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Optimizing Silicon Application to Improve Growth, Grain Yield, and Nutrient Uptake of *indica* Rice (*Oryza sativa* cv. Bw 367)

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ABSTRACT

The rice plant accumulates silicon (Si) in greater quantity, which varies among the rice genotypes. This study was conducted to determine the optimum fertilization rate and its effect on growth, yield, yield attributes, and soil nutrient uptake. Six different silicon dioxide (SiO_2) rates, including 0, 50, 75, 100, 125, and 150 kg SiO_2/ha, were applied initially. The optimum rate of SiO_2 was obtained by statistical analysis, utilizing the analysis of variance (ANOVA) and Duncan's Multiple Range Test (DMRT) to separate the means. The results showed that shoot dry weight and plant height were significantly affected by Si fertilization. The highest Si tissue concentration of 395.27 µg/100 mg was recorded in 100 kg SiO_2/ha treated plants, and their potassium, phosphorous, silicon, and magnesium uptakes were increased by 2, 1.3, 11 and 1.8 folds, respectively. Further, in yield attributes, 32 and 52% increments and a 30% decrease were observed in the total number of grains, filled grains, and unfilled grains per panicle, respectively, and were not significantly different from those observed in 125 kg SiO_2/ha rate. The highest grain yield of 104.6 g/pot was obtained with 100 kg SiO_2/ha level of Si fertilizer, and it was statistically at par with the yields obtained with 125 kg SiO_2/ha. The quadratic function found the rate of Si fertilizer for optimum grain yield (100.5 g/pot) as 115 kg SiO_2/ha;

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thus, it could be concluded that *indica* rice genotypes need to be fertilized with 115 kg SiO_2/ha for optimum yield for higher growth and nutrient uptake.

Keywords: Plant nutrients, silicon accumulation, silicon requirement, yield attributes

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INTRODUCTION

Rice is the primary source of daily calories and a staple food for nearly three billion of the world population, with Asian countries being the greatest consumers. A yield increase of around 50% in major food crops, including rice, has been projected to support the anticipated population by 2050 (Godfray et al., 2010). Therefore, all the rice-producing countries need to be lined up to increase production. Silicon fertilization has been a common practice among the various approaches to increase rice yield. Silicon as a nutrient has multifaceted benefits. Silicon nutrition in the plant has elucidated the beneficial effects of Si on growth and yield improvements in rice plant and its proactive role in mitigating the wide range of abiotic stresses, including drought, salinity, heavy metal toxicities, and biotic stresses, such as pest and disease infestations (Ma & Yamaji, 2006). Silicon enhances the rice plant growth determinants: plant height and shoot weight (Mahendran et al., 2021) and yield parameters, including total grains/panicle, filled grains/panicle, and 1,000 grains weight (Cuong et al., 2017). Moreover, using Si is a high-quality element to improve the productivity in rice lands toward ecologically green agriculture (Liang et al., 2006). Despite the abundance of Si in soil, naturally, the plant-available form of Si in heavily weathered soils in tropical and sub-tropical regions is particularly poor due to fixation with other compounds (Raven, 2003). Furthermore, in paddy lands, plant-available Si greatly decreases with repeated cultivation of high-yielding rice genotypes as a monocrop (Ning et al., 2017) and inadequate Si uptake decreases the rice yield and quality (Jinger et al., 2017). Approximately 20 kg SiO_2/hm^2 is taken up by each 100 kg of brown rice from the soil at each harvest (Song et al., 2016), emphasizing the need for exogenous Si application to increase the readily available Si in the soil and for sustainable rice production.

The beneficial effects of Si application on paddy production are related to the accumulated Si in the epidermal tissues. Plants must accumulate a higher amount of Si to obtain its benefits. Commonly, Si deposition occurs in leaves, roots, sheaths, and hulls of the cell walls, making the rice plant more resistant to pest and disease attack, unfavorable abiotic factors, and making the plant stem stronger to resist lodging (Ma & Yamaji, 2006). There is a considerable variation in Si absorption and accumulation in plants depending on the species and the genotypes in the same species. Rice is a heavy Si accumulator which shows wide genotypic variation in tissue Si content (Kim et al., 2012; Ma et al., 2006). Previous studies showed that subspecies *indica*-type rice genotypes significantly vary in the accumulation of Si

(Rupasinghe et al., 2021; Swain et al., 2016). Furthermore, Si concentration in shoots significantly differs between the *indica* and *japonica* genotypes (Gaur et al., 2020; Mitani & Ma, 2005). The Si requirement varied with the yield potential of the rice variety (Gill et al., 2007). Rice genotype Bw 367 is high yielding Si responsive having 105 days maturity period, and a popular short grain *indica* rice genotype grown in Sri Lanka.

