaerobic conditions. The soil moisture content was maintained at 60% FC where the lost water was compensated by recording the initial weights of the bottles and contents and adding deionized water according to the loss in weight at each sampling time.

Sequentially extracted P fraction analysis

Soil P was sequentially fractionated using the Hedley scheme (Hedley et al., 1982; Tiessen and Moir, 1993) to distinguish different soil inorganic (Pi) and organic (Po) P pools, as shown in Table 2. For the $NaHCO_3$, NaOH and concentrated HCl extracts, the filtrate was divided into two portions, with the first being acidified to precipitate extracted organic matter and then analyzed for Pi, while the second was digested with acidified ammonium persulfate in an autoclave at 103.4 kPa and 121°C for 90 min and then analyzed for total P (Pt) (Environmental Protection Agency, 1971). The Po amount in each of the $NaHCO_3$, NaOH and concentrated HCl extracts was obtained as the difference between Pt and Pi in the respective extract. Total soil P was equal to the sum of all measured P pools. The P concentration in all the extracts and digestion solutions was determined colorimetrically at 882 nm (Murphy and Riley, 1962).

Statistical analysis

The soil P fraction content was separately analyzed at each measurement during the incubation period using analysis of variance to detect treatment effects and Duncan's multiple range test to compare the differences between treatment means at the $p < 0.05$ level of significance. All statistical analyses of data were performed using the SPSS statistics software package, version 24 (IBM Corp., 2016).

Results

The relative distributions and trends of the P content of each bioavailability source over the sampling time up to 112 d are shown in Figs. 2 and 3, respectively. The inorganic (Pi) and organic (Po) P contents in the soil incubated with PR and different types and rates of organic wastes through the incubation period of 112 days are shown in Figs. 4 and 5, respectively.

Table 2 Sequential extraction determination for P speciation of soil inorganic (Pi) and organic (Po) P pools

P pool	Step	Reagent and condition	Soil: solution ratio	Shaking time at 100 rpm	P species	Symbol
Labile P	1	1M NH_4Cl	1:10	30 min	Loosely soluble Pi	NH_4Cl-Pi
	2	0.5M $NaHCO_3$ at pH 8.5	1:10	16 hr	Labile Pi	$NaHCO_3$-Pi
					Labile Po	$NaHCO_3$-Po
Moderately labile P	3	0.1M NaOH	1:10	16 hr	Pi associated with amorphous and crystalline Al and Fe oxides	NaOH-Pi
					Po associated with humic compounds	NaOH-Po
Relatively stable P	4	1M HCl	1:10	16 hr	Ca occluded Pi	HCl_{1M}-Pi
	5	10 mL of concentrated HCl at 80°C in a water bath for 10 min	-	-	Recalcitrant Pi	HCl_{conc}-Pi
					Recalcitrant Po	HCl_{conc}-Po
	6	Digestion with a 5:2 mixture of concentrated HNO_3:$HClO_4$	-	-	Residual P	Res P

