Response of Rice to Silicon Fertilizer Application and Its Effects on Silicon Availability in Soil of Phra Nakhon Si Ayutthaya, Thailand

การตอบสนองของข้าวต่อการใช้ปุ๋ยซิลิคอนและผลต่อความเป็นประโยชน์ของซิลิคอนในดินพระนครศรีอยุธยา ประเทศไทย

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บทคัดย่อ: งานวิจัยนี้มีวัตถุประสงค์เพื่อประเมินอัตราปุ๋ยซิลิคอนที่เหมาะสมต่อการเจริญเติบโต ผลผลิตและองค์ประกอบของผลผลิต ปริมาณซิลิคอนในส่วนต่าง ๆ ของข้าวพันธุ์ปทุมธานี 1 และผลต่อความเป็นประโยชน์ของซิลิคอนในดินจังหวัดพระนครศรีอยุธยา วางแผนการทดลองแบบ 2 x 5 แฟคทอเรียลแบบสุ่มสมบูรณ์ จำนวน 3 ซ้ำ 2 ปัจจัย ปัจจัยแรกคือชนิดของดิน (ชุดดินท่าเรือและชุดดินเสนา) ปัจจัยที่สองคือระดับปุ๋ยซิลิคอน 5 อัตรา ได้แก่ 0, 0.42, 0.84, 1.26 และ 1.68 กรัม SiO_2ต่อกระถาง ผลการทดลองพบว่า ชนิดของดินมีผลอย่างชัดเจนต่อการเจริญเติบโต ผลผลิต และปริมาณซิลิคอนที่สะสมในส่วนต่าง ๆ ข้าว โดยข้าวที่ปลูกในชุดดินเสนามีความเขียวใบ จำนวนรวงต่อกอ ผลผลิตเมล็ดและตอซัง อีกทั้งปริมาณการดูดใช้ซิลิคอนในส่วนต่าง ๆ สูงกว่าข้าวที่ปลูกในชุดดินท่าเรือ การใส่ปุ๋ยซิลิคอนอัตรา 0.42 กรัม SiO_2ต่อกระถาง ให้ผลผลิตเมล็ดสูงที่สุด โดยเฉพาะข้าวที่ปลูกในชุดดินเสนา (26.6 กรัมต่อกอ) ขณะที่การใส่ปุ๋ยซิลิคอนอัตรา 1.68 กรัม SiO_2ต่อกระถาง ให้ปริมาณการดูดใช้ซิลิคอนในเนื้อเยื่อส่วนต้น ใบ และเมล็ดสูงที่สุด (0.38, 0.48, 0.50 กรัมต่อกอ) อัตราการใส่ปุ๋ยซิลิคอนที่เพิ่มขึ้นส่งผลให้ความเป็นประโยชน์ของซิลิคอนในดินเพิ่มขึ้นอย่างชัดเจน โดยการใส่ปุ๋ยซิลิคอนอัตรา 1.68 กรัม SiO_2ต่อกระถาง ส่งผลให้มีปริมาณซิลิคอนในรูปที่ละลายน้ำได้ รูปที่แลกเปลี่ยนได้ รูปที่เป็นประโยชน์ต่อพืช และซิลิคอนในรูปที่ตกค้างในดินสูงที่สุด (49, 224, 274 และ 15,278 มิลลิกรัมต่อกิโลกรัม สำหรับชุดดินท่าเรือ และ 56, 87, 143 และ 13,692 มิลลิกรัมต่อกิโลกรัม สำหรับชุดดินเสนา ตามลำดับ)

