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Reducing Phosphorus Fertilizer Input in High Phosphorus Soils for Sustainable Agriculture in the Mekong Delta, Vietnam

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Abstract: High rates of phosphorus (P) currently being applied to soils for the production of vegetables in the Mekong Delta, Vietnam, has led to concern regarding negative effects on the economy and the environment. This research presents a comprehensive study on the determination of P supplying capacity in this region of Vietnam to examine the possibility of reducing P fertilizer input. In total, 120 soil samples were collected to evaluate total P and Bray 1 available P in the soils. Phosphorus maximum sorption, degree of P saturation, P release, and the effect of P fertilizer on corn (*Zea mays* L.) yield in greenhouses and fields were also determined. Total P concentrations in 57% of the soil samples evaluated yielded high P concentrations (>560 mg P/kg), while 74% of the samples had high Bray 1 available P concentrations (>20 mg P/kg soil). Maximum P sorption ranged from 149 to 555 mg P/kg soil, respectively, and had negative correlation with available P ($r = -0.63^*$). The percentages of P saturation ranged from 0.63% to 5.5% and correlated with available P ($r = 0.98^{**}$). Maximum P release ranged from 1.2 to 62 mg P/kg soil, respectively, and correlated with available P ($r = 0.96^{**}$). Corn grown in soils with available P concentrations >15 mg P/kg did not respond to P fertilizer in greenhouse or field experiments. We conclude that many farmers in this region can reduce P fertilizer input, thus increasing their profits and reducing negative environmental impacts associated with excess soil P for sustainable agriculture.

Keywords: total P; Bray 1 available P; P sorption; P saturation; P release; P fertilizer input; corn yield

1. Introduction

Much has been written about nitrogen (N), the primary nutrient driving world crop production [1]. However, another element, phosphorus (P), is no less important for supporting crop yields [2], with greater implications for the environment in terms of eutrophication [2,3]. Phosphorus fertilizer use in Vietnam more than doubled from 2011 to 2015 [4]. The highest rates of P fertilizer application are generally associated with high value crops, such as vegetables, and are applied by most of the farmers in the vegetable planting areas in the Mekong Delta of Vietnam (MD). This fragile area of Southeast Asia supplies a high percentage of food to Vietnam and is a source of food exports to surrounding countries. The water drained from the Mekong Delta also influences the environmental quality and the quality of life for millions of people, which has led to questions related to (1) whether additional P fertilizer inputs for the enhancement or maintenance of vegetable production are needed, and (2) if continuous high P application will increase P leaching into the environment, causing negative environmental impacts.

Ketterings et al. [5] reported that in New York, USA, 47% of the soil samples tested had values equal to or higher than the critical agronomic soil test phosphorus value for field crops (4.5 mg kg^{-1} soils for Morgan extractable P). According to Wortmann et al. [6], no yield increase of sorghum observed in soils with available Bray 1 P concentrations exceeded 15 mg P kg^{-1}. Additionally, no response was reported by Cahill et al. of corn (*Zea mays* L.) or cotton (*Gossypium* spp.) to P fertilizer in soils with available P concentrations of 60–120 mg P dm^{3-1} or more [7]. Cong et al. [8] reported on P enrichment in Podzols soil in southeastern Vietnam. In the vegetable growing areas in Tien Giang province in the MD, where P fertilizer was applied at high rates, available Bray 1 P concentrations in soils ranged from 129 to 234 mg P kg^{-1} [9]. These values are much higher than the 15 mg kg^{-1} available P level, where no further yield response to P fertilizer occurred, as reported by Wortmann et al. [10].

The level of P leaching into the environment depends on P fertilizer and other P inputs, as well as the adsorption–release characteristic of soil, which affects available P levels. In soils with high available P, the P release may also be high. Hence, the P supplying capacity is high and can provide enough P for plants. However, if the amount of P release is surplus to crop demands, it may cause P to move into the environment, resulting in negative environmental impacts [7]. Knowledge of the relationships between P fertilizer application regimes, total P, available P, and the level of soil P saturation is, therefore, needed to improve P management in soil [11]. This information is missing for the vegetable growing regions of the Mekong Delta, Vietnam, which should be studied to examine the possibility of reducing P fertilizer inputs in these regions.

Therefore, objectives of the study were to evaluate phosphorus content, phosphorus sorption and release capacity, and to determine the response of the corn plant to P fertilizer in soils of high and low soil P contents in order to have an appropriate recommendation for farmers in the area.

