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Full Length Article

Influence of Silicon Application on Phosphorus Uptake in Rice and Phosphorus Availability in Acid and Neutral Soils, Central Thailand

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Abstract

Phosphorus (P) deficiency is a major problem in agricultural soils, and this problem can be addressed by various methods, one of which is the addition of silicon (Si) materials. The aim of this study was to examine the impact of Si on rice yield, P uptake, P use efficiency in rice, and P availability in two types of soil: very strongly acidic (Se) and neutral (Tr) soils, following rice harvesting. The experiment was conducted in a pot experiment using a completely randomized design (CRD) with five treatments and three replicates. The treatments were: control (no addition of Si) and addition of Si at 0.42, 0.84, 1.26 and 1.68 g SiO_2/pot. The results showed that the application of Si at low doses (0.42 g SiO_2/pot) increased the highest grain yield of rice (26.6 ± 1.07 g/plant) only in Se soil, while in Tr soils, increasing the amount of Si did not contribute to the increase in grain yield. The P concentration in grain and straw of rice grown on both Se and Tr soils tended to increase with increasing Si supply (1.26 - 9.46 and 0.16 - 34.7% for grain and 15.7 - 29.0 and -4.93-22.7% for straw in Se and Tr soils, respectively). In Se soil, P uptake was highest at low Si doses (0.42 g SiO_2/pot), while in Tr soil, application of Si at high doses (1.68 g SiO_2/pot) resulted in the highest P uptake. Only in Se soil did the phosphorus harvest index (PHI) decrease significantly with increasing Si application. For P availability in both Se and Tr soils after rice harvest, an increase in Si dose resulted in a significant increase in available P and phosphorus activation coefficient (PAC). The results indicate that increasing the amount of Si significantly increases P availability in the soil, but in acidic soils, applying Si at half the recommended dose is better for rice production and P uptake in rice.

Keywords: Silicon; Phosphorus uptake; Phosphorus in soils; Rice yield

Introduction

In Thailand, phosphorus (P) deficiency can generally occur in acidic soils, but also in neutral soils, as the P content in the parent material is sometimes low, resulting in low P availability in the soils. In Phra Nakhon Si Ayutthaya province, most soils (75-80% of the area) are acidic and are classified as post-active acid sulfate soils (pH > 4.0) (Sukyankij *et al*. 2023). The main problem of these soils is that the mineralization of plant nutrients is inhibited, that certain elements such as phosphorus are strongly bound and that some toxic metals (iron, aluminum, manganese and heavy metals) can sometimes be released (Sukyankij *et al.* 2024). Some areas of the province are not classified as post-active acid sulfate soils. The districts of Tha Ruea and Phachi, for example, are influenced by the limestone mountains of the neighboring province. The soil in this area is therefore not acidic, but has a high pH value approaching neutral and has low P availability. Improving acidic soils with a high P fixation or neutral soils with a low P availability is therefore important for increasing crop yields in this area.

P plays a multidimensional role in the development of plant production and is a component of nucleotides, nucleic acid and adenosine triphosphate in plant cells (Ghosh *et al*. 2024). P is a mobile element and has an important function in energy storage and maintaining membrane integrity. Plants can take up P in the form of $H_2PO_4^-$ and HPO_4^{2-}, which depends on the pH of the soil, *i.e.*, if the soil pH is above 7.2, they can take up P in the form of HPO_4^{2-}, but if the soil pH is between 4.0 to 7.2, they

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take up P in the form of $H_2PO_4^-$ (Sukyankij *et al*. 2023). The dynamics of P in the soil are involved in both inorganic and organic P forms (Shen *et al*. 2011). For inorganic P dynamics, Schaller *et al*. (2019) found that at pH above 6.5, inorganic P in soil tends to immobilize and become calcium phosphate minerals, while at lower soil pH, inorganic P can be adsorbed with soluble iron, manganese, aluminum or hydrous oxides, and at neutral soil pH, the inorganic P can react with silicate minerals and turn into clay minerals. In organic P dynamics in the soil, P is present in organic forms such as inositol phosphates, orthophosphate di-esters or organic polyphosphate. These forms can be converted into an available form by mineralization processes of soil microorganisms, which are controlled by various environmental conditions such as soil moisture, pH and temperature (Shen *et al*. 2011). However, P deficiency in agricultural soils can be found all over the world, especially in acidic and calcareous soils (Dobermann and Fairhurst 2000). There are various methods for improving P deficiency in the soil by increasing P availability, *e.g*., by applying organic or inorganic fertilizers. In addition, it has been reported that the application of silicon, *e.g*., in the form of silicate fertilizer (calcium, sodium or potassium silicate), basic slag or plant residues, also increases the amount of available P in the soil (Barman *et al*. 2023; Ghosh *et al*. 2024). Some others have mentioned that the annual application of sodium silicate has increased and maintained crop yields and available P content in the soil (Barman *et al*. 2023).