คำสำคัญ: ปุ๋ยซิลิคอน ความเข้มข้นของซิลิคอน รูปของซิลิคอนในดิน ผลผลิตข้าว

Abstract: This research aimed to evaluate the optimal rates of silicon (Si) fertilizer on the growth, yield components, yield, and Si uptake in each part of Pathum Thani 1 rice and its effects on Si availability in the soil of the Phra Nakhon Si Ayutthaya province. The experiment was arranged in a 2x5 factorial in a completely randomized design with three replications and two factors. The first factor was the soil series; Tha Rua (Tr), and Ayutthaya (Ay). The second factor was the Si fertilizer, which was set at five different levels; 0, 0.42, 0.84, 1.26, and 1.68 g SiO_2/pot. The findings revealed that soil types significantly impacted plant growth, yield, and the amount of Si content in various plant parts. The rice planted in the Se soil series illustrated higher leaf greenness, number of panicles per hill, rice yield (straw and grain), and Si uptake in various plant parts; more than that of the Tr soil series. Applying Si fertilizer at 0.42 g SiO_2/pot gave the highest grain yield, particularly in the Se soil series (26.6 g/hill). The application of Si fertilizer at 1.68 g SiO_2/pot provided the highest Si content in culms, leaves, and grain; at 0.38, 0.48, and 0.50 g/hill, respectively. Increases in Si fertilizer rates noticeably increased the Si availability in both soil types. Applying Si fertilizer at 1.68 g SiO_2/pot gave the highest amount of Si in water-soluble, exchangeable, available, and residual fractions at (49, 224, 274, and 15,278 mg/kg in the Tr soil series and 56, 87, 143, and 13,692 mg/kg in the Se soil series, respectively).

Keywords: Si fertilizer, Si concentration, Si forms in soils, rice yield

Introduction

Silicon (Si) is the second most abundant and stable electropositive element in the earth's crust (Kabata-Pendias and Pendias, 1992; Szulc *et al.*, 2019). The total Si content in soil ranges from 1 - 45 % depending on the soil type and parent material (Sommer *et al.*, 2006). Soluble Si in a soil solution was recorded at roughly 1 - 200 mg/L, which was dependent on the soil type and climatic factors (Kabata-Pendias and Pendias, 1992). Generally, Si is taken up by plants as mono-silicic acid (H_2SiO_4), which is a water-soluble and exchangeable form of Si in the soil colloid system. Both forms are classified as available forms, which are beneficial for plant growth. However, the majority of silicon found in soil is its residual fraction, which is a composition of a rock or mineral. Soil pH, which affects the solubility of Si concentration in soil via the processes of soil weathering and adsorption-desorption of Si in the soil solution (Szulc *et al.*, 2019), is one of the influential factors of available Si in soil. The solubility of Si usually decreases in acidic soil (fixed with Fe and Al oxide) but increases in alkaline soils (pH approximately 9.5) (Kabata-Pendias and Pendias, 1992; Szulc *et al.*, 2019). Therefore, the available Si in acidic soil tends to be restricted, as silicate ions can be precipitated with other cations (Kabata-Pendias and Pendias, 1992). Similarly, in calcareous soil, Sandhya and Prakash (2019) demonstrated that the solubility of Si increased as the soil pH increased from neutral to alkaline. In the lowland rice cultivation areas within Thailand, Phra Nakhon Si Ayutthaya province, the mostly flooded soil is post-active acid sulfate soil, such as in the Ayutthaya and Sena soil series (Sukyankij *et al.*, 2022), which is limited in its release of Si into the soil solution (Kabata-Pendias and Pendias, 1992). While the

Tha Rue soil series had lower soil fertility and organic matter, its soil pH was higher and closer to neutral (Sukyankij *et al*., 2022); which can promote the increase of available Si in soil.

Si is classified as a beneficial element in plants (Dobermann and Fairhurst, 2000) and can be accumulated differently in every plant species. Several high-Si-accumulating species of plant were reported in the Poaceae family, such as rice, which accumulates Si at about 10 - 15 % (DW). Rice is known as a Si accumulator plant, as the Si uptake of this plant can be more than 10 % (DW) (Dobermann and Fairhurst, 2000), and presents a positive response to Si fertilizer in terms of productivity (Chaiwong *et al*., 2022). Si plays an important role in rice; aiding in the development of strong leaves, stems, and roots; increasing available phosphorus in soil (Dobermann and Fairhurst, 2000), and aiding in the meliorate tolerance of biotic and abiotic stress; such as relieving water loss, impeding fungal infections, and improving drought resistance via the enhancement of the water contents in plants (Ma, 2004; Savant *et al.,* 1996; Surapornpiboon *et al*., 2008; Yan *et al*., 2018). Dobermann and Fairhurst (2000) reported that the optimal ranges and critical levels of Si in rice straw at the maturity stage were 8 - 10 % and less than 5 %, respectively, whereas the critical Si deficiency in soil was 54 mg/kg (extracted with 0.5 M acetic acid) (Narayanaswamy and Prakash, 2009). Cuong *et al*. (2017) reported that the recommended rate of SiO_2 fertilizer was 329 kg/ha for rice production in a tropical zone. Consequently, the addition of Si fertilizer in soil with low availability of Si or in acidic soils is necessary for improving the growth and yield of rice. Hence, the objectives of this study were to estimate (1) the effects of Si fertilizer rate on growth, yield, and yield components, (2) Si uptake in different plant parts, and (3) Si in different fractions in the soil after rice cultivation.

