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Phosphorus behaviour under long-term fertilisation in the intensive rice cultivation system

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Abstract: Advocating proper phosphorus (P) fertilisation is necessary to save this limited natural resource and to save the investment in rice cultivation. This study aimed to evaluate changes in phosphorus availability, total phosphorus in soil, phosphorus buffering capacity, and phosphorus saturation in the long-term phosphorus fertilisation in the paddy rice system. Soil samples were collected in the harvest stage after seven consecutive crops over three years at Can Tho city, Vietnam. The applied phosphorus fertiliser rates were: no phosphorus fertilisation (P_0), 17.4 kg P/ha ($P_{17.4}$), and 26.2 kg P/ha as farmer's practice ($P_{26.2}$). The results showed that the soil phosphorus buffering capacity in P_0, $P_{17.4}$ and $P_{26.2}$ treatments was 9.49, 9.08 and 9.04 mg/kg, respectively. The degree of phosphorus saturation of $P_{17.4}$ and $P_{26.2}$ treatments ranged from 17.7% to 25.5%, showing the medium to high risk of phosphorus leaching. This study indicated that the application of phosphorus rate higher than 17.4 kg P/ha might result in the reduced soil phosphorus buffering capacity in the intensive rice cropping system in the Vietnamese Mekong Delta region. Our results implied that the application of a rate lower than 17.4 kg P/ha/crop could be extended to the other rice-growing (double/triple rice) areas in the Vietnamese Mekong Delta region or other paddy rice on alluvial soils in Asia.

Keywords: adsorption isotherms; Langmuir; Olsen; *Oryza sativa* L.; paddy soil

Phosphorus (P) is a macronutrient for the growth of crops besides nitrogen and potassium. Recently, P has been identified as an unrenewable resource due to the prediction that natural phosphate rock resources are nearing depletion (Cooper et al. 2011, Cordell and White 2015). In soils, the pool of P available for crop utilisation is often limited because many P forms are insoluble compounds and they are adsorbed onto clay minerals (Weil and Brady 2017). To improve P nutrition, farmers apply P fertiliser to overcome this production constraint.

In some circumstances, farmers have applied more P fertiliser than the amount of P removed with the harvest, which has caused soil P accumulation and potential eutrophication (Wang et al. 2013). Farmers in the Vietnamese Mekong Delta (VMD) region have increased production intensity from single rice crops to double and triple rice crops per year. Most farmers have maintained the P fertiliser dose higher than the recommended rate of 26.2 kg P/ha for each crop needed for a double and triple rice cropping system (Long et al. 2016). According to Long et al. (2016), 87% of farmers applied more than 26.2 kg P/ha, and 60% used more 39.2 kg P/ha for one cropping season in triple rice cultivation in the VMD region. Besides, Rakotoson et al. (2022) reported that the P fertiliser rate applied to paddy rice ranged from 17.0 to 25.0 kg P/ha in several countries in Southeast Asia such as Philippines, Indonesia, Cambodia, and Vietnam. After harvesting, rice straw is mainly burned in the field or ploughed into the soil (Long et al. 2016, Hung et al. 2019). Therefore, the amount of P was mainly

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removed with the grain yield. In the triple rice system in the VMD region, Long et al. (2016) reported that about 122 kg P/ha fertiliser were removed with the grain yield after 7 cropping seasons but farmers applied more than 183 kg P/ha fertiliser. Over the years, the remaining P from fertilisation is accumulated in the soil. The overall long-term risk of excessive P application is mobilisation and leaching to the environment (Wang et al. 2013, Fischer et al. 2017).