2. Materials and Methods

A total of one hundred and twenty (120) soil samples were collected from four (4) provinces in the major vegetable planting areas in the MD, Vietnam. These samples were from Thot Not (30 soil samples) in Can Tho province, Cho Moi (30 soil samples) in An Giang province, Binh Tan (30 soil samples) in Vinh Long province, and Chau Thanh (30 soil samples) in Tra Vinh province. These studied soils belong to different soil reference groups, namely fluvisols, gleysols, and arenosols [12]. Total P was determined by digesting the soil with concentrated sulfuric acid (H_2SO_4) and perchloric acid ($HClO_4$), and available P was measured by the Bray 1 method (0.05 M HCl + 0.03 M NH_4F) [13]. Figure 1 shows the corn field and research location of the study.

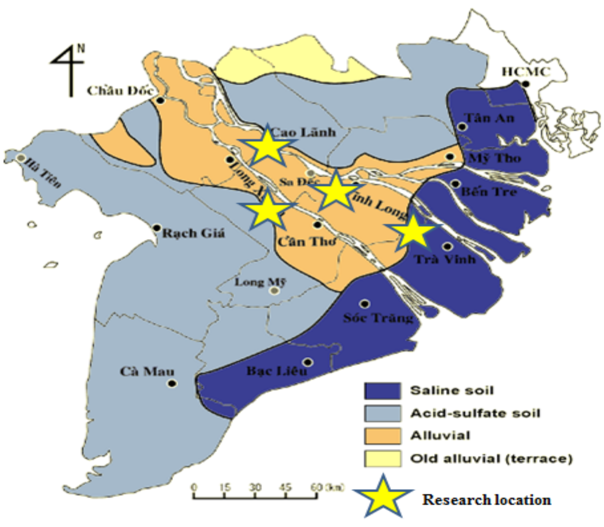


Figure 1. Research location in the Mekong Delta, Vietnam [14].

Can [15] reported the rating category for total P as being 170–260 mg P kg^{-1} soil for low, 270–350 mg P kg^{-1} soil medium; 350–560 mg P kg^{-1} soil medium-high, and > 560 mg P kg^{-1} high content. The rating category for Bray 1 available P content was according to the report of [13], classified as (3–7 mg P kg^{-1} soil) for low, (7–20 mg P kg^{-1} soil) medium, and (> 20 mg P kg^{-1} soil) high content. Phosphorus sorption was determined according to the method described by Houba et al. [16], using nine (9) soil samples selected from the four (4) provinces, which had available P contents ranging from low to high values (6.8–120 mg P kg^{-1}). The amount of P added to soils ranged from 120 to 2400 mg P kg^{-1}. The ratio of soil-to-solution in these tests was 1:20. The amount of phosphorus sorbed by the soil was determined by the Olsen method, using 0.5 N $NaHCO_3$ (pH 8.5) as the extracting solution. Maximum P sorption in soil was determined based on the Langmuir equation for the relationship between phosphorus sorption and phosphorus concentration at equilibrium in soil solution, given as

$$\frac{C}{q} = \frac{1}{b}C + \frac{1}{k\,x\,b} \tag{1}$$

where C represents the concentration of the solution after equilibrium (mg P L^{-1}), q is the amount of P sorbed (mg P kg^{-1} soil), b is the maximum phosphorus sorbed, and k is a constant. The slope of the line when plotting C/q (*y*-axis) versus C (*x*-axis) is equal to 1/b and the y-intercept value is equal to 1/(k × b).

The degree of P saturation was examined as an index for evaluating the possibility of P release causing negative impacts to the environment. The degree of P saturation was calculated according to the method described by Schoumans et al. [17]:

$$\text{DPS} = (\text{Pox}/\text{PSC}) \times 100 \tag{2}$$

where DPS is the degree of P saturation (%), Pox is the P extracted by ammonium oxalate (mg P kg^{-1}), and PSC (maximum phosphorus sorption capacity of the soil, mg P kg^{-1}) is the maximum P sorption determined based on Langmuir equation.

Phosphorus release was determined following the method described by Sui et al. [18] for the nine (9) soil samples used for the P sorption study. The amount of P release extracted at ratios of 1:10; 1:60; 1:120; and 1:240 soil/water was measured at different shaking extraction times (that is, after 1, 12, 24, or 48 h, respectively). Maximum P release (mg P kg^{-1} soil) was calculated as the difference between the highest P release value and the P release value at 1 h for the 1:240 ratio.