Materials and Methods

Plants and Soils Preparation

The study was conducted in a greenhouse from November 2021 to March 2022 at the Faculty of Science and Technology, Phranakhon Si Ayutthaya Rajabhat University, Thailand. Rice seed (Pathum Thani 1) was obtained from the Prachin Buri Rice Research Center, Rice Department. The soil in the experiment consisted of two soil series, representing the availability of Si at low and high levels. The Tha Rua (Tr) soil series (Vertic (Aeric) Endoaquepts), collected from the Wang Dang subdistrict in the Tha Ruea district (14°52’90.27” N 100°67’28.60” E), was presented with high exchangeable Si (176.9 mg/kg). The Sena (Se) soil series (Sulfic Endoaquepts), collected from the Chai Na subdistrict, Sena district, Phra Nakhon Si Ayutthaya province (14°27’74.09” N 100°35’76.80” E), was represented with low exchangeable Si (68.5 mg/kg) (Division of Soil Survey and Soil Resource Research, 2019). The soil samples were collected at 0 - 20 cm in the paddy field in each location and then air-dried for 14 days in the greenhouse. The soil was then divided into two portions. The first portion was ground and passed through a 2 mm sieve and analyzed for physical and chemical properties; i.e., soil texture (Gee and Bauder, 1986), soil pH (Thomas, 1996), saturated electrical conductivity (Rhoades, 1996), organic matter (Walkley and Black, 1934), available phosphorus (Bray and Krutz, 1945), exchangeable potassium, calcium, and magnesium (Thomas, 1982), water-soluble

Si (Khalid *et al*., 1978), exchangeable Si (Korndorfer *et al*., 1999), available Si (water-soluble Si plus exchangeable Si), and residual Si (Jones and Dreher, 1996) before the start of the experiment.

The second portion was used to study the effects of Si fertilizer on yield and Si uptake in Pathum Thani 1 rice under greenhouse conditions. The experiment design was a 2 x 5 factorial in a completely randomized design (CRD) with three replications and two factors. The first factor was the soil series (Tha Rua soil series (Tr) and Sena soil series (Se)). The second factor was the Si fertilizer application used: no addition of Si fertilizer (control) and Si fertilizer application at rates of 0.5, 1.0, 1.5, and 2.0 times the Si recommended rate. The recommended rate of Si for tropical rice was 329 kg SiO_2/ha, reported by Cuong *et al*., 2017. In the pot experiment, a total of 5 kg of dried soil was put into each 6.5 L plastic pot. The rates of Si fertilizer, silicic acid (H_2SiO_4), in the pot treatments were 0, 0.42, 0.84, 1.26, and 1.68 g SiO_2/pot. Distilled water, without Si contamination, was added to the soil plots and stirred until muddy. The soil series were mixed well and flooded for seven days prior to transplanting the 20-day-old Pathum Thani 1 rice seedlings in the experiment pots. Flooding was maintained at 5 cm above the soil surface from the start of the planting stage through the harvesting stage. The primary plant fertilizer (NPK) was applied in accordance with the site-specific nutrient management program (SimRice2000_V110) at the rates of 0.13-0.06-0.11 and 0.03-0.06-0 g N-P_2O_5-K_2O per pot for both the Tr and Se soil series. At the maturity stage, Pathum Thani 1 rice was harvested at 107 days after transplanting. The plant samples were separated into grain and straw. The samples were then oven-dried in a hot air oven at 80 $^{\circ}$C for 48 hours, after which the samples were recorded for the dry weight of both grain and straw. Next, straw samples from each treatment were divided into culm and leaves. All samples (grain, culm, and leaves) were cut into small pieces and crushed to less than 0.5 mm in size, and the whole plant samples were taken for Si concentration analysis in the next step.