Olsen-P in the soil was considered as an index measure of P that can be absorbed by the root of the plant and that reflects the P supply capacity of the soil (Ziadi et al. 2013, Weil and Brady 2017). The production of the crop is limited if available soil P ranges at a low level (Yu et al. 2013). Phosphorus is often lightly available to crops in the soils because P is fixed by soil clay minerals, Fe and Al forming insoluble compounds, and only 10–15.0% of P content could be taken by the plant each season (Weil and Brady 2017). The degree of P saturation (DPS) is an index to predict the risk of P runoff to the environment (Wang et al. 2016). According to Wang et al. (2016), overfertilised P application results in the P sorption of many soils becoming increasingly saturated, soil P buffering capacity (PBC) is decreased, and the DPS index increased. A previous study reported that the soil DPS value higher than 15% is generally associated with a medium risk of P runoff or leaching (Huang et al. 2013).

We hypothesised that overuse of P throughout long-term fertilisation has led to an accumulation of P in the soils, thus reducing the soil P buffering capacity, which is a mechanism to prevent P loss to the environment. The objectives of this study were to determine the effect of long-term phosphorus fertilisation on the pool of phosphorus in the soil, phosphorus buffering capacity, and phosphorus saturation in the paddy rice cultivation system.

MATERIAL AND METHODS

Experimental site and soil properties. The experiment was conducted in the intensive rice (3 crops per year) area in Can Tho city, which is located in the VMD region (10°07'26.6"N, 105°34'49.3"E). The study region has a tropical monsoon climate with rainy season (from April to November) and dry season (from November to April). In 2016, the average monthly precipitation was 23.4 mm, varying between 1.00 and 39.4 mm. The average annual temperature in this study site was 27.6 °C, ranging from 27.1 °C to 28.1 °C.

The experimental soil was classified as Dystric Gleysols according to the International Union of Soil Sciences Working Group, World Reference Base for Soil Resources (WRB 2014). At 0–20 cm soil depth, the soil is slightly acidic (pH 4.60), and soil electrical conductivity (EC) is 0.46 mS/cm. Soil organic carbon (4.82% C) ranged at a medium level for paddy rice. Soil texture was classified as clay with clay, silt and sand contents that were 61.5, 38.3 and 0.20%, respectively. The total P and Olsen-P were 0.039% P and 13.5 mg/kg. Soil cation exchange capacity ranged at a medium level for paddy rice (16.9 cmol/kg).

Experimental design and treatments. The field experiment was implemented during seven consecutive rice crops, of which three rice crops were implemented per year. It was laid out in a completely randomised block design with three replicates. The treatments included three P fertiliser rates: no P fertilisation (P_0), fertilised with 17.4 kg P/ha/crop ($P_{17.4}$), and fertilised with 26.2 kg P/ha ($P_{26.2}$) as the farmer's practice (control). Each replicate had 3 treatment plots of 30 m^2 (5 m × 6 m) in size separated by the bund walls, which were 0.5 m high and had a central plastic line core. This construction minimised hydrological connectivity between each plot. All treatments were continuously flooded from 20 days after sowing (DAS) until two weeks before each season's harvest. Nitrogen and potassium fertilisers were applied with 100N-24.8 kg K/ha) in each treatment plot. Phosphorus fertiliser was applied before sowing, and urea fertiliser was topdressed at 10, 20, and 45 DAS while potassium fertiliser was applied at 20 and 40 DAS. The rice cultivar used for the experiment was OM4900, with growth duration of 95–105 days – supported by the Cuu Long Delta Rice Research Institute, Vietnam.

Soil sampling and analyses. Soil samples were taken at 0–20 cm soil depth in the fields at the harvest stage after seven consecutive crops. Soil texture was analysed using the pipette method (Kroetsch and Wang 2008). Soil pH and EC were determined by extracting the soil with deionised water at a ratio of 1:2.5 (soil to water, *w/v*), measured using pH and EC meters. Soil organic carbon (%C) content was determined using the Walkley-Black method (Walkley and Black 1934). Soil available P was determined as Olsen-P by extracting the soil with 0.5 mol $NaHCO_3$ (pH 8.5) at a ratio of 1:20 (*w/v*) (Olsen et al. 1982). Soil total phosphorus concentration was estimated by alkaline digestion, followed by molybdate colorimetric measurement (Murphy and Riley 1962) using the UV spectrophotometer (UV-1800, Shimadzu, Japan).