A greenhouse study was carried out at Can Tho University from January to September 2011. Two consecutive crops of baby corn (*Zea mays* L.) with the trade name "Amaizing" were grown in forty (40) soil samples selected from the four (4) provinces and conducted in a randomized complete block design (RCBD). The two factors considered were (1) 10 different soils in each province (40 soil samples in 4 provinces), which had available P Bray 1 content ranging from low to high values; and (2) 2 rates of P fertilizer application (0 and 90 kg P_2O_5 ha^{-1}). Treatments were replicated thrice to give a total experimental unit of 240 pots, at one plant per pot with 7 kilogram soil, which were frequently irrigated with water. The 40 different soil samples had Bray 1 available P values ranging from 5.8 to 77 mg kg^{-1} soil for Can Tho province, 6.8 to 87 mg kg^{-1} soil for An Giang province, 13.1 to 120 mg kg^{-1} soil for Vinh Long province, and 13 to 224 mg kg^{-1} soil for Tra Vinh province. N and K fertilizers were applied at a rate equivalent to 160 kg N ha^{-1} and 90 kg K_2O ha^{-1} according to the recommendation of the Ministry of Agriculture and Rural Development, Vietnam [19]. The soils used in experiments were the fluvisol and gleysol groups, which had pH values ranging from 4.9 to 6.2, belonging to the silty clay textural class, the parent material of which is alluvial sediment; and the arenosols group, which had pH values ranging from 6.2 to 7.0 and belongs to the sandy loam textural class, the parent material of which is a mixture of alluvial and marine sediments. Baby corn was planted as the test crop for the two cropping seasons and yield was determined by measuring the total dry weight of the corn ears.

Corn response was calculated by the yield difference between the 90 kg P_2O_5/ha treatments and the 0 kg P_2O_5/ha treatments for each crop.

Field experiments were also carried out in an village, Cho Moi district, An Giang province, from January to September 2011, with two consecutive crops grown at two sites (sites 1 and 2), having high and medium available P contents of 21 and 15 mg P kg^{-1}, respectively. At the onset of planting the second crop, one more site (Site 3) with low available P content of 6.8 mg P kg^{-1} was selected for examining corn response to P fertilizer in low available P soil. Hybrid sweet corn of F1 M × 10 variety was used in these experiments. The experiments were carried out using a randomized complete block design (RCBD), with three P fertilizer rates (0, 45, and 90 kg P_2O_5 ha^{-1}) and four replications produced from 12 experimental plots in each of the sites. The sizes of the experimental plots were 33–47 m^2. Nitrogen and potassium fertilizer were fixed at doses of 160 kg N ha^{-1} and 90 kg K_2O ha^{-1}, respectively, according to the recommendation of the Ministry of Agriculture and Rural Development, Vietnam [19]. Corn yield was determined by measuring the total fresh fruit weight of a 6 m^2/plot. Fresh fruits included grain, pericarp, and endosperm.

3. Statistical Analysis

Data were statistically analyzed for ANOVA (Minitab 13) using the general linear model function and treatment means were differentiated using Tukey's test. Simple linear Pearson's regression and correlation were also calculated. The level of significance used for the tests was at least 5%. The Minitab software version 16 was used for all statistical analysis.

4. Result and Discussion

4.1. Total and Available Phosphorus Concentrations

Table 1 shows the total phosphorus contents in the evaluated soils. Soils in the high category (total P > 560 mg P kg^{-1}) accounted for 57% of the total studied samples. Debusk et al. [20] reported that there was total P in 48% of the area in 1990 and an increase of 73% in 2001 due to P run-off from the agricultural soils in the Everglades in the United States, and total P > 500 mg P kg^{-1} was considered as rich. Table 1 shows that Bray 1 available P concentrations ranged from 3.6 to 224 mg kg^{-1}, with 74% of the soil samples classified as high (that is, concentrations were 20.4 mg P kg^{-1} or higher). The reason may be the high rates of P applied to soils for the production of vegetables in the Mekong Delta of Vietnam. Along with this study by Hoa et al. [9], the survey results of 120 farmers in 4 provinces of Can Tho, An Giang, Vinh Long, and Tra Vinh showed that farmers applied 109 to 194 kg P_2O_5 ha^{-1} on leaf vegetables, baby corn, hybrid sticky corn, and tomato.

