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Phosphorus availability in different aggregate sizes of tropical red soils amended with cassava starch waste

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Abstract

The study was conducted to determine the role of aggregate size in three red tropical soils with varying clay content on the phosphorus (P) availability and the adsorption and desorption of P with the addition of cassava starch waste (CSW). Seven ranges of aggregate size up to 8 mm in diameter were carried out using dry-sieving method and each aggregate size was taken for the study of P sorption isotherm and determining P content. CSW had no impact on the P adsorption capacity of soils with a lower clay content but slightly increased the P adsorption capacity for most aggregate sizes of clay-textured soil, especially in the sizes 0.25 mm to <0.053 mm. Smaller aggregates adsorbed more P, resulting in P desorption being significantly being lower than that of larger aggregates; in turn, the latter released greater P, especially with CSW applied. The results indicated that most P was fixed in different aggregate sizes in different capacities, demonstrating the aggregation effect on plant P availability.

Introduction

Phosphorus (P) is a major limiting nutrient for plant growth in highly weathered soils of the Tropics (Sanchez, 1976), particularly in Thailand. These soils are dominated by soil aggregates with high stability. They usually have low P bioavailability owing to their high P adsorption capacity due to the abundance of Al and Fe in these soils (Fontes and Weed, 1991; Bunemann et al., 2004). Available P levels are low in these soils with the critical levels of 4–10 mg/kg was reportedly to limit cassava yields (Howeler, 1985). Phosphorus fertilization of 50–100 kg P per ha per year has been recommended for acid, low-P soils to obtain high and stable yields (Howeler and Cadavid, 1990). Soil P availability is, in part, governed by the ability of soil to adsorb phosphate and there are many factors controlling P availability to plants including soil pH, organic matter content, type of clay mineral and the amount of sesqioxides (Burt et al., 2002; Jin et al., 2006).

Soil aggregate is one of the important keys that has an impact on P sorption, as well as the bio-availability of P due to different sizes of pores in the aggregate which may fit with phosphate (Whalen and Chang, 2002). McDowell et al. (2007) demonstrated that P availability is related to soil aggregate size. Phosphorus attachment to soil aggregates depends on the particle size (Hao et al., 2004). Extractable P is sometimes higher in larger size aggregates, which will probably result in increased P release from aggregates. Linquist et al. (1997) found that the P sorption capacity in Typic Palehumult soil decreased with increasing aggregate size. Therefore, more P was adsorbed by smaller aggregates than larger aggregates, giving the latter higher P availability. This may have been due to the greater surface area associated with these micro-aggregates to sorb more P than

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macro-aggregates. Lima and Anderson (1997) showed that the larger aggregates (1–2 mm) from an Oxisol soil contained more clay, goethite and extractable Fe and Al than the smaller aggregates (0.1–0.2 mm) and, therefore, the larger aggregates could adsorb more P than the smaller aggregates. Barber (1984) reported that P desorption from large aggregates was lower than from small aggregates due to a longer diffusion path length. In addition, soil disturbance increases the contact between soil mineral particles and phosphate (Redel et al., 2007). However, in contrast, Wang et al. (2001) found that 4–6 mm aggregates could release less P than 0.5–1 mm aggregates which could release the highest P in all periods. This suggested that in well-structured soils, the inner surfaces may have a minor effect on adsorption because they are markedly less exposed to phosphate in the soil solution (Hantschel et al., 1988).

Phosphorus availability is partly influenced by aggregates in these tropical soils. However, repeated tillage in these tropical soils has resulted in a decrease in the soil organic matter content and in turn soil aggregation (Sanchez, 1976; Barthes et al., 1999; Simansky, 2012). Organic matter inputs through organic amendment is well known to increase aggregate stability (Tisdall and Oades, 1982; Angers, 1992; Annabi et al., 2007) and may affect the P adsorption capacity (Ma and Xu, 2010; Azeez and Van Averbeke, 2011) by the effect of organic compounds competing with phosphate for adsorption sites (Guppy et al., 2005). In the starch manufacturing industry, the process that produces cassava starch from fresh cassava tuber leaves substantial industrial wastes such as tails and stalk, cassava peel and cassava starch waste. One tonne of cassava fresh tuber produces 0.25–0.35 t of cassava starch waste. Cassava wastes from the starch manufacturing industry, especially cassava starch waste, is tending to increase annually and cause environmental problems, with an estimated 9.54 million t of cassava starch waste being produced annually (Northeastern Tapioca Trade Association, 2016). Using this agricultural waste as soil amendment is a sustainable solution to tackle the problem of disposing of this organic waste, resulting in a valuable substrate for production of economic crops in degraded soils, especially in areas where there is a scarcity of other soil amendments such as animal manures. The current aimed to examine P adsorption and desorption in different aggregate sizes of red soils in Thailand and the effect of applying cassava starch waste as a soil amendment. The results should provide better understanding of the relationship between soil aggregation and phosphorus availability and adsorption and desorption of P in soil aggregates of red tropical soils, particularly when amended and also provide useful information on an alternative use of cassava starch waste to reduce the cost of its disposal.