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Determination of soil P buffering capacity and degree of P saturation indicators. 20 mL P 0.01 mol $CaCl_2$ solutions containing 3, 6, 9, 12, 18, 24, 30, 60, 70, 80, 90, and 100 mg P/L were added to 1 g (2 mm air-dried) soil samples in 50 mL centrifuge tubes for each treatment plot and they were shaken at 25 °C for 24 h. The amount of sorbed P was measured by the difference between the concentration of soluble P added and P in the solution after 24 h.

The soil P buffering capacity index was determined from the slope of the linear equation:

$$q = \frac{K_L q_m C}{1 + K_L C} \quad (1)$$

where: q – equilibrium P sorbed per unit mass of soil (mg/kg); C – equilibrium P concentration (mg/L); K_L – the constant related to the bonding energy of soil P (L/mg); q_m – maximum P adsorption capacity of the Langmuir model (mg/kg) (Langmuir 1918). The maximum P buffering capacity (MBC) was calculated as the maximum slope of the Langmuir equation, evaluated at C = 0 (Mejias et al. 2013):

$$\frac{dq}{dC} = K_L \frac{q_m}{1 + K_L C} \quad (2)$$

The DPS (%) was the ratio of soil test P and the P sorption index (PSI) was recommended by Mejias et al. (2013):

$$\text{DPS (\%)} = \frac{\text{Olsen} - \text{P}}{\text{PSI}} \times 100 \quad (3)$$

where: Olsen-P – available soil P was determined by the Olsen method (mg/kg), and PSI – calculated as the quotient between the amount of P sorbed (q) and the logarithm of C (Sims 2009).

Statistical analyses. The data collected from the experiment were statistically analysed with Minitab 16 using a general analysis of variance (ANOVA). Only treatments with significant differences were submitted to the Tukey's comparison test at the 5% significance level.

RESULTS

Soil P availability and total P after 7 consecutive crops. After 7 consecutive crops, the contents of available soil P at the harvest stage in year 7 ranged from 10.7 to 17.0 mg/kg (Figure 1A). There were no significant differences in Olsen-P between the treatments applied with 17.4 and 26.2 kg P/ha. However, the content of Olsen-P in the treatment with no P fertiliser (10.7 mg/kg) was significantly lower than in the treatments that received 17.4 kg P/ha (15.6 mg/kg) and 26.2 kg P/ha (17.0 mg/kg).

The determination of the soil total P pool in crop 7 indicated that applying P fertiliser at different rates significantly changed total P in the soil after 7 crops. The study showed that total P in the continuous application of P fertiliser at 26.2 kg P/ha (0.043% P) was significantly higher than in the treatment receiving no fertiliser P (0.036% P) during 7 consecutive crops (Figure 1B). However, there were no significant differences in total P in soil between the treatments applied 0 (0.036% P) and 17.4 kg P/ha (0.043% P), neither between those applied 17.4 and 26.2 kg P/ha.

Phosphorus adsorption isotherms. The adsorption of P in relation to its equilibrium concentration (C) in the solution for three rates of P fertiliser was well described by the nonlinear Langmuir model (Figure 2). The results showed an increasing amount of sorbed P when P was added from 0 to 100 mg P/L in all P fertiliser rates.

The fitted Langmuir plots were highly linearly correlated with r = 0.99 in all treatments showing