Rice is the most important economic crop in this area, with a cultivated area of around 14,000 hectares (Ayutthaya Provincial Agricultural Extension Office 2024). However, both P and Si are recorded as important plant nutrients in rice. The main function of Si in rice plays a crucial role in strengthening the vigor of leaves, stems, and roots and increases tolerance to biotic and abiotic stresses (Ma 2004; Zamani *et al.* 2017; Yan *et al.* 2018), while P is to promote flowering, root development, stimulated tillering and the ripening of seeds (Dobermann and Fairhurst 2000). And most importantly, the use of Si fertilizers can increase the bioavailability of P in the soil (Dobermann and Fairhurst 2000). The interaction between P and Si in the soil is positive because the phosphoric acid (H_3PO_4) is partially physiologically replaced by silicic acid (H_4SiO_4) at the sorption site in the soil (Ghosh *et al*. 2024). Besides, Schaller *et al*. (2022) pointed out that the availability of P in soils is promoted by increased Si availability, as silicic acid from amorphous Si in the soil can replace P ions ($H_2PO_4^-$ or HPO_4^{2-}) on the surface of amorphous and crystalline iron phases, increasing the amount of available P in the soil solution. Thus, the plant root can better absorb the released P from the solution, and it also has an effect on the increased P uptake in the plants. The hypothesis of this study was that the different Si applications can lead to an increase in rice yield, P content, P use efficiency of rice and P availability in the soil. The aim of this study was therefore to evaluate the changes in rice yield, P content and P utilization efficiency in the plant and to check the P availability in the soil after Si application.

Materials and Methods

Soil collection and preliminary analysis

The experiment was carried out with soils from the province of Phra Nakhon Si Ayutthaya, which consist of two soil series. The Sena soil series (Se) (Sulfic Endoaquepts) was classified as an acidic soil, while the Tha-Rua soil series (Tr) (Vertic (Aeric) Endoaquepts) was classified as a representative of the neutral soil in the province. The soils Se and Tr were collected in Chai Na, Sena district (14°27’74.09” N 100°35’76.80” E), and Wang Dang, Tha Ruea district (14°52’90.27” N 100°67’28.60” E), respectively (Division of Soil Survey and Soil Resource Research 2019). At each site, approximately 200 kg of soil was kept with collected at a depth of 0-20 cm, and the soil was then dried in a greenhouse. After drying the soil, we divided the sample into 0.5 kg and conducted three replicates of the analysis basic soil properties. The basic soil properties, *i.e*., the pH value of the soil, were determined with a pH meter at a ratio of soil-to-distilled water of 1:1 (Thomas 1996), saturated soil electrical conductivity (EC_e) was measured using a conductivity meter (Rhoades 1996), organic matter (OM) was determined using the wet oxidation method (Walkley and Black 1934), available silicon (Avail. Si) was extracted with 0.5 *M* acetic acid at a ratio of 1:2.5 soil-to-solution ratio (Snyder 2001), available phosphorus (available P) was extracted using the Bray II method at a soil-to-solution ratio of 1:10 (Bray and Krutz 1945), total phosphorus in soil (Total P) was digested using the perchloric acid digestion method and the P content was determined using a spectrophotometer (Kuo 1996) and the phosphorus activation coefficient (PAC) was calculated from the ratio of available P and total P in the soil (Yang *et al.* 2019; Sukyankij *et al.* 2024) (Table 1).

Experimental details

The test of the effectiveness of silicon on P uptake was carried out under greenhouse conditions. The source of Si used in the experiment was silicic acid (H_4SiO_4) purchased from Central Drug House (Pvt.) Ltd. New Delhi, India. A completely randomized design (CRD) with five treatments and three replicates was conducted: T1 as control (no addition of Si) and T2 to T5 treated with 0.5, 1.0, 1.5 and 2.0 times the Si recommendations. The recommended rate of Si was referred from Cuong *et al.* (2017); they reported that the optimal dose of Si fertilizer for tropical rice is 329 kg SiO_2/ha. This rate corresponds to 0.84 g SiO_2/pot. Accordingly, the treatment in the experiment was the addition of Si at 0.42, 0.84, 1.26 and 1.68 g SiO_2/pot. For the greenhouse growing practices, we used the dried soil sample, weighing 5 kg of dried soil into a 6.75 L plastic pot.