Materials and Methods

Cassava starch waste

The cassava starch waste (CSW) used in the incubation study was collected from Chaodee Modified Starch Co., Ltd. in Nakhon Ratchasima province, Thailand. The waste was air dried, hand crushed and sieved (0.5 mm) before use. Its composition consisted of 251 g/kg of organic carbon, 3.5 g/kg of total N, 0.68 g/kg of total P, 2.38 g/kg of total K, 6.16 g/kg of total Ca, 1.41 g/kg of total Mg, 0.28 g/kg of total S, 0.27 g/kg of total Na, 80 mg/kg of total Fe, 17.8 mg/kg of total Zn, 4.6 mg/kg of total Mn and 3.13 mg/kg of total Cu. The electrical conductivity and pH (in aqueous extract at 1:1 ratio) were 0.6 dS/m and 5.8, respectively, and the cation exchangeable cation was 27.8 cmol/kg.

Soil samples

The effect of CSW on P sorption was tested using three red soils with different clay contents: Rhodic Kandiustox (Pak Chong soil series: Pc, 600 g/kg of clay content), Typic Paleustults (Yasothon: Yt soil series, 80 g/kg of clay content) and Typic Rhodustalfs (Si Khiu: Si soil series, 170 g/kg of clay content). All soil samples were collected from farm fields used for growing corn in Nakhon Ratchasima province, northeast Thailand. Each soil sample was randomly collected from a ploughed layer (0–30 cm) and mixed well to determine the property before use in the incubation study and P desorption experiment. The three soils were chosen because they were very strongly acid (pH 4.4–5.0) with varying properties (Table 1). The soils had a total P content in the same range 198–464 mg/kg with the Pc soil series having much lower available P (BrayII) content (6.42 g/kg) than the other two soils.

Incubation experiment

Field moist samples were sieved (8 mm), homogenized and stored at 25°C for 14 d prior to commencing the experiment. The incubation experiment was carried out in the laboratory using 300 cm^3 plastic containers. The container contained 500 g of soil sample with CSW being applied at the rates of 0 g per 500 g soil and 2.56 g per 500 g soil (equivalent rate of 10 t/ha), the latter basing on the recommendation for field crops in Thailand (Department of Agriculture, 2004), and mixed evenly. Each treatment comprised four replicates. The soil water content during the incubation period was maintained at 60% field capacity (The gravimetric water content determined from un-amended soils prior to conducting the experiment was 25.5%, 11.6% and 9.1% for Yt, Si and Pc soil series, respectively). The water content was adjusted accordingly on a daily basis by adding deionized water gently onto the soil surface. All containers were covered with plastic film and incubated at a constant temperature (30°C) for 21 d.

Aggregate stability determination

After incubating the soil for 21 d, the aggregate stability of the amended and un-amended soils was determined using the wet-sieving method described below. Samples of 4 g of aggregate (dry weight) were placed on a 0.25 mm sieve and left to stand in 100 mL of deionized water for 15 min to achieve saturation, after which the wet-sieving apparatus (Eijkelkamp Agrisearch Equipment; Giesbeek, the Netherlands) was set in motion and the aggregates were dipped into the water 95 times within 3 min. Water and detached soil materials were then transferred into a plastic tray and the soil suspension was oven-dried at 105°C for 24 hr and then weighed to determine the mass. All remaining aggregate was returned to dip in 1 M NaOH and soaked 95 times within 3 min. After that, the soil suspension was transferred to a clean plastic tray. The soil fractions were oven-dried at 105°C for 24 hr and then weighed to determine the mass. The mass of water-stable aggregate (WSA) was calculated as a difference between the mass originally taken for the aggregate stability analysis and the mass of the soil material detached during the wet-sieving (Kemper and Rosenau, 1986).

Phosphorus in soils

Eight aggregate-size fractions of amended and un-amended soils were obtained by dry-sieving (De Leenheer and De Boodt, 1959) using a Tyler Ro-Tap test sieve shaker equipped with US standard test sieves (RX-29-10 specification) to obtain sizes of <0.053 mm, 0.053 mm to <0.125 mm, 0.125 mm to <0.25 mm, 0.25 mm to <0.5 mm, 0.5 mm to <1 mm, 1 mm to <2 mm and 2 mm to <8 mm after 21 d of incubation. All aggregate-size fractions were further used for investigation of the P contents and P sorption isotherm.