Rpm = revolutions per minute; Res P = residual phosphorous

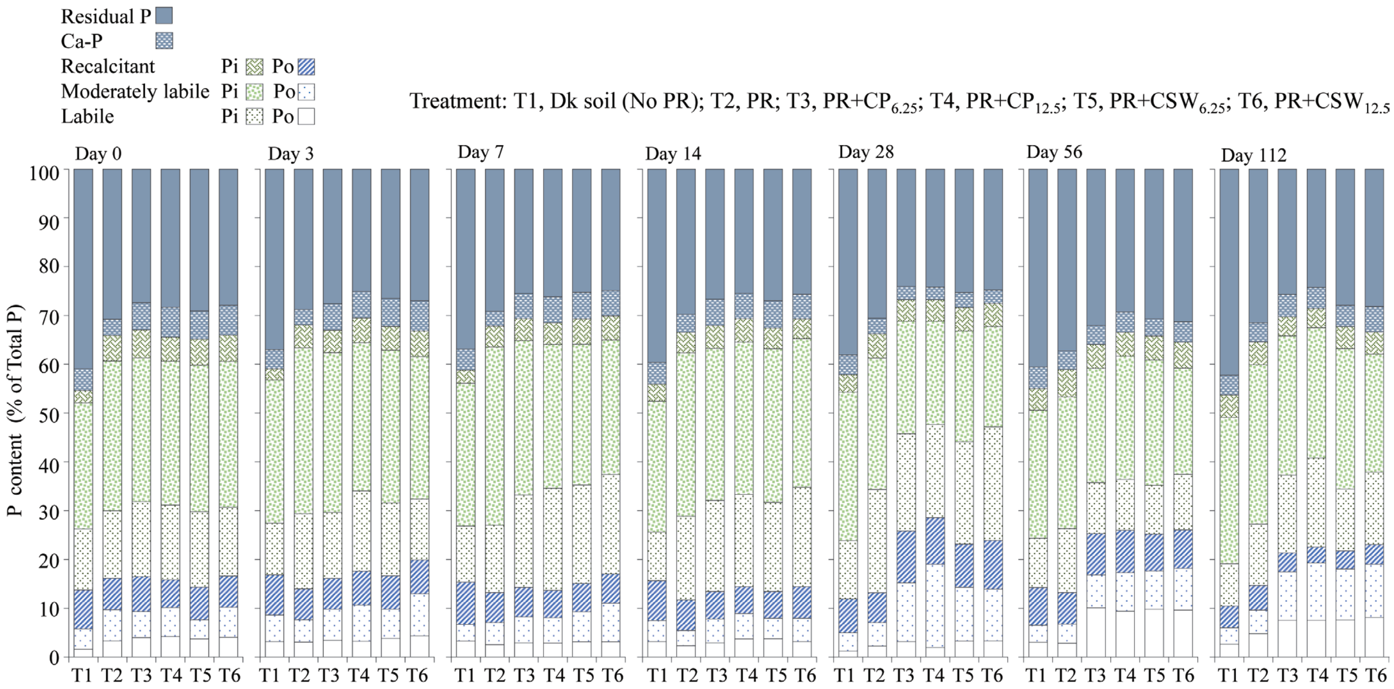

Fig. 2 Relative distribution of soil P fraction in each group as a percentage of total P. Bioavailability fractions of P: labile P inorganic (Pi) (NH_4Cl-Pi + $NaHCO_3$-Pi) and P organic (Po) ($NaHCO_3$-Po); moderately labile Pi (NaOH-Pi) and Po (NaOH-Po); recalcitrant Pi (HCl_{conc}-Pi); and Po (HCl_{conc}-Po), Ca bound P (HCl_{1M}-Pi), and residual P