Table 1: Soil properties (0-20 cm depth) use in the experiment (mean ± standard deviation; n = 3)

Soil series	pH $_{(1:1)}$	EC_e (dS/m)	OM (%)	Available P (mg/kg)	Total P (mg/kg)	PAC (%)	Available Si (mg/kg)
Se	4.81 ± 0.15	1.24 ±0.16	5.02 ± 0.24	13.7 ± 1.42	1499 ± 87	0.91 ± 0.04	68.5 ± 3.15
Tr	6.60 ± 0.35	2.16 ± 0.21	1.36 ± 0.12	4.58 ± 0.85	609 ± 52	0.75 ± 0.06	176 ± 5.35

Distilled water (without Si contamination) was added to the soil and mixed until it became muddy. The Si was added to the soil in varying amounts (0, 0.42, 0.84, 1.26 and 1.68 g SiO_2/pot). After 7 days, the seedlings of the rice variety cv. Pathum Thani 1 (20 days old) were transplanted in the pots, two seedlings per pot. The amount of fertilizer used for rice cultivation was taken from the site-specific nutrient management program (SimRice, http://www.ssnm.info/download) and was 0.13-0.06-0.11 and 0.03-0.06-0 g N-P_2O_5-K_2O/pot for Tr and Se soils, respectively. Throughout the entire experimental period, we maintained flooding with 5 cm of water and managed weed-free experimental pots using the hand removal method. At harvest, the rice plant was harvested 107 days after planting and cut 5 cm above the soil surface. It was then divided into straw and grains and dried in a hot air oven at 80°C for 48 h. After the samples were completely dried, the weight of the dry straw and grains were recorded and calculated as the weight of grain yield at 14% moisture.

Analysis of P in plant

The samples were crushed to less than 0.5 mm using a plant crusher and stored in a desiccator glass to determine the P content of the plant. For the analysis of P in plant tissue, 0.2 g of plant samples were placed in a 250-mL Erlenmeyer flask and 10 mL of a mixed acid (HNO_3-$HClO_4$ in a ratio of 10:3 (-v/v)) was added. The solution was heated on a hotplate at 130°C until the brown vapors disappeared, after which the temperature was raised to 203°C for 20 min (Pequerul *et al.* 1993; Kuo 1996). After digestion was completed, the solution was filtered through filter paper No. 5 and the volume of the solution was adjusted to 50 mL with deionized water. The total P concentration in the plant was determined using the vanadomolybdophosphoric acid method, which was carried out with a spectrophotometer at a wavelength of 420 nm (Kuo 1996). P uptake was determined by multiplying the P concentration in the plant tissue by the dry matter of the rice plant (Sukyankij *et al.* 2023). In addition, the phosphorus harvest index (PHI), physiological efficiency of phosphorus (PEP) and agrophysiological efficiency of phosphorus (APEP) were calculated according to the following formula by Fageria (2009) and Jinger *et al.* (2022):

$$\text{PHI (\%)} = \frac{\text{Uptake of P by grain (mg/plant)}}{\text{Total uptake of P in biomass (mg/plant)}} \times 100 \quad \text{----- (1)}$$

$$\text{PEP (g/plant)} = \frac{\text{Biomass in treated pot (g/plant)} - \text{Biomass in control pot (g/plant)}}{\text{P uptake in treated pot (g/plant)} - \text{P uptake in control pot (g/plant)}} \quad \text{---------- (2)}$$

$$\text{APEP (g/plant)} = \frac{\text{Grain yield in treated pot (g/plant)} - \text{Grain yield in control pot (g/plant)}}{\text{P uptake in treated pot (g/plant)} - \text{P uptake in control pot (g/plant)}} \quad \text{---(3)}$$

Analysis of P in soil

After harvesting the rice plants, about 100 g of soil was collected from each pot, air-dried, crushed and sieved through a 2 mm sieve. The Bray II method (0.03 *M* NH_4F + 0.1 *M* HCl) was used to determine the available P in the soil. 3 g of the dried soil was placed in a 250-mL conical flask and extracted with 30 mL of Bray II extractant for 40 s (Bray and Kunzt 1945), after which the solution was filtered with No. 5 filter paper. The available P content of the purified solution was determined using the ascorbic acid-molybdenum blue method, in which the absorbance was measured at a wavelength of 882 nm using a spectrophotometer (Kuo 1996). In the total P analysis, the method of perchloric acid digestion was used to determine total P (Kuo 1996). A 1.0 g of the dried soil was placed in a 250 mL conical flask, 10 mL of 70% perchloric acid and 6 mL of 15.8 *M* nitric acid were added to the flask. The solution was then digested on the hotplate at 130°C until the dark color disappeared and then further heated at 203°C for 20 min. After completion of the digestion, the flask was removed and cooled. The volume of the solution was adjusted to 50 mL with deionized water and filtered through filter paper No. 5. The vanadomolybdophosphoric acid method was used to determine total P in soil by measuring the absorbance with a spectrophotometer at a wavelength of 420 nm. The phosphorus activation coefficient (PAC) indicates the potential total P in the soil that could be converted into available P. This value is calculated from the ratio between available P and total P in the soil (Yang *et al.* 2019; Sukyankij *et al*. 2024).