Table 1. Total P and Bray 1 available P concentrations and ratings of 120 soils from 4 provinces in major vegetable planting areas in Vietnam.

Range of Soil P	Rating Category	Samples in Rating Category (%)
Total P (mg kg^{-1} soil)		
568–1048	High	57
393–524	Medium-High	36
306–349	Medium	6.2
131	Low	1.0
Bray 1 available P (mg kg^{-1} soil)		
20.4–224	High	75
7.3–19.5	Medium	20
3.6–6.8	Low	5.0

4.2. Maximum Phosphorus Sorption

Table 2 shows that the correlation between P sorption content and equilibrium P in soil solution, which followed a simple Langmuir equation, had a high determination coefficient (R^2 of 0.72 to 0.99). Therefore, this equation could be used to calculate the qm value. Maximum P adsorption concentrations (qm) were high (384–588 mgP kg^{-1}) in soils with low and medium available P content and lower (149–454 mg kg^{-1}) in soils with high available P. It seems that the soil samples with initially high available P contents had mostly saturated P fixation sites, with less P sorbed. These results are in line with the report of Can [21], indicating that P fixation occurred rapidly at low concentrations and depended on soil characteristics. The predominant reactions are precipitation at high P concentration in solution and adsorption at low P concentration [22,23].

Wang et al. [24] reported on a higher sorption in calcareous soils with qm = 691–1664 mg P kg^{-1}, while Villapando et al. [25] found similar results to our study for spodosols (qm = 224–560 mg P kg^{-1}). Our results also showed a negative correlation between maximum P sorption and available P, with correlation coefficient $r = –0.63^*$ ($p < 0.05$); therefore, the more available P in soils, the less P from fertilization was sorbed, resulting in high P content leaching to the environment. Hence, it is important to note that when more P fertilizer is added to soils already containing high amounts of available P, P sorption in soil decreases and the risk of P run-off to environment becomes high in these soils. Therefore, P fertilizer rates in these major vegetable growing areas should be adjusted to prevent the risk of P run-off to the environment, especially in high available P soils.

Table 2. Langmuir equation and its determination coefficient (R^2), maximum P sorption, degree of P saturation (DPS), maximum P release, and correlation coefficient (r) between these parameters in the studied soils from 4 provinces in Vietnam. Note: ns, not significant.

Available P Category	Available P Content (mg kg^{-1})	Langmuir Equation $C/q = C/q_m + (1/k)\ q_m$	R^2	Maximum P Sorption (mg kg^{-1})	DPS (%)	Maximum P Release (mg kg^{-1})
Low	6.8	C/q = 0.0018C + 0.0038	0.98	555	0.63	1.2
Medium	13	C/q = 0.0026C + 0.0071	0.96	384	1.1	4.3
	13	C/q = 0.0017C + 0.0083	0.73	588	0.97	6
High	21	C/q = 0.0022C + 0.0045	0.72	454	2	6.2
	38	C/q = 0.0050C + 0.0263	0.98	200	2.4	6.7
	47	C/q = 0.0029C + 0.0145	0.99	344	3.1	30
	87	C/q = 0.0023C + 0.0133	0.97	424	5.3	33
	92	C/q = 0.0067C + 0.0112	0.97	149	4.7	37
	120	C/q = 0.0037C + 0.0039	0.99	270	5.5	62
The *r* values of maximum P sorption, DPS, and maximum P release with available P, respectively				−0.63*	0.98**	0.96**
The *r* values of DPS and maximum P release with maximum P sorption.					−0.61*	-0.52^{ns}
The *r* value of maximum P release with DPS.						0.91*

Where q is the amount of P adsorbed (mg kg^{-1} soil), q_m is the maximum amount of P adsorbed (mg kg^{-1} soil), C is the concentration of the solution after equilibrium (mg kg^{-1} soil). k is a constant, ns, no difference; * significant difference at 5%; and ** significant difference at 1%.