Data collections

Data were collected for the assessment of (1) growth, yield, and yield components (i.e., plant height, leaf greenness (SPAD), day after flowering, number of tillers per hill, number of panicles per hill, panicle length, number of grains per panicle, fertile grain, 100-grain weight, dry straw weight, and grain yield at 14 percent moisture), and (2) the concentration of Si in different plant tissues (grain, culm, and leaf), which were digested by conc. HNO_3 (Nayar *et al*., 1975) and determined through the molybdenum blue colorimetric method (Babu, 2015; Hallmark *et al*., 1982). Total Si uptake in each part was then calculated by multiplying the Si concentration by the basic dry matter content. The fractions of Si in soils were water-soluble, exchangeable, available, and residual. Water-soluble and exchangeable Si were extracted by the methods of Khalid *et al.* (1978) and Korndorfer *et al*. (1999), respectively, and the amount of Si was determined by the molybdenum blue colorimetric method (Babu, 2015; Hallmark *et al*., 1982).

For available Si, we calculated the sum of water-soluble and exchangeable Si in the soil. Residual Si was digested with a mixture of aqua regia, HF, and H_3BO_3, and the amount of Si was measured by the blue silicomolybdous acid method (Jones and Dreher, 1996).

Statistical analysis

The data from the experiment were subjected to an analysis of variance (ANOVA), and Duncan's new multiple range test (DMRT) with a significance of $P < 0.05$ probability level. The means of each treatment were compared.

Results and Discussion

Soil properties at the start of the experiment

The soil properties at the start of the experiment are shown in Table 1. The Tr and Se soil series were classified as Vertic (Aeric) Endoaquepts and Sulfic Endoaquepts, respectively (Division of Soil Survey and Soil Resource Research, 2019). The soil texture was characteristically silty clay in the Tr soil series and clay in the Se soil series and were slightly acidic (pH = 6.57) and strongly acidic (pH = 4.81), respectively. No saline was noted in both soil series, and the organic matter contents ranged from medium (Tr = 13.6 g/kg) to very high levels (Se = 50.2 g/kg). Available phosphorus contents were low to medium in the Tr soil series (4.58 mg/kg) and (13.7 mg/kg) in the Se soil series. In the Tr soil series; exchangeable potassium was high (94 mg/kg), calcium was very high (5,031 mg/kg), and magnesium content was high (385 mg/kg). And, in the Se soil series; exchangeable potassium was high (157 mg/kg), calcium was high (24,185 mg/kg), and magnesium content was high (443 mg/kg). The basic chemical properties of each soil series were interpreted according to the FAO Project Staff and Land Classification Division (1973). We observed a high level of exchangeable Si in the Tr soil series (176 mg/kg) and a medium level (68.5 mg/kg) in the Se soil series (Narayanaswamy and Prakash, 2009).

Table 1. The properties of topsoil (0 - 20 cm depth) prior to the experiment (mean ± S.E.)

Soil property	Tha Rua (Tr) soil series	Sena (Se) soil series
Texture classes	Silty Clay	Clay
Soil pH reaction (1:1 H_2O)	6.57 ± 0.35	4.81 ± 0.15
Electrical conductivity, EC_e (dS/m)	2.16 ± 0.21	1.24 ± 0.16
Organic matter (g/kg)	13.6 ± 1.24	50.2 ± 2.45
Available phosphorus (mg/kg)	4.58 ± 0.85	13.7 ± 1.42
Exchangeable potassium (mg/kg)	94.1 ± 3.15	157 ± 2.90
Exchangeable calcium (mg/kg)	5,031 ± 25.5	2,418 ± 21.0
Exchangeable magnesium (mg/kg)	385 ± 12.6	443 ± 21.4
Exchangeable silicon (mg/kg)	176 ± 5.35	68.5 ± 3.15
Water soluble silicon (mg/kg)	36.5 ± 1.75	32.3 ± 2.04
Available silicon (mg/kg)	213 ±15.4	101 ± 11.5
Residual silicon (mg/kg)	12,420 ± 105	11,385 ± 85.5