Total P, available P and organic P in soil aggregate

The total P in the soil aggregate fractions was determined using the vanado-molybdate yellow color method (Murphy and Riley, 1962) after digesting using $HClO_4$–HNO_3 (Kuo, 1996). The available P in these soil fractions was extracted using BrayII solution (Bray and Kurtz, 1945) followed by a determination of P in the extracts using the colorimetric method (Murphy and Riley, 1962). The organic P in the soil aggregate fractions was determined according to the method of Aspila et al. (1976). In this method, inorganic and total P were determined as 1 M HCl-extractable P (for 24 hr) before and after ignition of the soil sample at 550°C (for 2 hr), after which the content was measured using a spectrophotometer at 770 nm (Steward and Oades, 1972). The difference between the total and inorganic P was used as a measure of organic P.

Phosphorus sorption isotherm

A soil sample from each aggregate size was taken for the study of the P sorption isotherm (Fox and Kamprath, 1970), with 1 g of the sample being accurately weighed and placed into a 50 mL centrifuge tube mixed with 25 mL of 0.01 mol per liter $CaCl_2$ containing 0 mgP per liter, 2 mgP per liter, 4 mgP per liter, 8 mgP per liter and 10 mgP per liter. All samples were shaken end-over-end to avoid breaking down of the soil aggregate for 24 hr to reach equilibrium at a constant temperature of 25°C. Then, the suspensions were centrifuged and filtered through a Whatman No. 42 filter. The P concentration of the supernatant was determined using the ascorbic blue method (Murphy and Riley, 1962), followed by the calculation of the P adsorption rate. A sample of 25 mL of 0.01 mol per liter of $CaCl_2$ was added into the residual soil in the centrifuge tube and the soil mixture was shaken end-over-end for 16 hr to reach equilibrium. Then each mixture was centrifuged to separate the soil and extracted solution. The extracted solution was filtered through a Whatman No. 42 filter and then analyzed for the P content using the method of Murphy and Riley (1962) and subsequently the P desorption rate was calculated.

Table 1 Selected properties of the soils studied

Property	Soil series		
	Pc	Si	Yt
Texture class	Clay	Loamy sand	Loamy sand
Sand (g/kg)	120	700	770
Silt (g/kg)	450	130	150
Clay (g/kg)	600	170	80
Soil pH (1:1 H_2O)	5.0	4.9	4.4
Organic matter (g/kg)	39.4	35.6	30.3
Total N (g/kg)	0.9	0.3	0.2
Total P (g/kg)	464	240	198
Available P (mg/kg)	6.42	24.3	13.6
Available K (mg/kg)	51.6	39.7	30.8
CEC ($cmol_{(+)}$/kg)	13.8	4.5	3.8
Extr. Ca ($cmol_{(+)}$/kg)	14.0	4.3	2.3
Extr. Mg ($cmol_{(+)}$/kg)	2.28	0.43	0.67
Extr. Na ($cmol_{(+)}$/kg)	0.10	0.08	0.13
Extr. $Fe_{(DCB)}$ (g/kg)	51.3	10.8	3.22
Extr. $Fe_{(oxalate)}$ (gkg)	3.41	0.71	0.38
Extr. $Fe_{(pyrophosphate)}$ (g/kg)	2.65	0.34	1.55

Pc = Pak Chong soil series; Yt = Yasothon soil series; Si = Si Khiu soil series.

Phosphorus adsorption and desorption isotherms were described using the Freundlich equation: $q = K_f C^n$, where q represents the amount of P sorbed by the solid phase (milligrams of P per kilogram of soil), C is the solution P concentration (milligrams per liter) after equilibration, K_f is a constant related to the sorption capacity referring to the ratio of P adsorbed to P in the soil solution and n is the phosphate sorption energy as described by the non-linearity of the adsorption curve (Shafqat and Pierzynski, 2014).

Statistical analyses

All parameters were computed using the SPSS software (version 17.0; SPSS Inc. Chicago, IL, USA) to determine any statistical significance. A t test at a significance level of $p < 0.05$ was used to compare means of treatments treated with and without CSW added. Analysis of variance and mean separation using Duncan's multiple range test at a significance level of $p < 0.05$ were performed to test the effect of aggregate size on soil parameters.

Results and Discussion

Effect of cassava starch waste on soil aggregate

The distribution of aggregate size fractions separated from control and CSW amended soils is given in Table 2. The effect of CSW on aggregate formation was observed only in the 2 mm to 8 mm, 0.5 mm to <1 mm, 0.25 mm to <0.5 mm and 0.125 mm to <0.25 mm aggregate sizes of the Pc soil series. The mass of the 2 mm to <8 mm aggregates size significantly increased with the application of CSW whereas the non-amended soil had significantly smaller-sized aggregate (0.25 mm to <1 mm). This indicated that CSW evidently promoted soil macro-aggregates in this soil. This was confirmed by Tisdall and Oades (1982) who found that micro-aggregates (<0.25 mm) were bound together by organic compounds of different origins to form macro-aggregates (>0.25 mm). Large aggregates are more sensitive to management effects of organic matter, and consequently can serve as a better indicator of changes in soil physical quality. The application of CSW also resulted in some changes in the small macro-aggregate size fractions (0.25 to <1 mm) because destabilization of the aggregates occurred due to the presence of some specific organic matter fractions, including soluble organic anions (Kay and Angers, 1999). In addition, dispersing agents in manure may cause destabilization of large soil macro-aggregates in some soil types (Whalen and Chang, 2002). However, no effect was found for aggregates with a size smaller than 0.125 mm because of the more dominant effect of the clay content and iron oxides in those sizes (Wang et al., 2001).