4.3. Degree of P Saturation

In soils with low and medium available P, the degree of P saturation (DPS) ranged from 0.63% to 1.1%. Table 2 shows that the DPS values were higher in soils with high available P, ranging from 2% to 5.5%. The DPS in these soils from Vietnam were lower than the critical level of DPS (25%) for evaluating P contamination in ground water established by van der Zee et al. [26]. They reported that a DPS > 25% indicates a surplus of P in soils, for which P fertilization is not advised. However, in another study, Schoumans et al. [17] evaluated P leaching risk by comparing the actual DPS of the soils and the critical DPS of the soil type. They observed that the critical phosphorus saturation degree varies from 5% to 78%, and about 43% of the agricultural land in the Netherlands exceeded the critical DPS value for the soil type. They concluded that a large area of agricultural land in the Netherlands contributes to the P pollution of surface water or is expected to contribute to the P pollution of surface water in the near future. According to Schoumans et al. [27], the degree of phosphate saturation is defined as DPS = 100 × P_{act}/PSC, where DPS is the degree of P saturation (%), P_{act} is the actual amount of sorbed P in soil (extractable by oxalate; kg ha^{-1}, and PSC is the maximum phosphate sorption capacity of the soil (kg ha^{-1}). They also reported that a critical DPS of 25% had been established by van der Zee et al. [26].

Zhou et al. [28] reported that when P sorption increases due to high P application, P release also increases, and hence the risk of P contamination in water increases. Zhou et al. [28] observed DPS values of 0.02–0.27% in submerged soils, 4–20% in vegetable soils, and 4–10% in fruit garden soils. The DPS values of our studied soils were in the low value range reported by Zhou et al. [28], and were in the low value range for the DPS critical values reported by Schoumans et al. [27]. Since P sorption–precipitation in different soil groups has a particular behavior and as DPS may be calculated by different methods, the above comparisons only provide information regarding the value ranges of DPS in different soil groups.

In our study, the available P concentrations in these same soils were observed to increase by 7.2 and 56 mg P kg^{-1} after five applications of 90 kg P_2O_5 ha^{-1} in the greenhouse study. Therefore, the risk of P run-off to the environment is expected to increase if P fertilizer is continuously applied at this high rate. Sharpley et al. [1] also reported that excess P can cause P run-off or leaching to water resources, raising concerns about the agricultural contribution to eutrophication of inland waters and marine environments.

4.4. Phosphorus Release and Correlation

Phosphorus released from soil reached a maximum content at an extraction ratio of 1:240 for soil/water (Figure 2). There were some soil types with high available P content that also released high amounts of P at the extraction ratios of 1:60 and 1:120, however the differences were not statistically significant ($p < 0.05$) compared to the 1:240 extraction ratio; therefore, P release values at 1 h for the 1:240 ratio were selected for the calculation of maximum P release.

Maximum P released ranged from 1.2 to 6.0 mg P kg^{-1} in soils with low and medium available P contents, and from 6.2–62 mg P kg^{-1} in soils with high available P content (Table 2). The linear correlation analysis between P release and available P concentrations showed a high correlation coefficient of $r = 0.96^{**}$. A positive correlation also existed between maximum P release and degree of P saturation ($r = 0.91^{**}$), meaning when soil is saturated with P, most of the site for P sorption is occupied and more P is released. Hence, there was a tendency for an increase in maximum P release with an increase in P availability, along with increased risk of P run-off to the environment in high available P soils. Although soil P testing alone will not answer all questions about P loss, as the potential P loss depends on run-off potential and management practices at the site, these relationships, however, can provide scientific bases for establishing preliminary soil tests for P criteria to identify the P leaching potential. Testing can be combined with site hydrology and P management practices for a more comprehensive P loss risk assessment [24].