Effect of Si fertilizer on growth and yield

Growth and yield of rice were determined based on plant height, leaf greenest (SPAD unit), number of panicles per tiller, percent fertile grain, 100-grain weight, dry straw weight, and grain yield at 14 percent moisture (Table 2). The difference in soil types significantly affected the SPAD value, number of panicles per tiller, and rice yield (straw and grain) ($P < 0.01$). Resultingly, the Se soil series produced greater rice growth and yield than that of the Tr soil series. The application of Si fertilizer was statistically different only in SPAD value, number of panicles per tiller, and grain yield ($P < 0.01$). The application of Si fertilizer at 1.26, 0.84, and 0.42 g SiO_2/pot gave the highest leaf greenness, number of panicles per tiller, and grain yield (38.2 SPAD units, 10.0 panicles/tiller, and 19.3 g/hill, respectively). The interaction of soil types and various Si fertilizer applications produced significant differences in SPAD value, number of panicles per tiller, and straw and grain yields ($P < 0.01$). Applying Si fertilizer at 0.42 g SiO_2/pot in the Se soil series provided the highest SPAD value, straw and grain yields; at 41.2 SPAD units, 26.8, and 26.6 g/hill, respectively.

Table 2. Effects of soil types and Si fertilizer application on growth and yield of rice

Factors	Height (cm)[1]	SPAD unit[1]	No. Panicle (panicle/tiller)[1]	Fertile grain (%)[1]	100-grain wt. (g)[1]	Straw yield (g)[1]	Grain yield (g)[1]
Factor 1 (Soil series)							
Tr soil	85.5	31.6^{b}	7.1^{b}	94.1	2.54	12.0^{b}	13.1^{b}
Se soil	87.7	39.3^{a}	10.7^{a}	93.5	2.58	23.9^{a}	22.3^{a}
F-test	ns	**	**	ns	ns	**	**
Factor 2 (Si fertilizer application, g SiO_2/pot)							
0	84.8	31.9^{c}	9.3^{ab}	91.9	2.55	18.3	17.8^{bc}
0.42	85.7	36.2^{a}	9.2^{ab}	94.8	2.54	19.0	19.3^{a}
0.84	88.8	34.2^{b}	10.0^{a}	93.8	2.58	18.8	18.4^{b}
1.26	87.3	38.2^{a}	8.0^{b}	94.4	2.56	17.1	16.9^{c}
1.68	86.3	36.9^{a}	8.0^{b}	94.1	2.58	16.6	16.2^{c}
F-test	ns	*	*	ns	ns	ns	**
Interaction Factor 1 x Factor 2							
Tr x Si_0	83.0	27.8^{d}	7.7^{cd}	90.4	2.54	13.6^{c}	13.2^{d}
Tr x $Si_{0.42}$	87.0	31.2^{cd}	6.3^{d}	94.7	2.51	11.2^{c}	11.9^{d}
Tr x $Si_{0.84}$	86.7	30.9^{cd}	8.0^{cd}	93.3	2.58	11.6^{c}	13.8^{d}
Tr x $Si_{1.26}$	85.7	35.4^{abc}	6.7^{d}	96.3	2.53	11.3^{c}	12.7^{d}
Tr x $Si_{1.68}$	85.3	32.9^{bcd}	6.7^{d}	95.9	2.55	12.2^{c}	13.7^{d}
Se x Si_0	86.7	35.9^{abc}	11.0^{ab}	93.4	2.56	22.9^{ab}	22.4^{b}
Se x $Si_{0.42}$	84.3	41.2^{a}	12.0^{a}	94.9	2.57	26.8^{a}	26.6^{a}
Se x $Si_{0.84}$	91.0	37.4^{bc}	12.0^{a}	94.3	2.59	26.1^{ab}	23.0^{b}
Se x $Si_{1.26}$	89.0	40.9^{a}	9.3^{bc}	92.6	2.58	22.8^{ab}	21.0^{b}
Se x $Si_{1.68}$	87.3	40.9^{a}	9.3^{bc}	92.3	2.60	21.0^{b}	18.6^{c}
F-test	ns	**	**	ns	ns	**	**
CV (%)	3.3	8.8	13.8	3.2	2.1	15.3	7.6

[1/] Means with the different letters in each column are significant differences according to DMRT at $P < 0.05$; **,* are significant difference at $P < 0.01$ and 0.05 probably levels, respectively, and ns is not significantly different; Tr and Se are the Tha Rua and Sena soil series, respectively