Statistical analysis

The P content, the P use efficiency in the plant and the P content in the soil were statistically evaluated using the statistical program SPSS (version 22). An analysis of variance (ANOVA) estimated the treatment effects and Duncan's new multiple range test (DMRT) was used to compare the significant differences between the treatment at the $P < 0.05$ significance level. A Pearson correlation test was used to determine the relationship between the rice yield, P content in plants, P content in soils and Si application at the significance level $P < 0.05$.

Results

Properties of soil used in the experiment

The properties of the soils used for the experiment are listed in Table 1. In Se soil, the soil was classified as a very fine, mixed, active, acid, isohyperthermic Sulfic Endoaquepts. The soil pH was very strongly acidic (pH 4.81 ± 0.15), the soil was non-saline (EC_e 1.24 ± 0.16 dS/m), organic matter was very high (5.02 ± 0.24%), while available P and available Si were medium (13.7 ± 1.42 and 68.5 ± 3.15 mg/kg, respectively). In the Tr soil, the soil was classified as very-fine, mixed, active, nonacid, isohyperthermic Vertic (Aeric) Endoaquepts. The pH of the soil was neutral (pH 6.60 ± 0.35) and non-saline (EC_e 2.16 ± 0.21 dS/m). The content of organic matter and available P was low (1.36 ± 0.12% and 4.58 ± 0.85 mg/kg, respectively), but the content of available Si was high (176 ± 5.35 mg/kg). The Se soil had a higher PAC value (0.91 ± 0.04%) than the Tr soil (0.75 ± 0.06%).

Rice yield

The yield of rice is determined based on dry straw weight and grain yield at 14% moisture, as listed in Fig. 1. Only Se soil, straw dry weight and grain yield were significantly different ($P < 0.05$). The application of Si at 0.42 g SiO_2/pot provided the highest grain yield (26.6 ± 1.07 g/plant), while the dry straw weight in this treatment had the value 28.8 ± 1.61 g/plant, which was no significant difference from the highest treatment (Si at 0.84 g SiO_2/pot). The results showed that the application of Si at higher doses led to a reduction in straw dry weight and grain yield, with the highest dose of Si application resulting in the lowest rice yield (21.1 ± 1.62 and 18.6 ± 1.44 g/plant for straw dry weight and grain yield, respectively). In Tr soil, the results were not significantly different ($P > 0.05$) between treatments; straw dry weight and grain yield ranged from 11.2 ± 0.71 to 12.8 ± 1.02 and 11.9 ± 1.15 to 13.7 ± 0.49 g/plant, respectively.

P concentration and P uptake

Fig. 2 shows the P concentration in grain and straw of rice grown on Se and Tr soil. The application of Si at different rates resulted in statistically significant differences ($P < 0.05$) in P concentration in both grain and straw in all soils. In Se soil, increasing the Si rate resulted in an increase in P concentration in rice tissue, especially in straw and application of the highest Si dose resulted in the highest P concentrations (6.60 and 13.5 g/kg for grain and straw, respectively) and percent increase in P content (9.46 and 29.0%, respectively). For the Tr soil, the application of Si resulted in an increase in P concentration, except P concentration in straw in the treatment with received Si at 0.42 g SiO_2/pot, which gave the lowest amount of P concentration (9.86 g/kg) but this treatment was not significantly different from the control. The highest P concentration and percentage increase in P content in Tr soil was achieved in the treatment with 1.26 g SiO_2/pot for grain and 1.68 g SiO_2/pot for straw. The value of P concentration was 7.83 and 12.7 g/kg for grain and straw, respectively, while the percentage increase in P content in grain and straw was 34.7 and 22.7%, respectively.

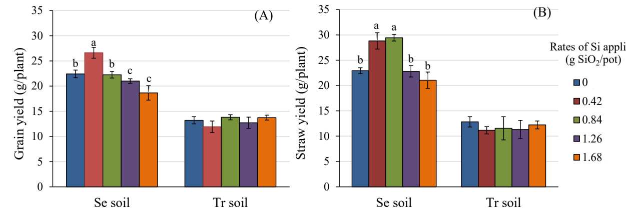

Fig. 1: Effect of different rates of Si on grain (**A**) and straw yield (**B**) grown in Se and Tr soils; the letters above the histograms indicate a statistical significance at $P < 0.05$ level using the DMRT test; vertical bars represented standard deviation (n = 3)