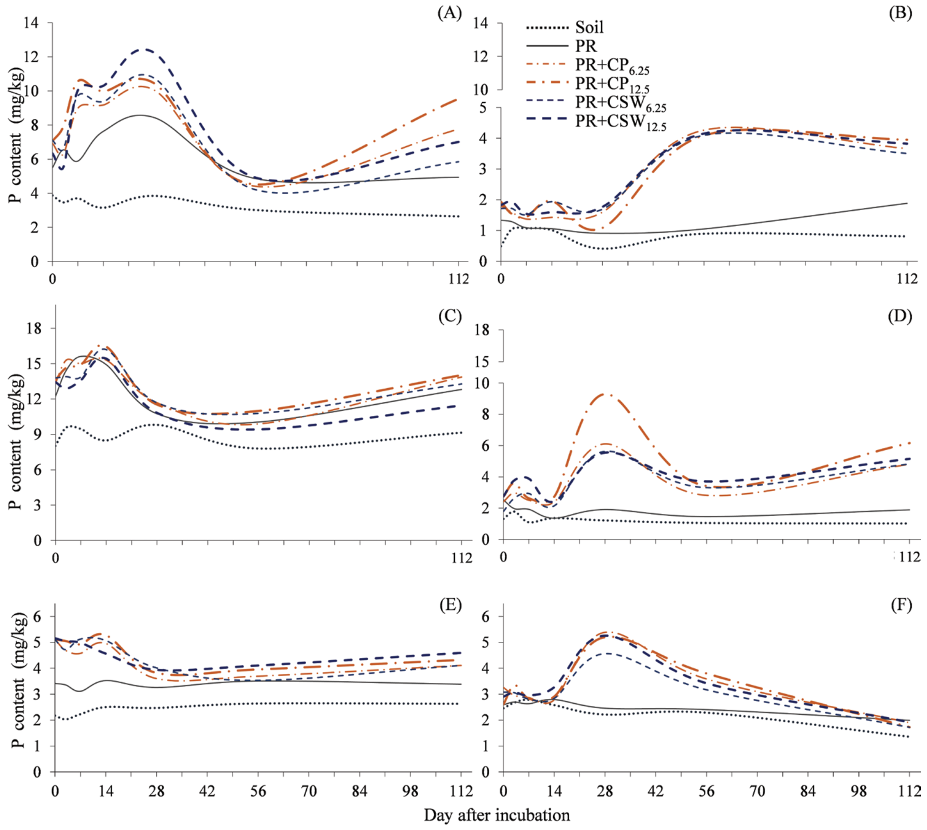

Fig. 3 Trend of P contents up to 112 d for soil incubated with added phosphate rock and different types and rates of organic wastes. Bioavailability fractions of P: (A) labile inorganic P (Pi) (NH_4Cl-Pi + $NaHCO_3$-Pi) and (B) organic P (Po) ($NaHCO_3$-Po); (C) moderately labile Pi (NaOH-Pi) and (D) Po (NaOH-Po); (E) relatively stable Pi (HCl_{1M}-Pi + HCl_{conc}-Pi) and (F) Po (HCl_{conc}-Po)