Generally, when plants receive an adequate amount of Si, they can increase their photosynthetic rate and chlorophyll contents (Song *et al*., 2014), however, the initialized value of the soil's fertility is also important for this parameter. The results indicated that the high fertility of the Se soil series had a higher effect on the photosynthetic rate and chlorophyll contents than soil with a high Si content (Tr soil series). Moreover, the increased Si fertilizer rate (0.42-1.68 SiO_2/pot) produced increased chlorophyll contents (SPAD value) when compared to the control treatment (Table 2). Ju *et al*. (2020) reported that a nutrient solution containing Si at a concentration of 1, 2, or 4 mM increased the chlorophyll contents of rice seedlings significantly compared to the control (0 mM). According to our study, increased rates of Si fertilizer (0 - 1.68 g SiO_2/pot) increased leaf greenness (SPAD value) of rice in both soil types, as well as the number of panicles per tiller. The applied Si fertilizer at 0.84 g SiO_2/pot promoted a higher number of panicles per tiller than the other treatments. According to Chaiwong *et al.* (2022), the sufficiency of the Si supply may be increased by increasing the number of panicles per plant, as well as the number of grains per panicle and the percentage of filled grains. Moreover, the lack of Si in rice led to a decrease in spikelet fertility and a reduced harvest index (Ma *et al*., 1989). The optimal rate of Si fertilizer for rice was 0.42 g SiO_2/pot, as this rate was able to promote the highest grain yield (Table 2), especially in soil with low available Si (Se soil series at 26.6 g/hill). However, the rice yield in this soil tended to decrease if Si fertilizer over 1.26 g SiO_2/pot was applied. The application of Si fertilizer at the highest rate (1.68 g SiO_2/pot) produced the lowest grain yield (18.6 g/hill). Cuong *et al*., 2017; reported that the application of Si fertilizer at rates between 100 - 400 kg/ha increased the straw and grain yields of rice by 12 - 19 % and 13 - 22 %, respectively. Similarly, applying Si fertilizer at optimal rates increased rice yield and quality (Surapornpiboon *et al*., 2008; Yan *et al*., 2018). Si can protect rice plants from stress caused within their environment (biotic and abiotic factors), as well as promote the efficient use of light and nitrogen (Dobermann and Fairhurst, 2000).

Effects of Si fertilizer on Si uptake

Both soil types demonstrated that the application of Si fertilizer significantly affected Si uptake in the rice culm, leaves, and grain ($P < 0.01$), which was significantly higher in the Se soil series, with the exception of the Si uptake in leaves ($P > 0.05$) (Table 3). The application of Si fertilizer at the highest rate (1.68 g SiO_2/pot) generated Si uptake values in the culm, grain, and total at 0.38, 0.50, and 1.36 g/hill; whereas Si applied at the rate of 0.42 - 1.26 g SiO_2/pot were not statistically different from the highest rate. When considering the interaction between soil type and Si fertilizer application, the application of Si fertilizer at the rate of 0.42 g SiO_2/pot in the Se soil series gave the highest Si uptake in culm, leaf, and total (0.43, 0.55, and 1.53 g/hill). No significant differences were observed in the treatment of Si at the rates of 0.84, 1.26, and 1.68 g SiO_2/pot, respectively.

Soil fertility is important for determining the Si uptake by plants, as the uptake parameter is calculated from the dry weight of the plant multiplied by the element's concentration. Our results showed that rice planted in the Tr soil series had higher Si concentrations in several plant parts than that in the Se soil series (data not shown). The Tr soil series produced lower Si uptake and plant biomass, yet higher Si concentration than that of the Se soil series. Chaiwong *et al.* (2022) and Phommuangkhuk *et al.* (2020), in their studies of Si fertilizer applied for grain yield production and Si accumulation in rice, reported that increasing rates of Si fertilizer increased the Si concentration in the different organs of rice; aligned with our own findings herein. Moreover, they also reported that Si concentrations were higher in leaf tissues than in other plant parts and that above-ground plant parts generally accumulated more Si than in the roots (Meena *et al*., 2014).

Table 3. Effects of soil types and Si fertilizer application on Si uptake in different organs of rice