Although much research has focused on Si nutrition in *japonica* rice, Si nutrition in *indica* rice genotypes has been sparsely studied. Particularly, data on plant growth performances, including physiological changes, nutrient uptake, and yield performance with the application of Si to *indica* rice genotypes, are inadequate. Therefore, the following experiment was carried out to identify the optimum Si requirement for the maximum yield and to observe the effects of Si on plant nutrient uptake and growth of *indica* rice for sustainable rice production.

MATERIALS AND METHODS

Plant Materials and Growing Conditions

A pot experiment was conducted in a plant house at the Universiti Putra Malaysia (UPM) with the test rice genotype Bw 367. It is a Si-responsive rice genotype, which showed the highest growth in nutrient solution fortified with 2mM Si (Sigma Aldrich, Germany) (Rupasinghe et al., 2021). Healthy and uniformed seeds of Bw 367 rice genotype obtained from the Rice Research and Development Institute (RRDI), Sri Lanka, were taken, and 10% hydrogen peroxide (H_2O_2) (Sigma Aldrich, Germany) was sprayed with aiming the surface sterilization of seeds. After 10 min, treated seeds were thoroughly rinsed with distilled water for few times. Then seeds were soaked in distilled water for 24 h, followed by incubating in the dark for another 48 h in a Petri dish lined with a moist filter paper to induce germination (Ullah et al., 2017). The pre-germinated seeds were then sown in the pots containing 9 kg of soil. Four seedlings maintained in each pot until harvest, were healthy and uniformly grown. Muriate of potash (MOP, 60% potassium oxide [K_2O], Cap Segi Tiga, Belarus), triple super phosphate (TSP, 45% phosphorous pentoxide [P_2O_5], ZZ International, China), and urea (46% nitrogen [N], Agrenas, Malaysia) were uniformly applied at the rate of 110, 55, 100 kg/ha, respectively. All experimental units were treated alike with other agronomic practices as well. One of our previous studies identified the optimum Si concentration for the growth of test rice genotype in a hydroponic media as 2 mM (Rupasinghe et al., 2021). Six Si levels as 0, 50, 75, 100, 125, and 150 kg SiO_2/ha were formulated as treatments. Silicon was applied as a basal dressing to each pot (Ullah et al., 2017). The experiment was laid out in a randomized complete block design (RCBD) with three replicates per treatment.

Soil Analysis

Soil for the study was collected representing the plow depth (0-20 cm) from a paddy land in Sekinchan, Malaysia (3^o 6’ 19.3” N, 101^{o}28’3.5” E). Then the soil was air dried and sieved using a 2-mm sieve. The initial soil’s important physical and chemical characteristics were determined and presented in Table 1. Standard analytical methods were followed to characterize the soil. Electrical conductivity (EC) and soil reaction (pH) were measured using soil: water ratio of 1: 5 and 1: 2.5, respectively, by using an electrical conductivity meter (Mettler Toledo SevenEasy™ Conductivity Meter S30, New Zealand) and pH meter (Model Metrohm 827, USA). Organic carbon content was estimated using the Walkley and Black (1934) procedure. Exchangeable magnesium (Mg) and potassium (K) in soil were extracted using 1M ammonium acetate, pH 7 solution, and measured by atomic absorption spectroscopy (AAS) (AAnalyst 400, PerkinElmer, USA). Available phosphorus was measured using Bray and Kurtz’s (1945) method. Available Si (AvSi) in soil was estimated by the method described by Korndörfer et al. (2004).

Table 1
Important physicochemical characteristics of soils used in this study

Parameter	Value
Soil pH	6.16
Electrical conductivity (dS/m)	0.45
Available phosphorus (mg/kg)	88
Organic carbon (%)	1.7
Exchangeable potassium (mg/kg)	64.1
Cation exchangeable capacity (meq/100 g)	2.7
Available Si (mg/kg)	47.4
Texture	Clay
Sand (%)	0.95
Silt (%)	33.73
Clay (%)	65.32