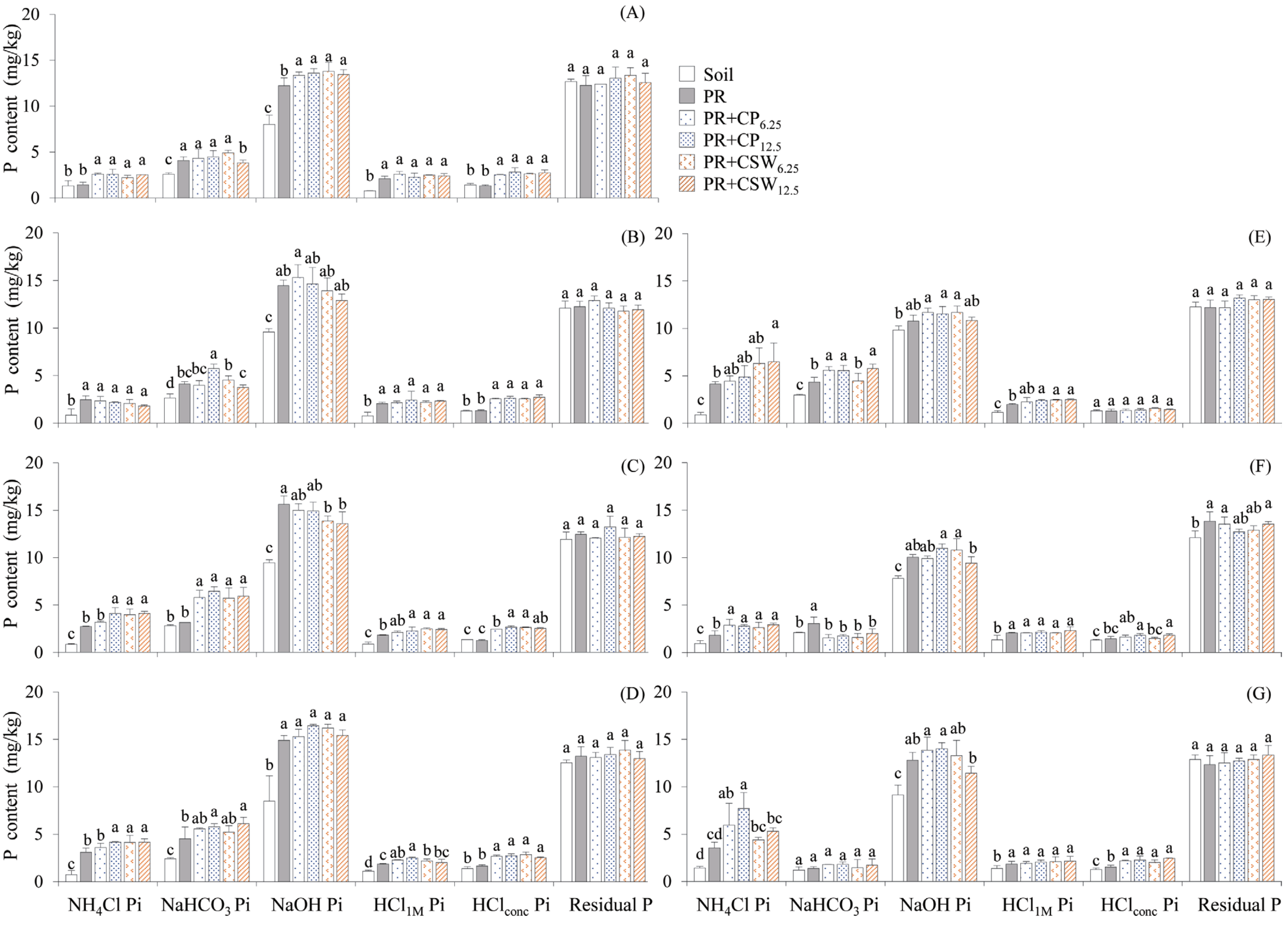

Fig. 4 Inorganic P (Pi) fraction in soils incubated with added phosphate rock and different types and rates of organic wastes at each measurement time: (A) 0 d; (B) 3 d; (C) 7 d; (D) 14 d; (E) 28 d; (F) 56 d; (G) 112 d after incubation with waste;
Different lowercase letters on bars grouped within the same fraction are significantly ($p < 0.05$) different; error bars represent ± SD

Bioavailability fractions of P

For the initial P in the studied soil, the Pi content was in the same ranges as the residual P (45.37% and 40.88% of total P, respectively). The moderately labile Pi constituted the largest pool of 25.88% of total P, being 2 times and 10 times higher than the labile Pi and the recalcitrant Pi, respectively. The total P in the initial soil in the control treatment was 13.97% Po, mainly in the recalcitrant pool (7.94%), whereas P extracted from the labile pool represented only 1.57% (Fig. 2).

The residual P fractions varied over the sampling time; however, no definite trends were detected (Fig. 2). Phosphorus in each group was mainly in the Pi form except for the relatively stable fraction where Pi was in the same range as Po (Fig. 3). As expected, the control treatment released the lowest amounts of both Pi and Po in each fraction and in a steady manner throughout the incubation period. The application of PR clearly increased Pi more than Po; however, the opposite trend occurred when applying wastes for all fractions.

Inorganic P pool

The Pi contents were significantly different among treatments during the 112 days of incubation, as shown in Fig. 4. Phosphate rock applied to the soil increased labile Pi where the $NaHCO_3$-Pi and NH_4Cl-Pi significantly increased after 0 and 7 DAI, respectively, in the ranges 0.32–1.32 mg/kg and 0.88–3.23 mg/kg, respectively. The incorporation of CP and CSW into the PR significantly induced higher labile Pi than did sole PR with the increment being 0.45–3.29 mg/kg for the $NaHCO_3$-Pi from 3–28 DAI and 0.45–4.13 mg/kg for the NH_4Cl-Pi after 7 DAI until the end of incubation period.