Factors	Si uptake (g/hill)			
	Culm[1]	Leave[1]	Grain[1]	Total[1]
Factor 1 (Soil series)				
Tr	0.27[b]	0.35[b]	0.36[b]	0.99[b]
Se	0.40[a]	0.52[a]	0.48[a]	1.39[a]
F-test	**	**	**	**
Factor 2 (Si fertilizer application, g SiO_2/pot)				
0	0.25[b]	0.37	0.35[b]	0.96[b]
0.42	0.34[a]	0.42	0.44[ab]	1.20[ab]
0.84	0.35[a]	0.44	0.42[ab]	1.21[ab]
1.26	0.35[a]	0.46	0.41[ab]	1.22[ab]
1.68	0.38[a]	0.48	0.50[a]	1.36[a]
F-test	**	ns	**	**
Interaction Factor 1 x Factor 2				
Tr x Si_0	0.20[c]	0.33[cd]	0.30[f]	0.84[e]
Tr x $Si_{0.42}$	0.26[bc]	0.29[d]	0.32[ef]	0.86[e]
Tr x $Si_{0.84}$	0.26[bc]	0.36[cd]	0.37[de]	1.00[de]
Tr x $Si_{1.26}$	0.27[bc]	0.37[cd]	0.36[de]	1.00[de]
Tr x $Si_{1.68}$	0.34[b]	0.42[bc]	0.48[bc]	1.23[bc]
Se x Si_0	0.29[bc]	0.41[bc]	0.39[d]	1.09[cd]
Se x $Si_{0.42}$	0.43[a]	0.55[a]	0.55[a]	1.53[a]
Se x $Si_{0.84}$	0.43[a]	0.52[ab]	0.47[bc]	1.41[ab]
Se x $Si_{1.26}$	0.43[a]	0.55[a]	0.46[c]	1.43[ab]
Se x $Si_{1.68}$	0.42[ab]	0.54[a]	0.52[ab]	1.49[a]
F-test	**	**	**	**
CV (%)	14.9	14.0	7.7	9.8

[1/] Means with the different letters in each column are significant differences according to DMRT at $P < 0.05$; ** is a significant difference at $P < 0.01$ probably level and ns is not significantly different; Tr and Se are the Tha Rua and Sena soil series, respectively

Effects of Si fertilizer on soil Si availability

The application of Si fertilizer was significantly different (P < 0.01) for water-soluble, exchangeable, available, and residual Si fractions in both soil series (Figure 1). The highest Si rate (1.68 g SiO_2/pot) was evidenced in the water-soluble fraction at 49.3 and 55.6 mg/kg; and 224 and 86.6 mg/kg in the exchangeable Si fraction in the Tr and Se soil series, respectively. For the available Si fraction, applying Si fertilizer at rates of 0.84 - 1.68 g SiO_2/pot in both soil series was not statistically different, where the highest value was presented in the treatment of Si fertilizer at the rate of 1.68 g SiO_2/pot, producing 274 and 142 mg/kg in the Tr and Se soil series, respectively. Similarly, the residual Si in both soil types was statistically different from the control (non-Si application). Applying Si fertilizer at the rate of 0.42 - 1.68 g SiO_2/pot in the Tr soil series was not significantly different, nor was the application of Si fertilizer at the rate of 0.84 - 1.68 g SiO_2/pot in the Se soil series. The highest amount of residual Si in each plot was displayed in the treatment of 1.68 g SiO_2/pot, producing 15,955 and 14,115 mg/kg in the Tr and Se soil series, respectively.