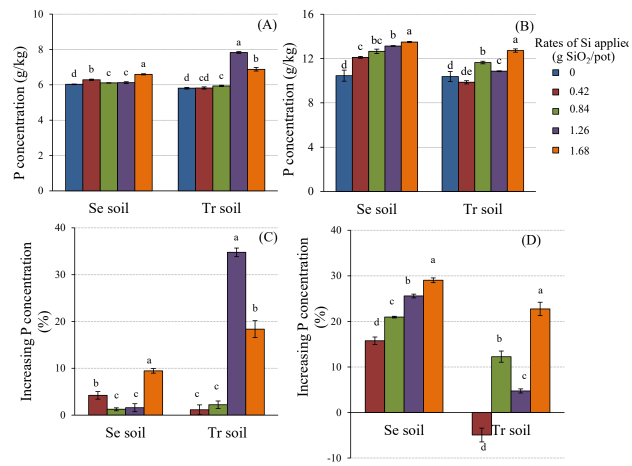

Fig. 2: Effect of different rates of Si on P in rice plant; (**A**) and (**C**) are P concentration and percentage of P increasing in grain and (**B**) and (**D**) are in straw; increasing phosphorus concentration (%) was calculated by comparison with the control treatment; the letters above the histograms indicate a statistical significance at $P < 0.05$ level using the DMRT test; vertical bars represented standard deviation (n = 3)

To measure P uptake in the different organs of rice, we measured it in both grain and straw and then summed these measurements to determine the total uptake at the harvest stage. Significant differences were found between treatments when different Si rates were used ($P < 0.05$) (Table 2). The application of Si at 0.42 g SiO_2/pot resulted in the highest total P uptake in rice planted in Se soil (516 ± 24 mg/plant), but this was not significantly different from the application of Si at 0.84 g SiO_2/pot. The total P uptake of rice grown on Se soils decreased with increasing Si application. In Tr soil, the highest Si application (1.68 g SiO_2/pot) resulted in the highest total P uptake (250 ± 10 mg/kg), followed by the application of Si at 1.26, 0.84, 0 and 0.42 g SiO_2/pot, respectively.

P use efficiency

P use efficiency was determined using the phosphorus harvest index (PHI), the physiological efficiency of phosphorus (PEP) and the agrophysiological efficiency of

Table 2: Effect of silicon fertilization on phosphorus uptake in different organs of rice (mean ± standard deviation; n = 3)

Rates of Si applied ($g\ SiO_2$/pot)	Phosphorus uptake (mg/plant) [1/]					
	Se soil			Tr soil		
	Grain	Straw	Total	Grain	Straw	Total
0	135±4^{b}	240±6^{c}	375±9^{c}	77±5^{bc}	133±8^{ab}	210±12^{b}
0.42	167±6^{a}	349±21^{a}	516±24^{a}	69±6^{c}	110±7^{b}	179±6^{c}
0.84	136±4^{b}	372±8^{a}	508±11^{a}	82±3^{b}	135±28^{ab}	217±25^{b}
1.26	129±15^{b}	300±15^{b}	428±30^{b}	100±8^{a}	123±19^{b}	223±11^{b}
1.68	123±8^{b}	284±20^{b}	407±11^{b}	94±3^{a}	156±9^{a}	250±10^{a}
F-test	*	*	*	*	*	*

Remarks: [1/] Means within the same column followed by the same letters indicated no significant difference among treatments by using DMRT; * is significant difference at 0.05 probability levels

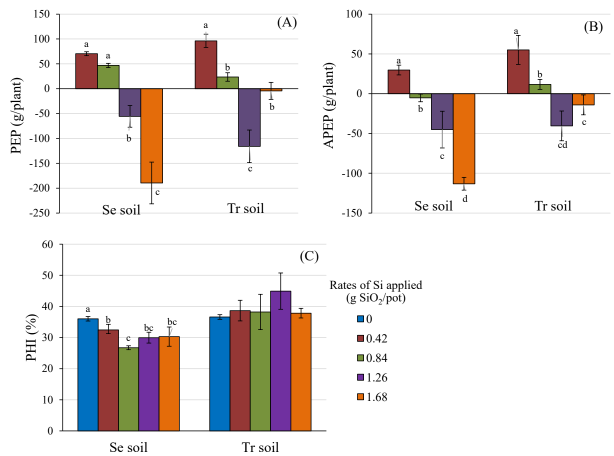

Fig. 3: Physiological efficiency of phosphorus (PEP) (**A**), agrophysiological efficiency of phosphorus (APEP) (**B**) and phosphorus harvest index (PHI) (**C**) under the influence of silicon at different rates; the letters above the histograms indicate a statistical significance at $P < 0.05$ level using the DMRT test; the vertical bars represent the standard deviation (n = 3)

phosphorus (APEP) (Fig. 3). Increasing the Si rate resulted in a decrease in PHI only in Se soil, with the control treatment having the highest PHI (36.0%), while the application of Si at a rate of 0.84-1.68 g SiO_2/pot resulted in the lowest PHI (26.7-30.3%) and showed no significant difference. The PHI in Tr soil was not significantly different from the application of Si at different doses, which ranged from 36.6 to 44.9%. The PEP and APEP showed similar tendencies in both Se and Tr soils. The highest PEP and APEP values were obtained in a Si treatment with 0.42 g SiO_2/pot in both Se and Tr soils, which amounted to 70.4 and 29.7 g/plant in Se soil and 96.2 and 55.0 g/plant in Tr soil. Increasing the amount of Si beyond 0.42 g SiO_2/pot led to a decrease in PEP and APEP and the value was negative, especially at an amount of Si at the rate 1.26-1.68 SiO_2/pot.