Plant Nutrient Analysis

Straw samples were oven-dried at 80 °C and ground to a fine powder to analyze the nutrient content of phosphorus (P), K, Mg, and Si. P, K, and Mg were extracted using the dry ashing method (Miller, 1998). Briefly, 0.2 g of finely ground plant material was taken into an ashing tube and heated in a muffle furnace for complete ashing under 500 ºC overnight. After cooling the ashing bottles, two drops of deionized water were carefully added to wet the ash. Then 0.5 ml of digestion mixture (25 ml concentrated nitric acid [conc. HNO_3] + 25 ml concentrated hydrochloric acid [conc. HCl] made to 100 ml final volume with distilled water) was added into the ashing bottle, followed by evaporating completely on the hot plate under low heat with shaking the mixture. Subsequently, 10 ml of 0.05N HCl was added to the contents and warmed gently to dissolve the residue. Finally, the mixture was vortexed. Phosphorus content in the plant extract was then determined as described in the molybdenum yellow method (Jackson, 1973) using the spectrophotometer (UV-1700 PharmaSpec, Shimadzu Corporation, Japan) at 420 nm wavelength. Magnesium and K in the extracts were measured using the AAS after suitable dilution with distilled water. Silicon was extracted by adopting the modified auto-clave digestion method (Elliott & Snyder, 1991). A plant sample of 100 mg was digested with 2 ml of 50% H_2O_2 and 3 ml of 50% sodium hydroxide (NaOH) in an autoclave under the pressure of 103 kPa for 30 minutes. After extracting Si, the colorimetric molybdenum method was followed to determine the Si concentration by measuring the absorbance at 620 nm using a UV Vis spectrophotometer (UV-1700 PharmaSpec, Shimadzu Corporation, Japan). All the chemicals used were analytical grade with a purity of 99.9% from Sigma Aldrich (Germany).

Growth and Yield Component

Plant height (cm) was recorded at the harvesting stage (105 days). After separating the grains, the straw was dried at 80 ºC in an oven to a constant weight (48 h) to get the dry weight (g). A number of productive tillers/plants was recorded in each pot. Five panicles of each treatment were randomly selected and counted for total grains/panicle, total filled grains/panicle, total unfilled grains/panicle, and 1,000-grain weight (g) was determined. Finally, pot yield (g) was measured and adjusted to the 12% moisture level.

Determination of Chlorophyll Content in Plant Tissues

The method explained by Coombs et al. (1985) was applied to determine the chlorophyll content. Briefly, a cork borer was used to take four leaf discs of 4 cm^2 from the fully opened third leaf from the top at the panicle initiation stage. Leaf discs were immediately transferred into a glass bottle containing 20 ml of 80% acetone (Sigma Aldrich, Germany) and covered with aluminum foil. Immediately, the bottle was placed in the dark at room temperature for three days until the green color was completely bleached out, confirming the pigments were fully extracted from the leaf discs. Finally, 3.5 ml of the extracted solution was collected in a cuvette to determine the chlorophyll absorbance. The peak absorbance of both chlorophyll *a* and chlorophyll *b* was assessed at two different wavelengths: 664 and 647 nm, respectively, using a spectrophotometer (Cecil, CE1011, 1000 series, United Kingdom). The total amount of chlorophyll was then calculated as follows (Coombs et al., 1985).

Chlorophyll a content (mg/cm^2 fresh leaf) = 13.19 (A664 – 2.57 (A647) [1]

Chlorophyll b content (mg/cm^2 fresh leaf) = 22.1 (A647) – 5.26 (A664) [2]

Total chlorophyll content (mg/cm^2 fresh leaf) = 3.5 (Chlorophyll a + Chlorophyll b)/4 [3]

Where A647 and A664 are the solution's absorbance at 647, and 664 nm, respectively, and 13.19, 2.57, 22.1, and 5.26 are the absorbance coefficients, 3.5 is the total volume used in the analysis (ml), and 4 is the area of the whole disc (cm^2) used.

Data Analysis

The data were statistically analyzed by adopting a two-way analysis of variance (ANOVA) using the Statistical Analysis

System (SAS) (version 9.4) (SAS Institute, USA). Duncan's multiple range test (DMRT) at $p < 0.05$ was used to separate means when the effects of treatments were significant. The optimal level of Si fertilizer for maximum grain yield was determined using quadratic regression (Cuong et al., 2017). Finally, Pearson's correlation study was used to find the relationship between Si uptake and selected parameters.

RESULTS

Changes in Plant Available Silicon in Soil with Silicon Fertilization

Based on the critical level of Si in the soil, about 40 mg/kg (Nagula et al., 2015), the investigated soil possesses Si concentration of less than the critical level for plant absorption (Table 1). As expected, higher rates (100–150 kg SiO_2 /ha) of Si fertilizer have significantly released a higher content of AvSi (Figure 1). At the harvesting stage, this value in soil increased with increasing Si rates, and 100–150 kg SiO_2/ha Si rates provided the AvSi content higher than the critical level for rice. However, there was no significant difference in this value for the rates greater than 100 kg SiO_2 /ha.