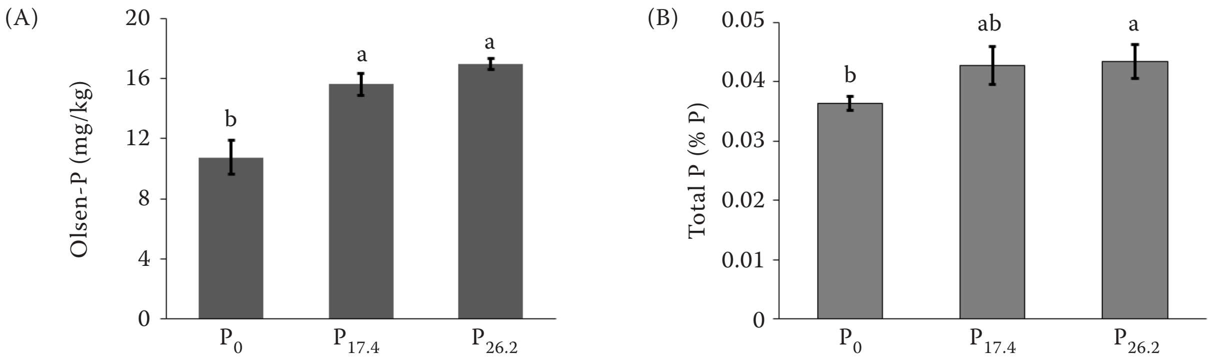

Figure 1. (A) The Olsen-phosphorus (P) and (B) total P of the soil after reduced P fertilisation in 7 consecutive cropping seasons. P_0 – no fertiliser P; $P_{17.4}$ – 17.4 kg P/ha/crop; $P_{26.2}$ – 26.2 kg P/ha/crop. Vertical bars are the standard deviations of the means. Columns with different letters (a, b) are significantly different at $P < 0.05$

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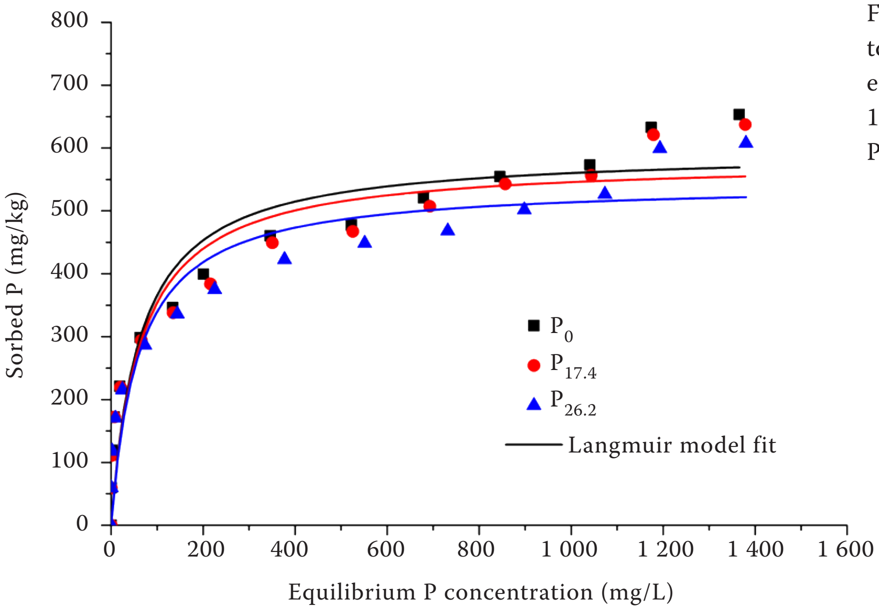

Figure 2. Fitted Langmuir equation to phosphorus (P) sorption of different P rates. P_0 – no fertiliser P; $P_{17.4}$ – 17.4 kg P/ha/crop; $P_{26.2}$ – 26.2 kg P/ha/crop

apparent high conformity of the adsorption data to the Langmuir model (Table 1). The application of the higher P fertiliser rate over the years resulted in decreasing the maximum buffering capacity of paddy soil (Table 1). However, there were no significant differences between the P_0, $P_{17.4}$, and $P_{26.2}$ treatments in determining the maximum P buffering capacity. The maximum P adsorption of the treatments applied 0, 17.4 and 26.2 kg P/ha was 545, 581 and 595 mg/kg, respectively. Our study confirmed that applying 26.2 kg P/ha resulted in the lower maximum P adsorption than in no P fertiliser or when applying 17.4 kg P/ha in rice cultivation. However, there were no significant differences between the rates of P fertiliser in determining the maximum P adsorption capacity.