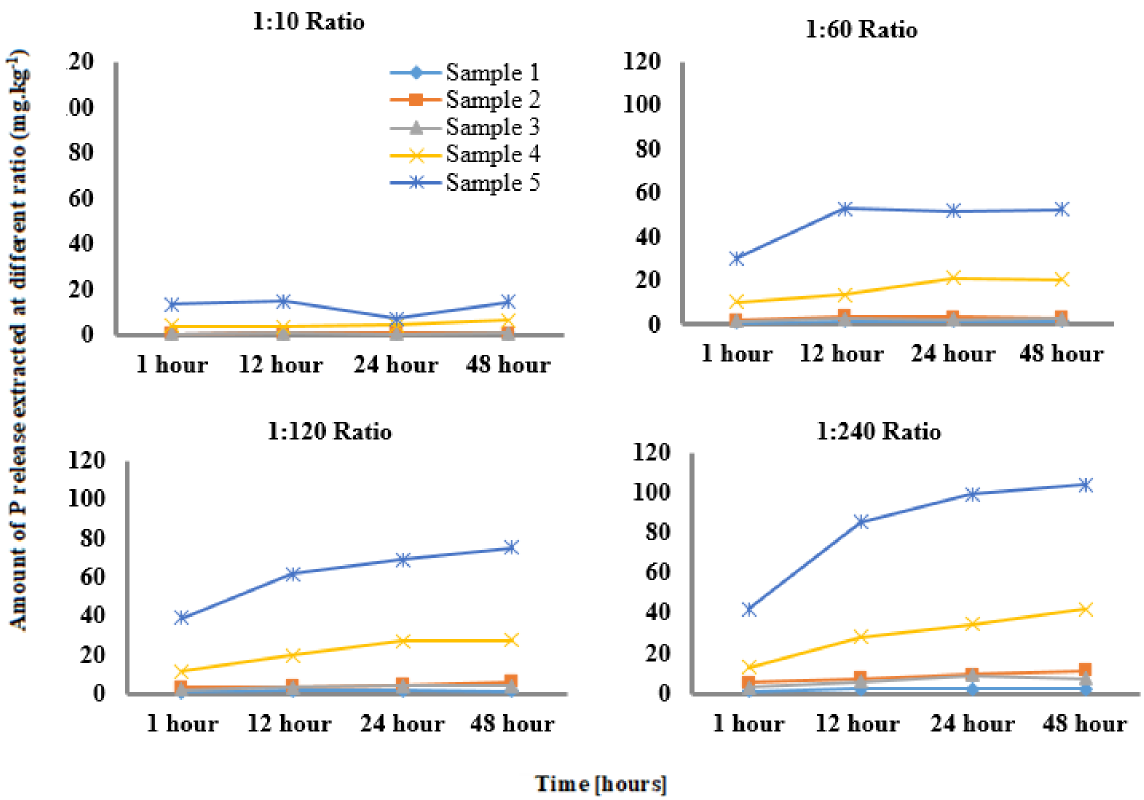


Figure 2. Phosphorus release over time at different extraction rates in surveyed soils. Note: Sample 1, sample 2, sample 3, sample 4, sample 5, and sample 6 have available P concentrations (mg k^{-1} soil Bray 1 P) of 13.1, 15.0, 54.1, 92.4, 105, and 120 mg k^{-1}, respectively.

4.5. Corn Responses to P Fertilizer

4.5.1. Greenhouse Experiment

Figure 3 shows the corn response to P fertilizer from two (2) consecutive crops in the greenhouse experiment on soils from Thot Not (Can Tho province), Cho Moi (An Giang province), Binh Tan (Vinh Long province), and Chau Thanh (Tra Vinh province). Results showed that there were no statistically significant differences in corn yield between 90 kg P_2O_5 ha^{-1} treatments and the zero P treatment (that is, the control) for all four studied sites. Although there were many more positive yield responses than no or negative yield responses, a general trend for lower yield response in high available P soils was observed. Because application of P fertilizer in soils of medium and high P available content did not result in a statistically significant increase in corn yield, reduction of P fertilizer use in these soils should be considered, especially where farmers have continually applied high rates of P fertilizer.