P availability in soils

The amount of available P, total P and the phosphorus activation coefficient (PAC) in the soil after the rice harvest is shown in Fig. 4. Using different Si rates resulted in

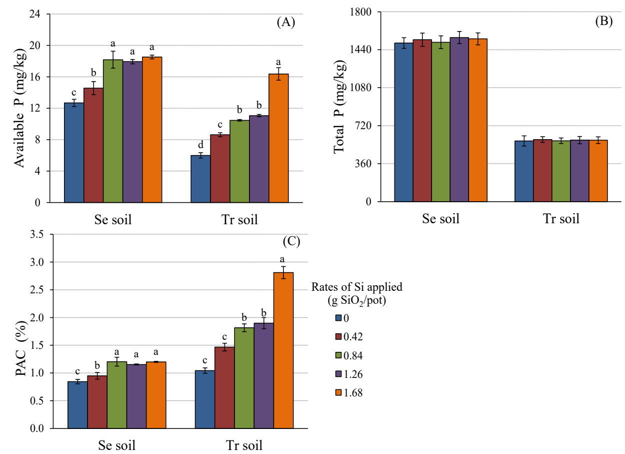

Fig. 4: Available P (**A**), total P (**B**) and PAC (**C**) under the influence of silicon at different rates; the letters above the histograms indicate a statistical significance at $P < 0.05$ level using the DMRT test; the vertical bars represent standard deviation (n = 3); PAC is the phosphorus activation coefficient

significant differences between treatments ($P < 0.05$) in terms of available P and PAC, while total P was not significantly different ($P > 0.05$). The application of Si at a dosage of 0.84-1.68 g SiO^2/pot in Se soil did not cause a significant difference in the values for available P (17.9-18.5 mg/kg) and PAC (1.15-1.20%). While the application of Si at the highest dosage (1.68 g SiO^2/pot) in Tr soil resulted in significantly higher values for available P (16.4 mg/kg) and PAC (2.81%) compared to the other treatments. For the total P content, the application of Si in varying amounts resulted in values between 1,503 to 1,555 and 575 to 588 mg/kg for Se and Tr soil, respectively.

Relationship between yield, P and Si

Pearson correlation test was used to evaluate the relationship between rice yield, P concentration in grain and straw, available P, PAC and Si input at different levels (Fig. 5). Only grain and straw yield of rice grown on Se soil showed a negative correlation with Si application (r = -0.719 and -0.404 for grain and straw, respectively), which did not significantly different (Fig. 5A and B), while the other parameters were positively correlated. The P concentration in the straw of rice grown on both Se and Tr soils showed a positive and significant correlation with Si application (r = 0.945* and 0.810* for Se and Tr soils, respectively) (Fig. 5D). In addition, available P and PAC also showed a positive relationship between available P and PAC and Si application in Se and Tr soils (r = 0.910* and 0.959* for available P and 0.910* and 0.958* for PAC in Se and Tr soils, respectively) (Fig. 5E and F). However, P concentration in the grains (Fig. 5C) showed a positive correlation with Si application (r = 0.685 and 0.793 for Se and Tr soils, respectively), but there was no significant difference.

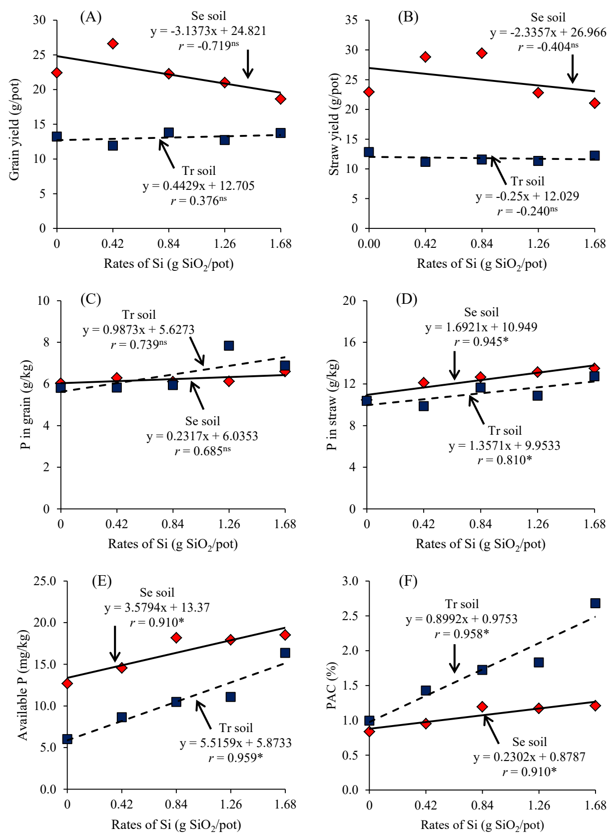

Fig. 5: The correlation between the rice yield (**A**, **B**), P in plant (**C**, **D**), P in soil (**E**, **F**) and the rates of Si application in Se (◆) and Tr (■) soils