The degree of P saturation. The DPS of the treatments applied 0, 17.4 and 26.2 kg P/ha were 11.0–13.2, 17.7–22.7 and 20.1–25.5%, respectively (Figure 3). The results showed that the application of 17.4 kg P/ha increased the DPS index compared with the treatment that received no P fertiliser. The risk of P leaching in $P_{17.4}$ treatment ranged at the medium level (Figure 3). Besides, the DPS index of the treatment that received 26.2 kg P/ha varied at the high-risk level for leaching P to the environment (23.6–60.0%).

DISCUSSION

Soil P availability after seven consecutive crops. Olsen-P – the fraction of P extracted with weak sodium carbonate – was strongly related to the P uptake of the plant, and the Olsen method can be used to evaluate the soil P-supply capacity in slightly acid or calcareous soils (Nawara et al. 2017). A previous study found that the Olsen-P requirement for a near maximum yield of paddy rice was met by soil Olsen-P of around 10 mg/kg (Shen et al. 2004). In this study, the rice crop would have no P deficiency because soil Olsen-P varied around 13.5 mg/kg and ranged between 10.7 to 17.0 mg P/kg after seven consecutive rice crops. In the VMD region, farmers have traditionally applied a high P fertiliser rate (26.2 kg P/ha) to compensate for P fixed in soil and P removed

Table 1. Phosphorus (P) sorption parameters of the Langmuir model at different P rates

Fertiliser P rates (kg P/ha/crop)	Affinity coefficient (L/mg)	Maximum buffering capacity (mg/kg)	Correlation coefficient (*r*)
0	0.01595	9.49	0.99
17.4	0.01562	9.08	0.99
26.2	0.01659	9.04	0.99
F-test	ns	ns	

P_0 – no fertiliser P; $P_{17.4}$ – 17.4 kg P/ha/crop; $P_{26.2}$ – 26.2 kg P/ha/crop; ns – non-significantly different ($P > 0.05$)

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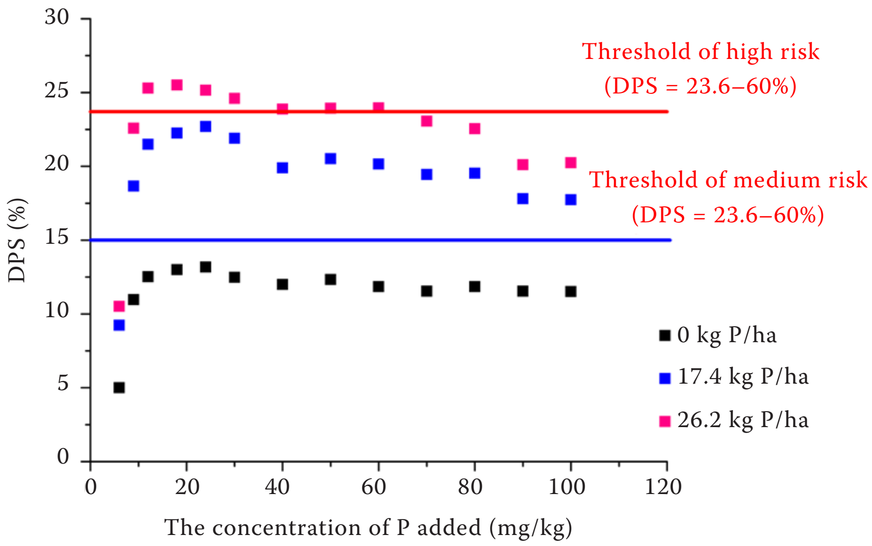

Figure 3. Soil degree of phosphorus (P) saturation (DPS) (%) and risk of P leaching to the environment under different P fertiliser rates after seven consecutive crops

with harvest (grain and straw). Over the years, this high application has increased soil P accumulation in the paddy soil (Long et al. 2016). In the triple rice areas, the soil is often in the permanent submergence condition, enhancing the available soil P (Zhang et al. 2003). Our results demonstrated that soil P availability and total P were significantly increased under applied 17.4–26.2 kg P/ha but they decreased in the treatment that received no P fertiliser compared to P in soil at the beginning of the study.