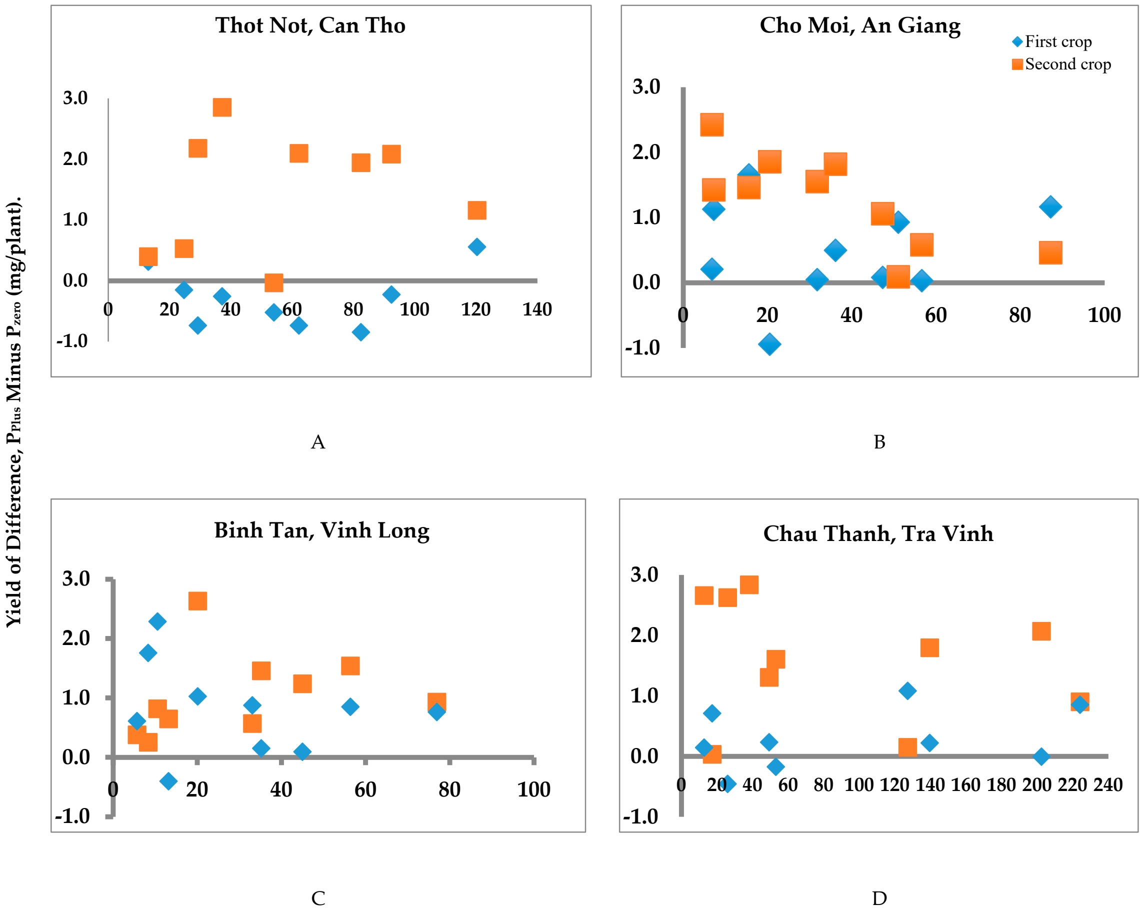
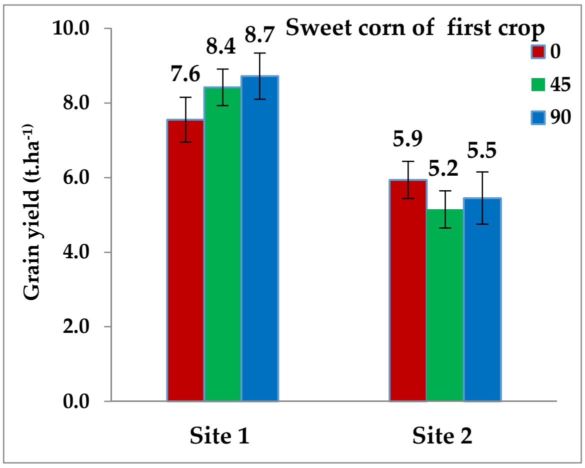


Figure 3. Baby corn yield differences (greenhouse experiment) grown in soils with different levels of initial Bray 1 available P, either unfertilized or fertilized at 90 kg P_2O_5 ha^{-1}. Sample of subfigure (**A**) have Initial available P concentrations (mg k^{-1} soil Bray 1 P) of 13, 15, 29, 37, 54, 62, 82, 105 and 120 mg kg^{-1}, respectively. Sample of subfigure (**B**) have Initial available P concentrations (mg k^{-1} soil Bray 1 P) of 6, 8, 7.3, 16, 21, 32, 36, 47, 51, 57 and 87 mg kg^{-1}, respectively. Sample of subfigure (**C**) have Initial available P concentrations (mg k–1 soil Bray 1 P) of 5.7, 8.4, 11, 15, 20, 33, 35, 45, 56 and 77 mg kg^{-1}, respectively. Sample of subfigure (**D**) have Initial available P concentrations (mg k^{-1} soil Bray 1 P) of 13, 17, 26, 38, 49, 53, 140, 127, 202 and 224 mg kg^{-1}, respectively.