The Yt and Si soil series had much lower clay content and were no significant difference between the treatments for these soils (Table 2). Aggregate sizes of 0.125 to <0.25 mm were dominant in both soils. The distribution pattern was somewhat similar to a previous study, which revealed that the dominant aggregate size fractions in a sandy soil were 0.50–0.25 mm and 0.25–0.125 mm, accounting for 80.6% of the total dry soil weight (Zhang et al., 2003). In another report, manure or fertilizer application had only a small effect on changing the distribution of aggregate size fractions (Geisseler et al., 2011). The portion of total micro-aggregates with sizes between 0.25 and <0.053 mm was 69.0–72.4% in CSW-amended soils and 70.7–73.6% in non-amended soils (Table 2). This indicated that these soils were vulnerable to the detachment process.

Water-stable aggregates in the Yt and Si soil series significantly increased when CSW was applied which was in contrast to the Pc soil series. This was due to the latter having higher levels of Fe oxides and organic matter and clay contents, which are highly stable soil cementing agents (Bunemann et al., 2004; Annabi et al., 2007). When CSW was applied, the proportion of water-stable aggregates increased by 76.1% and 83.4% in the Yt and Si soil series, respectively (Fig. 1). This clearly showed that CSW application improved the soil physical properties of sandy soils as the amount of stable aggregates increased.

Effect of cassava starch waste on P contents in soil aggregate

Comparison of the total P distribution patterns among the different aggregate size fractions in the control and CSW-applied soils indicated some differences (Table 3). There was a significant difference in all aggregate sizes in the Si soil series, for 2 mm to <8 mm and <0.053 mm in the Yt soil series and for <0.053 mm in the Pc soil series (Table 3).

Table 2 Effect of cassava starch waste (CSW) on aggregate size distribution

Aggregate class (mm)	Aggregate size distribution (g/100 g soil)^a					
	Pc soil series		Si soil series		Yt soil series	
	Control soil	CSW-soil	Control soil	CSW-soil	Control soil	CSW-soil
2 to 8	12.5^B	21.8^A	0.9^A	1.1^A	0.2^A	0.1^A
1 – <2	19.1^A	21.4^A	5.0^A	6.2^A	1.7^A	1.3^A
0.5 – <1	29.4^A	24.3^B	7.9^A	8.3^A	6.9^A	6.8^A
0.25 – <0.5	20.4^A	14.5^B	11.9^A	11.8^A	20.0^A	21.8^A
0.125 – <0.25	9.0^A	7.4^B	54.3^A	58.3^A	57.4^A	51.8^A
0.053 – <0.125	4.8^A	5.4^A	13.6^A	9.1^A	11.9^A	13.9^A
<0.053	4.8^A	5.2^A	6.4^A	5.3^A	1.9^A	4.2^A

Pc = Pak Chong soil series; Si = Si Khiu soil series; Yt = Yasothon soil series.^{a} Means followed by the same uppercase superscript letter within a row are not different at $p < 0.05$.

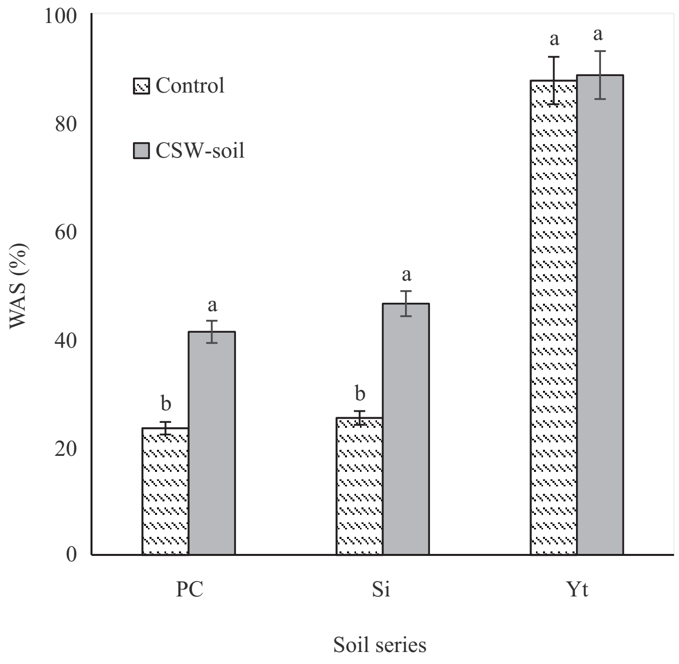

Fig. 1 Effect of cassava starch waste (CSW) on water aggregate stability (WAS), where error bar = ±SD within each soil series (Pc = Pak Chong soil series; Si = Si Khiu soil series; Yt = Yasothon soil series) and blocks with the same letter are not different at $p < 0.05$.