Soil P sorption capacity and the risk of P leaching. The alluvial soils (Dystric Gleysols) found at the study site have a high potential for P adsorption. After 24 h, the amount of sorbed P in all treatments P_0, $P_{17.4}$, and $P_{26.2}$ was highly increasing when the P solution was added to the soil (Figure 2). When adding the P solution containing 3–12 mg P/L to the soil, the percent of sorbed P in P_0, $P_{17.4}$ and $P_{26.2}$ treatments ranged from 90.9–98.7, 91.5–99.0 and 89.7–99.0%, respectively. This study agreed with Fan et al. (2014), who reported that applying the amount of sorbed P increased significantly with increasing amounts of added P. According to Weil and Brady (2017), the high clay content in the soil makes a possible fixation of large amounts of P to the clay surface. The soil of this study has a high clay content (61.5%), which explains why the soil in this study could have a high P adsorption capacity. However, the percent of sorbed P was decreased when increasing the P content in the soil, and it was 32.7, 31.9 and 30.4% in P_0, $P_{17.4}$ and $P_{26.2}$ treatments, respectively, when adding the solution containing 100 mg P/L to the soil. These results indicated that the excess phosphorus begins to saturate fixation sites when increasing P content, and it explains the reduction of soil P sorption capacity.

After seven consecutive crops, the soil maximum buffering capacity in the treatments applied 17.4 and 26.2 kg P/ha was from 9.04 to 9.08 mg/kg lower than in the treatment that received no P fertiliser (9.49 mg/kg). Soil P buffering capacity is an important index to evaluate the potential to supply P to plants and it reflects the amount of available P in the soil solution for crop demand (Recena et al. 2016, Rogeri et al. 2016). Long et al. (2019) studied the effects of long-term P fertiliser application on the paddy soil and they also reported that the soil P buffering capacity was decreased in the treatments applied 26.2 kg P/ha compared with the treatments that received 0–8.78 kg P/ha. This study confirmed that the application of 17.4–26.2 kg P/ha for a long time could reduce the P buffering capacity of the soil.

The DPS of the soil tended to increase in the treatments fertilised with 17.4–26.2 kg P/ha after seven consecutive crops. Degree P saturation is an index to determine the potential risk of P leaching into the environment, especially the water resources like rivers, lakes, or streams, which leads to eutrophication (Weil and Brady 2017). A previous study showed that the soil DPS value higher than 15% reflects the risk of P leaching into the environment (Ige et al. 2005). In this study, the DPS value of treatments applied 17.4–26.2 kg P/ha varied from 17.7% to 25.5%, which indicated the medium to high risk of P leaching compared with the treatment that received no P (11.0–13.2%). Applying P fertiliser could increase

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the soil saturation and decrease the soil P buffering capacity toward increasing the DPS value. According to Weil and Brady (2017), P leaching from P over-fertilisation could stimulate algae, leading to a lack of oxygen, which can suffocate aquatic fish.

The present study demonstrated that applying the P fertiliser rate greater than 17.4 kg P/ha over 7 crops in the intensive rice cropping system increases the risk of P leaching. This result is similar to a previous study that reported that applying 17.4–26.2 kg P/ha could increase the DPS (13.7–15.6%) in alluvial paddy soils (Long et al. 2019). The findings of this study suggest that if P fertiliser is applied at a higher rate than 17.4 kg P/ha for a long time, it may result in the reduced soil P buffering capacity and increased risk of leaching P to the environment in the alluvial soils (Dystric Gleysols). Similarly, our results implied that the application at a rate lower than 17.4 kg P/ha could extend to the other rice-growing (double/triple rice) systems on alluvial soils in the VMD region.

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