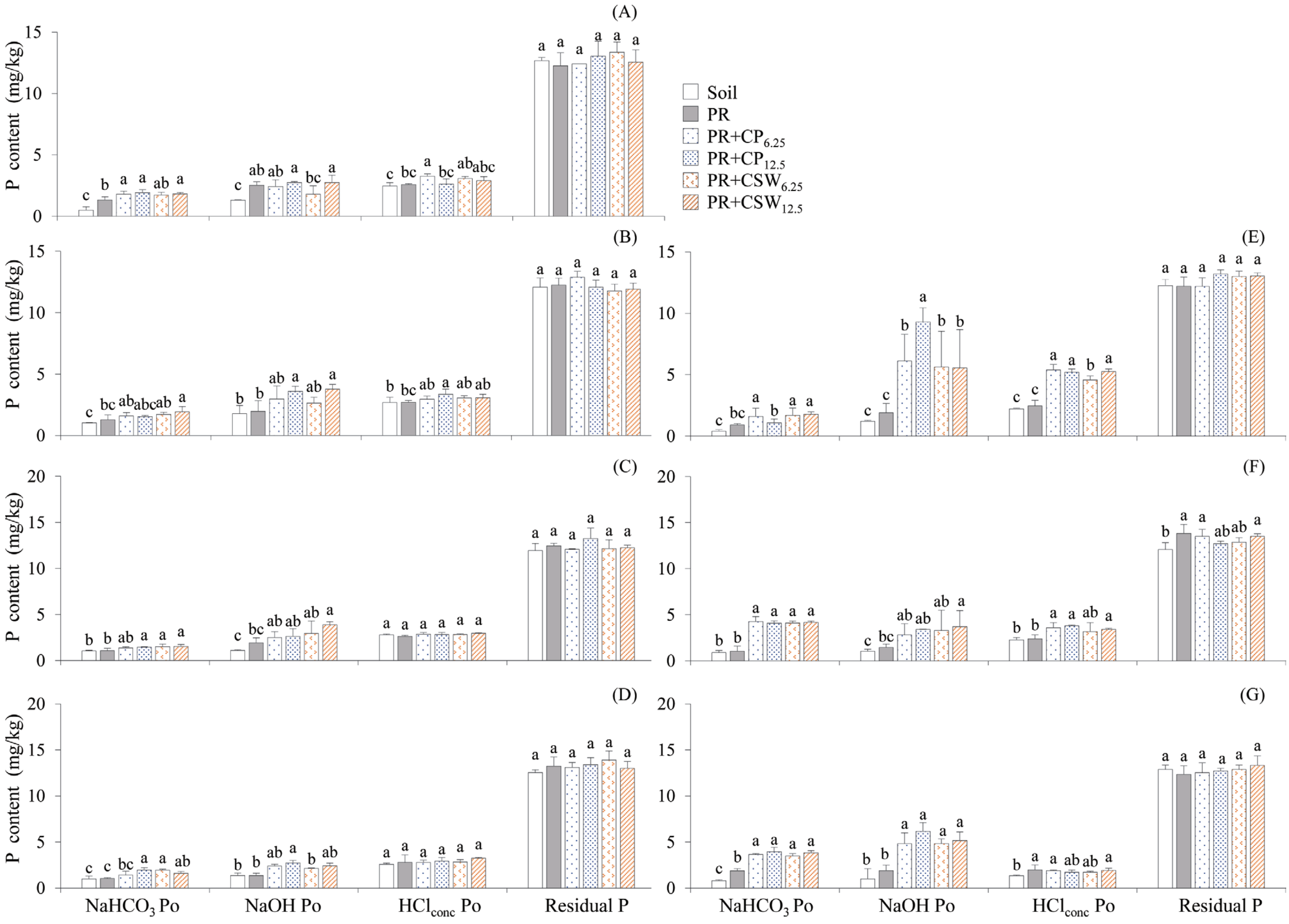

Fig. 5 Organic P (Po) fraction in soils incubated with phosphate rock and different types and rates of organic wastes at each measurement time: (A) 0 d; (B) 3 d; (C) 7 d; (D) 14 d; (E) 28 d; (F) 56 d; (G) 112 d after incubation with waste; Different lowercase letters on bars grouped within the same fraction are significantly ($p < 0.05$) different; error bars represent ± SD

However, there were no significant differences among the rates and types applied.