The application of CSW significantly increased the total P content in soil aggregates. The greatest proportion of the total P content was significantly distributed in the smaller-sized aggregates (0.053 mm to <0.125 mm in the Pc soil series and <0.053 mm in the Si soils series). This was due to most P being fixed by CSW in micro-aggregate fractions (Linquist et al., 1997; Wang et al., 2001; Hao et al., 2004). In addition, sesquioxides, carbonate and silicate clay have been reported as the predominant cementing agents in micro-aggregates (Hughes and Le Mare, 1982) so the P fixation in the current experiment was probably caused by the effect of sesquioxides which are commonly found in tropical red soils (Fontes and Weed, 1991; Bunemann et al., 2004).

CSW application had a significant effect on increasing the available P forms in all aggregate size fractions except for the 2 mm to <8 mm fraction in the Pc and Si soils series (Table 4). A comparison of the available P levels in individual aggregate fractions between CSW applied and the control soils revealed that the significantly highest amount of P was accumulated in the micro-aggregate size <0.53 mm in the Pc and Si soils series. This was due to the greater surface area of these micro-aggregates (Linquist et al., 1997; Redel et al., 2007). In general, this observation suggested that CSW that was applied to the soils can increase the available P forms, predominantly in the micro-aggregate fractions relative to the macro-aggregates. This agreed with Zhang et al. (2003) who found that greater proportions of Mehlich-3 extractable P were observed in aggregate sizes of 0.50–0.25 mm and 0.25–0.125 mm in sandy soil samples. Generally, they found that soils containing high levels of extractable P were considered more susceptible to losing P via runoff, and soil particles containing high amounts of extractable P are suggested to have a higher P release potential. Considering these facts, it is reasonable to suggest that the high levels of available P observed in the micro-aggregates, especially in the CSW-applied soils, may be of environmental concern due to the high P release potential associated with these micro particles. Phosphorus attached to these particles can be readily released to the environment via surface runoff or leaching.

The application of CSW significantly increased the content of organic P in all aggregate sizes in the Si and Yt soil series. For clayey soil in the Pc soil series, there were some differences in the organic P distribution patterns of different aggregate size fractions in non-amended and CSW-amended soils (Table 5) because the Pc soil series contained very high amount of iron, especially in the form of organic compounds which usually absorbed P (Makarov et al., 2004). As a consequence, the effect of CSW on organic P content was not clear. Moreover, the distribution of organic P in different sizes of aggregate fractions varied depending on the soil type (Table 5). This agreed with some previous studies (Whalen and Chang, 2002) in which there was a notable increase in organic P forms in certain micro-aggregate size fractions that may be beneficial for plants due to the ease of P mineralization (Hao et al., 2004; Wortman and Shapiro, 2008).

Table 3 Effect of cassava starch waste (CSW) on total P content in different aggregate sizes

Aggregate class (mm)	Total P (mg/kg)[a]					
	Pc soil series		Si soil series		Yt soil series	
	Control soil	CSW-soil	Control soil	CSW-soil	Control soil	CSW-soil
2 to 8	282^{abA}	258^{cdA}	142^{cB}	172^{cA}	95^{bB}	264^{aA}
1 – <2	284^{abA}	232^{dA}	144^{cB}	182^{cA}	129^{abA}	159^{cA}
0.5 – <1	277^{abA}	315^{bcA}	153^{bB}	215^{bA}	105^{bA}	131^{dA}
0.25 – <0.5	251^{abA}	294^{bcA}	128^{dB}	182^{cA}	105^{bA}	130^{dA}
0.125 – <0.25	276^{abA}	$282b^{cdA}$	144^{cB}	177^{cA}	104^{bA}	132^{dA}
0.053 – <0.125	303^{aB}	387^{aA}	146^{bcB}	170^{cA}	115^{bA}	123^{dA}
<0.053	228^{bB}	323^{bA}	191^{aB}	243^{aA}	162^{aB}	220^{bA}

Pc = Pak Chong soil series; Si = Si Khiu soil series; Yt = Yasothon soil series.[a] Within a row, means with the same uppercase superscript letter are not different at $p < 0.05$. Within a column, means with a common lowercase superscript letter are not different at $p < 0.05$.