Discussion

The properties of the soils used for the experiment can be divided into two groups: acidic soils (Se soil, pH = 4.81 ± 0.15) and neutral soils (Tr soil, pH = 6.60 ± 0.35). The properties of Se and Tr soils are different. The acidic soil had high organic matter content, but the available P contents and available Si contents were medium. In contrast, the neutral soil had a low organic matter and available P content, but a high content of available Si (Table 1) (Land Classification Division and FAO project Staff 1973; Narayanaswamy and Prakash 2009). Normally in acid or acid sulfate soils, the plants grown on this soil are likely to be deficient in Si or may mention that these soils have a low available Si, while in neutral or alkaline soils, the release of Si is higher, this is because in acid or acid sulfate soils abundance of iron and aluminum oxide, which can be fixed with Si (H_4SiO_4) in the soil (Kabata-Pendias and Pendias 1992; Szulc *et al*. 2019). The results of the experiment confirmed that in acidic soils (Se soil), the application of Si, especially at a low Si dose (0.42 g SiO_2/pot), was able to increase grain yield more than other treatments, while the application of Si at a dose of 0.42 - 0.84 g SiO_2/pot resulted in the highest similarity in straw dry weight. According to Sandhya and Prakash (2019), they studied the application of Si from different sources and its effects on rice yield in acidic, neutral, and alkaline soils in South India and reported that application of Si at the rate of 0.625 - 1.25 g Si/pot could significantly increase both grain and straw yield as compared to control and in this case, there was no statistical difference in grain and straw yield values at both Si application rates. However, the use of an overdose of Si causes adverse effects, as reported by Cuong *et al.* (2017). They found that increasing the amount of Si fertilizer from 300 to 400 kg SiO_2/ha reduced the grain and straw yield of rice by 0.3 and 0.2%, respectively. On neutral soils (Tr soil), on the other hand, the use of Si in varying amounts had no effect on rice yield and straw. This was due to the fact that the available Si in this soil was high, so that the application of Si fertilizer had no effect on growth and yield. According to the report by Li *et al.* (2020), it was found that in soils with a high content of available silicon, the rice grown on these soils showed no significant difference in yield between cultivation with and without silicon fertilizer. There are also other reports indicating that the application of Si can increase the growth and yield of rice, and help to resist biotic or abiotic stress in the environment (Dobermann and Fairhurst 2000; Surapornpiboon *et al*. 2008; Cuong *et al.* 2017; Yan *et al*. 2018; Chaiwong *et al.* 2022).

P concentration in rice under the influence of Si at different levels showed a favorable response to Si application. Increasing the amount of Si increased the P concentration in plant tissue (Fig. 2A, B), especially in the part of rice straw. According to Jinger *et al.* (2022), they investigated the combination of Si and P fertilizer on dry matter, grain yield and nutrient uptake in rice in India. Their results showed that the application of 40 to 120 kg Si/ha increased the P concentration in rice grain and straw by 13-40% and 0-25%, respectively, compared to the control. The results of the experiment showed that the percentage increase in P concentration with increasing Si application was 1.26-9.45 and 15.7-29.0% for grains and straw in Se soil and 0.16-34.7 and -4.93-22.7% for grains and straw in Tr soil (Fig. 2C, D). The main reason for the increased P concentrations in the plant tissue could be that the plants take up more phosphate anions from the soil. By adding Si to the soil, the silicate anion ($H_3SiO_4^-$) can be released and replaces the phosphate anion (HPO_4^{2-} or $H_2PO_4^-$) that is fixed in the soils, so that the phosphate anion is released into the soil solution and can be taken up by the plant roots. However, the changes in the soil chemical environment can release P fixation in the soil, *e.g*., by changing the redox conditions in the soil, application of P solubilizers and use of soil amendments (Ghosh *et al.* 2024) and the use of Si can improve the efficiency of nutrient utilization, resulting in higher rice productivity. An optimal Si dosage can increase root growth and P utilization efficiency by reducing the retention capacity of P in the soil (Jinger *et al*. 2022).