4.5.2. Field Experiment

Results in Figure 4 show that there was no statistically significant difference in corn yield among zero P fertilizer treatments (7.6 t ha^{-1}), 45 kg P_2O_5 ha^{-1} treatments (8.4 t ha^{-1}) and 90 kg P_2O_5 ha^{-1} treatments (8.7 t ha^{-1}) at site 1 (available P in soil was 20.5 mg P kg^{-1}), and among zero P fertilizer treatment (5.9 t ha^{-1}), 45 kg P_2O_5 ha^{-1} treatments (5.2 t ha^{-1}), and 90 kg P_2O_5 ha^{-1} treatments (5.5 t ha^{-1}) at site 2 (available P in soil was 15.1 mg P kg^{-1}) for the first growing season. In the second crop, similar results were obtained when no yield response was found at sites 1 and 2. Wortmann et al. [10] reported no increase in yield of sorghum in high phosphorus soil (>15 mg P kg^{-1} Bray 1), and a crop growth response to P fertilizer but no yield response observed in soils with medium to low available P contents (<15 mg P kg^{-1}). For corn plant, Wortmann et al. [10] observed that there is a high probability (>80%) of grain yield increase with starter P fertilizer for no-till corn in soils with Bray 1 available P ≤ 15 mg kg^{-1}, and that yield increase was lower in higher P soils.



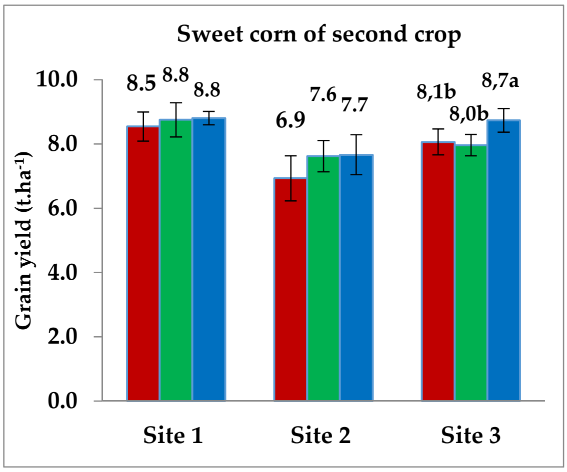


Figure 4. Corn yield at treatments of 0.45 and 90 kg P_2O_5 in three (3) studied sites at Cho Moi (An Giang province). Sites 1, 2, and 3 had initial available P concentrations (mg/kg soil) of 21, 15, and 6.8 mg P kg^{-1} respectively.

In our study, when soils with poor available P contents (6.8 mg P kg^{-1}) were treated with 90 kg P_2O_5 ha^{-1}, corn yield increased (8.7 t ha^{-1}) in comparison to the zero P fertilizer treatment of 8.01 t ha^{-1}. Low yield was obtained from soil treated with 45 kg P_2O_5 ha^{-1} (8.0 t ha^{-1}) and this yield was not statistically different from the zero P fertilizer treatments. Thus, it seems if soils from this region of Vietnam are deficient in P, at least a 90 kg P_2O_5 ha^{-1} treatment is needed to increase crop yield, however with medium to high Bray 1 available P contents (from 15 to > 20 mg P kg^{-1}), P fertilization is not advised. This result is in line with other reports [29–32].

5. Conclusions

Regarding fluvisols, gleysols, and arenosols in major vegetable growing areas of the Mekong Delta, Vietnam, where most of the farmers applied P fertilizer at high rates, 57% of the studied samples > 560 mg P kg^{-1} were considered rich in P. Available P in 74% of the soil samples was > 20 mg P kg^{-1}, which were classified as rich in available P.

Maximum P sorption ranged from 149 to 555 mg P kg^{-1} soil and was negatively correlated to available P (–0.63*). The degree of P saturation remained low, ranging from 0.63% to 5.5%, which was correlated with available P (r =0.98**), while maximum P release ranged from 1.2 to 62 mg P kg^{-1} soil and was also correlated with available P (r = 0.96**). In high available P soil, the degree of P saturation increased with decreasing P sorption and an increase in P release; hence, the risk of P leaching to the environment will increase if P fertilizer is applied continuously at a high rate, which should be considered for sustainable development.

In addition, corn yield did not significantly increase ($p < 0.05$) in soils where Bray 1 available P concentrations were > 15 mg P kg^{-1}. Therefore, it is advised not to apply P at reduced rates in these soils. In soils with low Bray 1 P (<7 mg P kg^{-1}), P sorption was high, with low P release and yield responses to P fertilizer application. Therefore, applying P fertilizer to these soils is recommended. The results of the study were provided to farmers to maximize P fertilizer use efficiency, which will reduce fertilizer costs, increase income, and reduce the adverse effects on the environment.

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Conflicts of Interest: The authors declare that they have no conflict of interest.

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