Table 4 Effect of cassava starch waste (CSW) on available P content in different aggregate sizes

Aggregate class (mm)	Available P (mg/kg)[a]					
	Pc soil series		Si soil series		Yt soil series	
	Control soil	CSW-soil	Control soil	CSW-soil	Control soil	CSW-soil
2 to 8	2.8^{bcA}	5.3^{cA}	5.7^{eA}	7.4^{fA}	18.0^{aB}	40.9^{aA}
1 – <2	2.7^{cB}	3.9^{cA}	$6.1d^{eB}$	9.6^{eA}	5.1^{eB}	21.9^{cdA}
0.5 – <1	3.1^{abB}	4.5^{cA}	6.8^{cdB}	11.6^{dA}	7.7^{dB}	15.3^{dA}
0.25 – <0.5	2.8^{bcB}	6.2^{cA}	6.6^{dB}	12.3^{cdA}	8.7^{cdB}	13.6^{dA}
0.125 – <0.25	3.1^{abB}	6.5^{bcA}	7.8^{bB}	13.9^{bA}	10.5^{cB}	27.4^{bcA}
0.053 – <0.125	3.3^{abB}	8.9^{bA}	$7.3b^{cB}$	12.7^{cA}	9.9^{cdB}	18.0^{dA}
<0.053	3.6^{aB}	14.0^{aA}	10.3^{aB}	20.8^{aA}	15.3^{bB}	30.8^{bA}

Pc = Pak Chong soil series; Si = Si Khiu soil series; Yt = Yasothon soil series.

[a] Means followed by the same uppercase superscript letter within a row are not significantly different at $p < 0.05$. Means followed by a common lowercase superscript letter within a column are not different at $p < 0.05$.

Table 5 Effect of cassava starch waste (CSW) on organic P content in different aggregate sizes

Aggregate (mm)	Organic P (mg/kg)[a]					
	Pc soil series		Si soil series		Yt soil series	
	Control soil	CSW–soil	Control soil	CSW–soil	Control soil	CSW–soil
2 to 8	25.3^{bcA}	22.8^{dB}	3.16^{fB}	15.7^{cA}	1.94^{eB}	10.1^{deA}
1 – <2	24.9^{cA}	26.1^{cA}	3.42^{fB}	10.9^{eA}	3.03^{dB}	18.7^{bA}
0.5 – <1	17.7^{dB}	26.2^{cA}	12.7^{bB}	19.9^{bA}	2.28^{eB}	10.5^{dA}
0.25 – <0.5	26.6^{aA}	21.3^{eB}	8.82^{cB}	11.2^{eA}	1.42^{fB}	28.3^{aA}
0.125 – <0.25	25.7^{bA}	20.6^{eB}	6.61^{dB}	12.8^{dA}	4.33^{cB}	9.30^{eA}
0.053 – <0.125	25.7^{bB}	28.8^{aA}	5.30^{eB}	8.74^{fA}	6.12^{bA}	2.17^{fB}
<0.053	25.3^{bcB}	27.2^{bA}	15.4^{aB}	23.6^{aA}	12.4^{aB}	16.3^{cA}

Pc = Pak Chong soil series; Si = Si Khiu soil series; Yt = Yasothon soil series.

[a] Means followed by the same uppercase superscript letter within a row are not significantly different at $p < 0.05$. Means followed by a common lowercase superscript letter within a column are not different at $p < 0.05$.

Effect of cassava starch waste on p sorption isotherm of different aggregates

The P adsorption characteristics in different aggregate fractions of all soils in the current study showed that the P adsorption contents from all aggregate sizes were rather similar, especially in the non-amended soil (Fig. 2A–2C). The P adsorption of the soil samples increased as the initial P concentration increased at lower P concentrations, and then increased to a lesser extent at higher P concentrations. The highest P adsorption capacity was recorded in the Pc soil series followed by the Yt and Si soil series, respectively (Table 6). This was due to the Pc soil series being rich in iron and aluminum oxides, which have high degrees of crystallinity and high P adsorption capacities (Bunemann et al., 2004). Although, the addition of organic materials can reduce the P adsorption capacity of soil as shown in previous reports (Guppy et al., 2005; Ma and Xu, 2010), the application of CSW had no impact on the P adsorption capacity in different size fractions of the Si and Yt soil series (Fig. 2B and 2C) but increased the P adsorption capacity slightly for most aggregate sizes in the Pc soil series (Fig. 2A), especially in the sizes between 0.25 mm to <0.053 mm. This was due to CSW being mainly composed of non-decomposed organic carbon. Hence, the addition of CSW increased the adsorption sites in the soil, inducing an increase in P adsorption. At the same time, mineralization can cause adsorption competition; hence, the magnitude of change was small (Zhuo et al., 2009). The P adsorption results were consistent with the P desorption characteristics where a lower P desorption capacity was found in the CSW-amended soil than in the non-CSW-amended soil (Table 6).