Nevertheless, solubilization was inconsistent of the moderately labile and recalcitrant Pi fractions from PR by co-application with both wastes (Fig. 4). Compared to sole PR, the co-application of both wastes at all rates with PR produced similar increases in NaOH-Pi only on the first day (increased by 1.13–1.56 mg/kg) but there were no significant differences thereafter. Sole PR and its combination with the wastes also significantly impacted the increase of HCl_{1M}-Pi (increased by 0.45–1.83 mg/kg over the control), except at 7 and 14 DAI when its content in PR with waste treatments was higher than in sole PR. Rather similar results occurred for HCl_{conc}-Pi, but there were no significant differences among treatments at 28 DAI. The HCl_{conc}-Pi content increased by 0.30 mg/kg in soil treated with sole PR only at 112 DAI while the significantly greatest contents were found identically in PR applied with both waste treatments, with the increment over the control being 0.33–1.48 mg/kg.

Organic P pool

The application of PR with and without wastes significantly affected the Po contents among the fractions in the soil but there was no detectable change in HCl_{conc}-Po at 7 and 14 DAI (Fig. 5). Nevertheless, P in each Po fraction was less affected by the PR alone than by wastes combined with PR, with $NaHCO_3$-Po, NaOH-Po and HCl_{conc}-Po significantly increasing at 0 and 112 DAI, 0 DAI and 112 DAI, respectively, when PR was added. The increments were 0.85–1.08, 1.21 and 0.64 mg/kg for $NaHCO_3$-Po, NaOH-Po and HCl_{conc}-Po, respectively.

Compared to sole PR, the incorporation of wastes into the PR significantly increased the contents of the Po fraction throughout the incubation period; however, there was no impact based on DAI and the rates of theses wastes. Nonetheless, after 56 DAI, these wastes both induced the highest $NaHCO_3$-Po and NaOH-Po amounts, with the increments over the control being 2.70–3.02 mg/kg and 1.77–5.18 mg/kg, respectively.

Discussion

In the current study, soil Pi played an important direct role in the availability of P; phosphorus in all the Pi fractions in soils treated with all treatments clearly released far higher contents compared to the control with rapid increases in labile Pi noted up to 14 DAI, apparently almost 2–3 times higher, especially for the PR+$CSW_{12.5}$ treatment. Although the labile Pi then continued to decrease after this period, especially at 56 DAI, the co-applications were still able to release labile Pi to some extent, as the amount released at 112 DAI still showed an increasing trend, especially for the PR + $CP_{12.5}$ treatment. Therefore, PR successfully provided labile Pi to the plant when applied to the studied soil due to the strong acidity of the soil that favored PR dissolution; however, the released P was likely insufficient for cassava growth, since the critical soil level for cassava is 10.0 mg/kg (Howeler, 1989; Howeler and Cadavid, 1990). The current results clearly indicated that these organic wastes enhanced the solubilization of PR to provide more labile Pi, though there were small differences in the Pi fractionations among the different applied rates of CP and CSW. The organic acids produced from these organic wastes strongly increased the P concentration by creating a favorable environment for P solubilization involving chelation and an exchange reaction (Mahimairaja et al., 1995; Sharpley et al., 2004; Menezes-Blackburn et al., 2016). Although CP was more acidic and had a narrower range in its C:N ratio than CSW, CP took longer to dissolve PR than CSW, which might have contributed to the slow and steady release of P to plants.

The moderately labile Pi (NaOH-Pi) was the largest pool of the studied soil P due to the relative abundance of Fe, Mn and Al in acidic soils; however, the increase in this P fraction was mainly due solely to the PR rather than to the wastes combined with PR. These results implied that after PR was applied to soil, P was transformed into a relatively active pool of P in the acidic soil. A similar result was observed by Hongqing et al. (2001) who reported that Fe-P and Al-P were the reaction products from PR dissolution. Although NaOH-Pi was less related to plant uptake than $NaHCO_3$-Pi, it can be a source of available P for P uptake by the plant, especially when the soil P is in deficit (Guo et al., 2000; Maranguit et al., 2017).