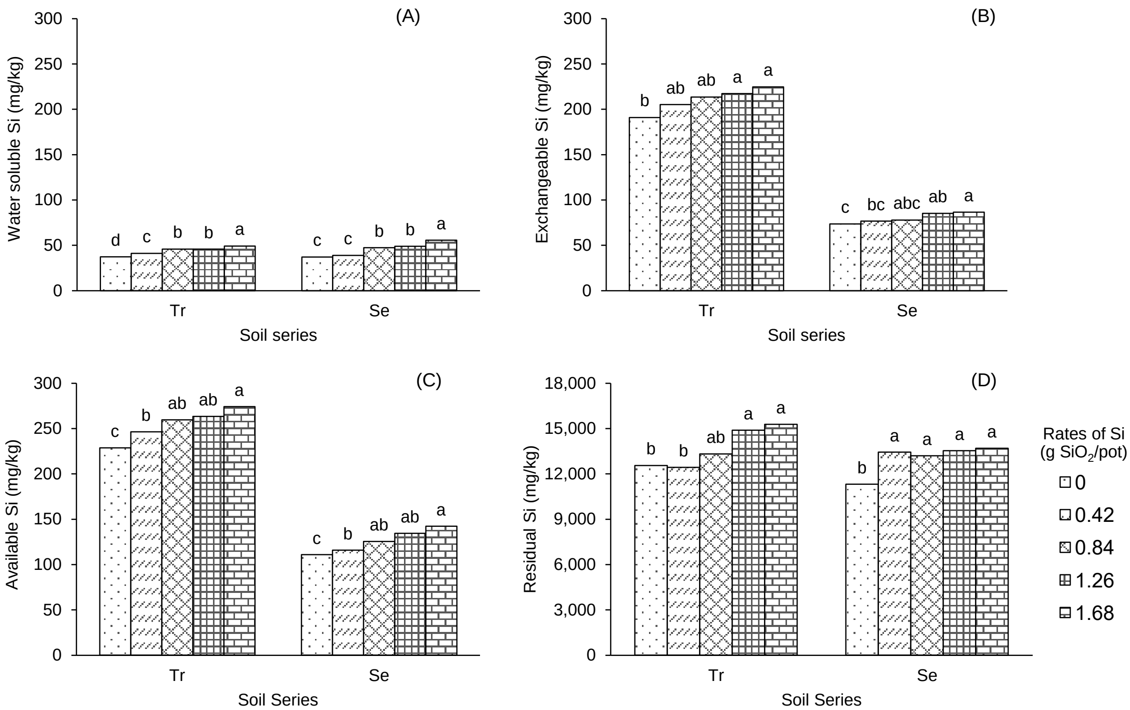

Figure 1. Effects of Si fertilizer applied on water-soluble (A), exchangeable (B), available (C) and residual Si (D) in two soil series after rice plantation. The lowercase letters above the bar indicated that significantly different among treatments by using DMRT at P < 0.05; Tr and Se are the Tha Rua and Sena soil series, respectively

The amount of Si in soil depends on several factors; such as parent material, utilization of an area for agricultural production, and the application of chemical fertilizer, specifically Si fertilizer. The results presented herein demonstrated that the application of Si fertilizer increased Si in all fractions of Si (water soluble (9.8 - 31.8 % and 5.1 - 49.8 %), exchangeable (7.3 - 17.5 % and 4.5 - 17.8 %), available (7.9 - 20.2 % and 5.2 - 29.1 %), and residual (1.0 - 22.9 % and 16.3 - 21.1 %)) in the Tr and Se soil series, respectively (Figure 1). Schaller *et al.* (2021) studied Si cycling in soil and reported that the application of Si fertilizer (silicic acid, potassium silicate, wollastonite, and steel slag) induced an increase in soil Si, which was in accordance with the results herein. The application of Si fertilizer may change the proportion of Si in soil in the form of silicic acid polymerization and de-polymerization, due to the increase in the concentration of silicic acid in the soil solution (Schaller *et al*., 2021). Yang *et al.* (2020) studied Si fractions in forest soil and reported that Si in soil presented a crystalline fraction of 97.7 - 98.5 %, whereas non-crystalline fractions (summation of dissolved and bioavailable, organic matter bound, pedogenic oxides/hydroxides, chemisorbed Si, and amorphous Si) ranged from 1.5 - 2.3 %. Our results, similar to that reported by Yang *et al.* (2020) expressed that the summation of dissolved and bioavailable Si in the soil was 1.74 - 1.94 and 0.85 - 1.03 % and that the residual fractions of Si were 98.06 - 98.26 % and 98.97 - 99.15 % in the Tr and Se soil series, respectively (Figure 1). The results indicated that the bioavailability of Si in both soil series was very low as compared to the residual Si fraction, as the majority of Si in the soil was present in Si compounds (quartz, crystalline silicate minerals, silicate clays, and amorphous silica compounds) rather than soluble Si (mono-silicic acid and polysilicic acids) (Sailaja *et al*., 2019).

Conclusion

In the study herein, soil type (Tr and Se) was an important factor supporting the growth and yield of rice. Leaf greenness, number of panicles per tiller, and rice yield were higher in soil with high fertility, the Se soil series versus soil with a high Si content, the Tr soil series. The application of Si fertilizer at higher rates (1.26 - 1.68 g SiO_2/pot) reduced grain yield, particularly in the Se soil series, however, when applied at a lower rate (0.42 g SiO_2/pot), rice yields increased. Notably, increases in Si fertilizer rates correlated to increases in Si uptake in all plant tissues; as well as increases in various Si fractions (water soluble, exchangeable, available, and residual Si). Our results determined that the application of Si fertilizer at the rate of 0.42 g SiO_2/pot was the optimal rate for rice production, specifically in soil with low available Si.

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