In the Yt and Si soil series, the P desorption capacity was rather similar between non-amended and CSW-amended soils. Overall, the smaller-size aggregates adsorbed more P (Fig. 2B and 2C); therefore, P desorption was significantly greater in larger-size aggregates (Fig. 3B and 3C). This agreed with Linquist et al. (1997) who found that P sorption continued to increase as the aggregate size decreased below 0.375 mm. Since P is sorbed on the periphery of aggregates, smaller aggregates should initially sorb more P than larger aggregates due to the greater surface area per unit mass of smaller aggregates. However, in the Yt soil series, P desorption in large aggregates was lower than in small aggregates (Table 6) due to a longer diffusion path length (Barber, 1984). This indicated that P fixed inside large aggregates was not rapidly released into the soil solution since the short-term release of P from aggregates was closely related to the reactive mass on the periphery of aggregates. Thus, P inside large aggregates of this soil was not immediately available to plants.

In general, tropical soils are often P deficient as well as highly aggregated. However, the aggregation can be broken down by repeated tillage since crop establishment requires loosening the soil, especially when soil organic matter is low (Angers, 1992; Redel et al., 2007). The current results indicated that the application of CSW from a starch manufacturing plant has potential for use as soil amendment because it can promote large aggregate (2–8 mm) formation in high clay content, red soil and improve the aggregate stability in very low clay content, red soil. Moreover, applied CSW slightly increased the P adsorption capacity for most aggregate sizes in the fine-textured Pc soil series, especially in sizes between 0.25 mm and <0.053 mm. The smaller aggregate sizes adsorbed more P; therefore, P desorption was significantly greater in larger aggregates and in turn, released P in greater amounts, especially when CSW was applied. The P remaining in all aggregate sizes was in an unavailable form, (accounting for 97.8–99.5%. A high level of available P was mainly found in the largest aggregates sizes (2 to <8 mm). Therefore, P would be more available to plants in soils with a high proportion of large aggregates.

Conflict of Interest

The authors declare that there are no conflicts of interest.

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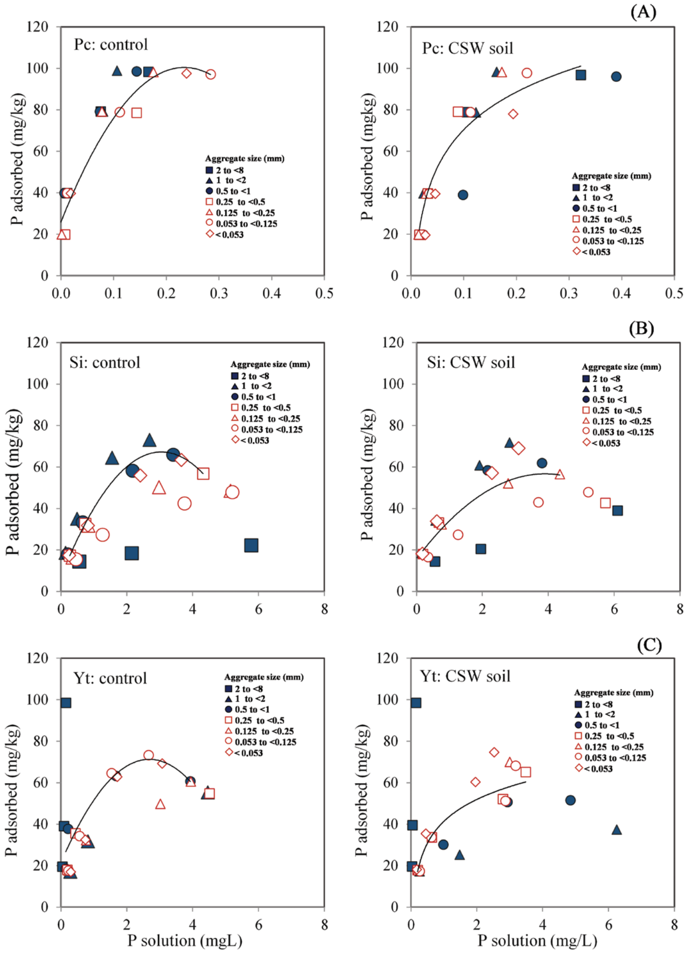

Fig. 2 Phosphorus adsorption isotherm from different aggregate sizes of Pak Chong soil series = Pc (A), Si Khiu soil series = Si (B) and Yasothon soil series = Yt (C) with and without (control) cassava starch waste (CSW) applied, where the line represents the P adsorption trend for all aggregate