For total P uptake, the results indicated that the soil type had an influence on the P uptake of rice. In acidic

(Se soil), a low Si dose (0.42 g SiO_2/pot) resulted in higher P uptake than a high Si dose (0.84-1.68 g SiO_2/pot), while in neutral (Tr soil) the highest Si dose (1.68 g SiO_2/pot) resulted in the highest P uptake. The total nutrient uptake of plants depends on two factors, namely the total dry mass of the plant and the total nutrient concentration (Sukyankij *et al.* 2023). In Se soil, dry matter of rice differed significantly, especially at low Si application (0.42 g SiO_2/pot), which gave the highest dry matter yield and resulted in higher P uptake compared to other treatments. However, the characteristics of the ions Si and P are the same ($H_3SiO_4^-$ and $H_2PO_4^-$), which are anions and have one negative charge. This characteristic may result in competition for entry into plant root cells. Thus, increasing the amount of Si in the soil may be affected by reduced P uptake in rice, especially in acidic soil where P availability is limited. According to our results, increasing the amount of Si reduced P uptake in rice tissue only in acidic soils. In Tr soil, dry matter yield was similar in each treatment, but P concentration varied, so that the treatment with Si application at 1.68 g SiO_2/pot, which had the highest P concentration, also had the highest P uptake. According to Ghosh *et al*. (2024), the application of Si at the highest dose in their experiment led to the highest P uptake in wheat. However, several authors have reported that Si has the potential to stimulate plant growth, improve P status in plant cells and increase P uptake, which is strength for reducing P fertilization (Neu *et al.* 2017; Soratto *et al.* 2019). With regard to P use efficiency, an increase in the amount of Si led to a decrease in PHI, PEP and APEP. This indicates that the application of Si cannot increase the efficiency of the plant in converting P in various plant organs (leaves and stems) into grain. In this case, the increased Si dose is not clearly reflected in the increase in rice yield. The results of this study are in agreement with the report of Jinger *et al.* (2022) and Kamruzzaman *et al.* (2022), who reported that the application of Si at higher doses impairs the nutrient use efficiency of the plant.

The available P concentration and the percentage of PAC increased in both soils with increasing Si addition, showing a strong correlation between available P and Si addition, as well as between PAC and Si addition (Fig. 5E, and F). Barman *et al.* (2023) mentioned about the interaction between Si and P in the soil that the addition of Si to the soil reduces P adsorption and increases P desorption in the soil. This is due to the fact that silicate anions ($H_3SiO_4^-$) from Si fertilizers can compete with phosphate anions (HPO_4^{2-} or $H_2PO_4^-$) for binding sites in the soil, so that phosphate anions are released into the soil solution, leading to an increase in P availability in the soil (Soratto *et al.* 2019). In most areas of the province, the P content is not low (Sukyankij *et al*. 2021), but most of the P is in unavailable form. At a lower soil pH, P tends to combine with Fe, Mn, Al or hydrous oxides, while at a higher soil pH, P reacts with Ca and appears as calcium phosphate minerals, and at a neutral soil pH, P reacts with silicate minerals. However, when P reacts with silicate minerals, P fixation is at its lowest (Brady and Weil 1999; Schaller *et al.* 2019). According to the test results, neutral soil (Tr soil) showed a stronger correlation between available P and Si application (r = 0.959*) than acidic soil (Se soil) (r = 0.910*) (Fig. 5E). The main reason for the increase in available P in the soil is influenced by the addition of Si. The Si anion ($H_3SiO_4^-$) can reduce the competition between Si and P at the sorption site, especially on the Fe mineral. In addition, Si has a higher potential to replace the sorption site on the surface of amorphous and crystalline Fe minerals than P (Schaller *et al*. 2019; Schaller *et al*. 2022).

Conclusion

To summarize, the application of Si can increase grain and straw yield only on acidic soils, especially the application of a low dose of Si, which significantly increases grain yield. The use of Si in higher doses led to an increase in P concentration in rice grain and straw in both acidic and neutral soils. The total P uptake of rice showed that in acidic soil, a small amount of Si caused the highest P uptake, while in neutral soils; the application of Si at high doses caused the highest P uptake. Regarding the P use efficiency, increasing the Si dose resulted in lower values, especially for PEP and APEP, and the application of Si at a low dose resulted in an improvement of both values. Applying Si at a higher dose increased available P in all soils and may also increase the soil's ability to convert total P to available P, suggesting that adding Si to soil helps to increase the amount of P released into the soil solution. For rice yield, a low Si dose (half the recommended Si dose) is optimal to increase rice yield, especially for rice grown on acidic soils.

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Author Contributions

Saychol Sukyankij planned the experiments, carried them out, interpreted the results and wrote the manuscript, Chalinee Khougsud analyzed the plants and soil samples, Dr. Mutchima Phun-Iam and Assoc. Prof. Dr. Thanawan Panich-pat reviewed the manuscript.

Conflicts of Interest

The authors declare no conflict of interest.

Data Availability

Data presented in this study will be available on a fair request to the corresponding author.

Ethics Approval

Not applicable to this article.

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