There was a marked increase in the Ca occluded P (HCl_{1M}-Pi) in the soil applied with PR, but there were no significant differences when applied together with CP and CSW at different rates. Similar results occurred with the recalcitrant Pi (HCl_{conc}-Pi) fraction. In addition, these two fractions continued to show an increasing trend until 112 DAI when PR was applied with and without wastes, perhaps because the decomposition of these wastes had slightly solubilized the PR to some degree, representing undissolved PR in the soil. Nevertheless, the increases in these amounts of non-available P fractions (HCl_{1M}-Pi and HCl_{conc}-Pi) did not enhance P utilization for plants, as they are mineralized to release P into the soil solution for crop use where there is extreme P deficiency (Brunetto et al., 2013) and are subject to changes into other forms over time.

The Po fractions hardly increased when only PR was applied, but they increased when applied together with CP and CSW. The Po in the labile fraction ($NaHCO_3$-Po) was less than in the moderately labile (NaOH-Po) and the relatively stable (HCl_{con}-Po) fractions; there were small differences in these Po fractions among the CP and CSW amounts applied at different rates. The similar increase in the soil Po fractions due to organic material addition was consistent with the application of manure (Pavinato et al., 2009), cow dunk (Saleque et al., 2004), pig manure (Yin and Liang, 2013) and organic wastes (Cui et al., 2011; Couto et al., 2017).

The moderately labile and relatively stable Po markedly increased within 28 DAI when CP and CSW at both rates were added to PR, especially for the $CP_{12.5}$ treatment. This clearly reflected that these wastes favored the binding of P into more stable organic bonds at an early stage within 1 mth after application. The potential of stable Po was effectively mineralized by microorganisms (Waigwa et al., 2003; Saleque et al., 2004; Schroeder and Kovar, 2006) and thus transferred into labile Po. In turn, this increased the soil content of labile Po, which was maximized at 56 DAI, with a concurrent decrease in the more stable forms of Po. On the other hand, Po was in an equilibrium with reserve Po, as the labile Po slightly decreased and then the moderately labile Po subsequently increased at the end of incubation. In addition, these results implied that the different Po fractions could be transformed into each other during soil incubation due to the existence of an organic P synthesis mechanism linked to wastes application. The results indicated that these organic wastes both took 56 d to solubilize PR due to the huge increment in labile Po (almost twice as high) compared to the soil samples with and without PR application. In addition, the increase in labile Pi during the early stage of incubation at 14 d further suggested that both CP and CSW may have fully enhanced the PR solubilization in this sandy soil because the organic humification by microorganisms enhanced soil P availability based on measurable amounts of P gradually turning into the available pool after mineralization (Turner and Engelbrecht, 2011; Yin and Liang, 2013; Menezes-Blackburn et al., 2016), and these transformations were time-related.

The current findings indicated that Thai PR used as supplemental P appeared to correct for P-deficiency in a loamy sand acidic soil and its effectiveness was further increased when amended with CP or CSW. Supplementing PR with either of these organic wastes increased the P contents in all Pi and Po pools; however, there were no significant differences between the rates of application (6.25 t/ha or 12.5 t/ha). Nevertheless, soil Po pools were hardly built when only PR was applied. Phosphate rock increased the P level in the labile Pi pool throughout the 112 d of incubation, but the soil P content remained below the critical soil level for cassava due to the P being transformed quickly to more stable Pi pools. Amending PR with CP or CSW led to changes in the soil P pools and especially contributed to the solubilization of Po from the moderately labile and chemically stable fractions into the labile fraction. The labile Pi and Po fractions were maximized at 14 d and 56 d, respectively, after application, with CP being superior to CSW in contributing to the slow and steady release of P to plants. However, both wastes appeared to be less effective at increasing the P solubility in the PR due to most P still being present in the moderately labile and chemically stable P fractions as a reserve source of P in the soils, especially when the Pi pool is limited.

Conflict of Interest

The authors declare that there are no conflicts of interest.

Acknowledgements

This work was mainly supported by a Graduate Scholarship for International Publication, Graduate School, Kasetsart University, Bangkok, Thailand and partly funded by the Thai Challenging Fund for Natural Resource and Environment Development supported by the NRCT and the Kasetsart University Research and Development Institute (KURDI).

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