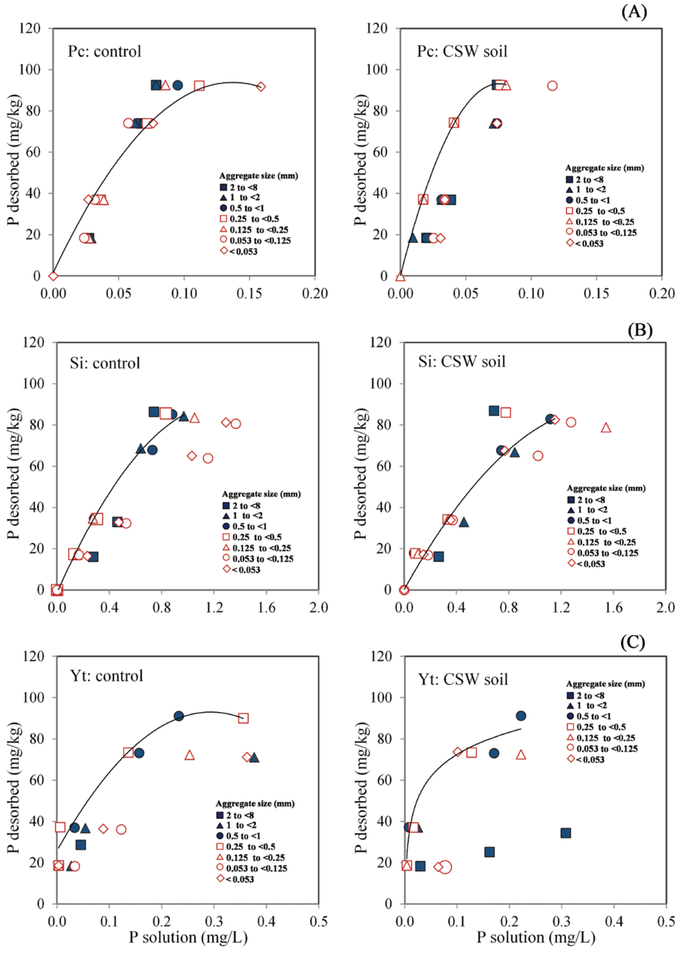

Fig. 3 Phosphorus desorption isotherm from different aggregate sizes of Pak Chong soil series = Pc (A), Si Khiu soil series = Si (B) and Yasothon soil series = Yt (C) with and without (control) cassava starch waste (CSW) applied, where the line represents the P adsorption trend for all aggregates

Table 6 Phosphorus adsorption and desorption (using the Freundlich equation) from different aggregate sizes of soils with and without cassava starch waste (CSW) applied

Aggregate class (mm)	Soil series	P adsorption						P desorption					
		Control soil			CSW–soil			Control soil			CSW–soil		
		K_f	n	r^2	K_f	n	r^2	K_f	n	r^2	K_f	n	r^2
2 to 8	Pc	187	0.3	0.99	205	0.5	0.92	4585	1.5	0.99	2251	1.2	0.99
1 – <2		211	0.3	0.98	214	0.4	0.99	5870	1.5	0.97	420	0.6	0.98
0.5 – <1		171	0.3	0.99	157	0.5	0.91	1554	1.1	0.95	1145	1.0	0.96
0.25 – <0.5		211	0.3	0.98	214	0.4	0.99	603	0.8	0.97	420	0.6	0.98
0.125 – <0.25		181	0.3	0.99	522	0.7	0.98	2740	1.3	0.97	451	0.6	0.95
0.053 – <0.125		142	0.3	0.99	302	0.6	0.97	5766	1.5	0.95	768	0.9	0.93
<0.053		161	0.3	1.00	219	0.5	0.98	254	0.5	0.96	2378	1.3	0.83
2 to 8	Si	16	0.2	1.00	17	0.4	0.96	136	1.6	0.98	168	1.7	1.00
1 – <2		49	0.4	0.99	44	0.4	0.99	94	0.8	0.98	64	0.6	0.93
0.5 – <1		39	0.4	0.99	38	0.4	0.98	93	0.8	0.99	79	0.5	0.99
0.25 – <0.5		32	0.4	0.96	30	0.2	0.85	99	0.8	0.99	90	0.7	0.94
0.125 – <0.25		29	0.4	0.99	34	0.3	0.99	83	0.7	0.97	62	0.5	0.99
0.053 – <0.125		23	0.4	0.99	25	0.3	0.99	58	0.7	0.97	68	0.7	0.99
<0.053		35	0.4	0.99	41	0.4	0.99	64	0.9	0.99	77	0.7	0.99
2 to 8	Yt	31	0.3	0.97	14	0.3	0.95	89	0.3	0.93	43	0.2	0.93
1 – <2		31	0.4	0.97	23	0.2	0.99	119	0.4	0.92	107	0.3	0.99
0.5 – <1		46	0.3	0.77	31	0.3	0.98	144	0.3	0.98	143	0.3	0.92
0.25 – <0.5		36	0.3	0.85	37	0.4	0.97	129	0.3	0.91	120	0.3	0.95
0.125 – <0.25		33	0.4	0.98	39	0.5	1.00	99	0.3	0.99	100	0.2	0.98
0.053 – <0.125		45	0.6	0.98	36	0.4	0.93	114	0.5	0.99	88	0.6	0.99
<0.053		38	0.6	0.97	46	0.4	0.97	144	0.5	0.99	84	0.2	0.96

Pc = Pak Chong soil series; Si = Si Khiu soil series; Yt = Yasothon soil series; K_f = sorption capacity (mg/kg), n = P sorption energy (mg/kg), r^2 = correlation coefficient

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