Effect of Different Rates of Silicon on Growth Parameters

The Si fertilization significantly increased both plant height and the shoot dry weight at the harvesting stage ($p < 0.05$). Among the Si fertilization rates, 100 kg SiO_2/ha soil fertilization rate resulted in the tallest plant at 127 cm. The control pot without Si had the shortest plant height of 113.3 cm. However, the plants fertilized with higher Si rates of 125 and 150 kg SiO_2/ha were shorter in height than 100 kg SiO_2/ha (Figure 2a). Furthermore, the plant achieved its highest relative dry matter accumulation of 52% when Si was fertilized at 100 kg SiO_2/ha, followed by 125 kg SiO_2/ha (Figure 2b).

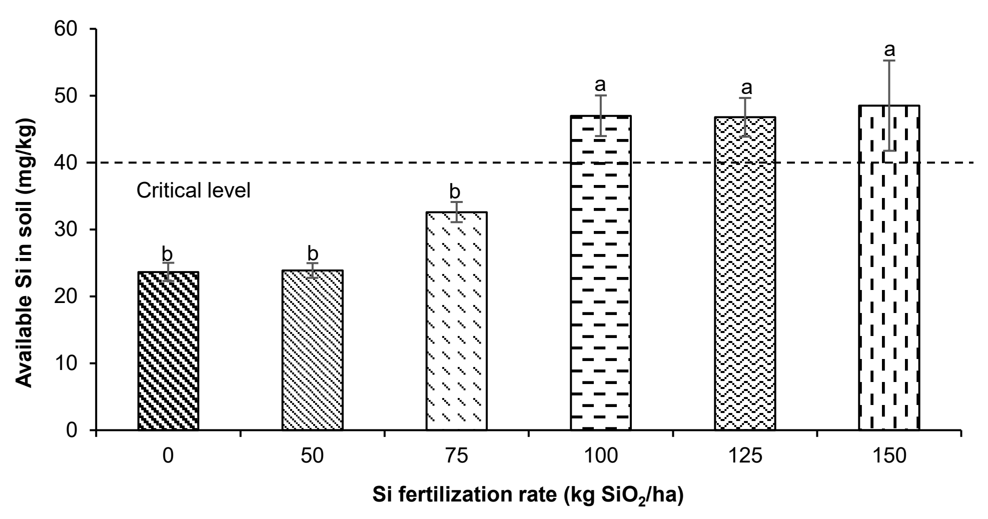
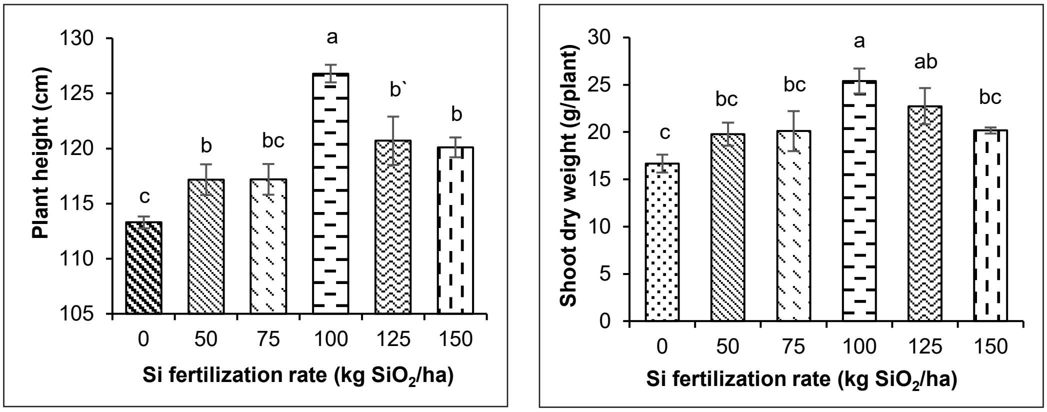


Figure 1. Available Si in the soil after harvest for each Si fertilization rate
Note. Means with the same letters are not significantly different ($p < 0.05$) using DMRT



(a) (b)

Figure 2. (a) Plant height and (b) shoot dry weight at harvesting stage with different rates of Si fertilization
Note. Means with the same letters are not significantly different ($p < 0.05$) using DMRT

Effects of Different Rates of Silicon on Biosynthesis of Chlorophyll

The biosynthesis of chlorophyll pigment was significantly affected by Si fertilization. The gradual and significant increase in total chlorophyll content was observed with the increasing rate of Si applied up to the rate of 125 kg SiO_2/ha and then decreased with a further increase of Si (Figure 3). The addition of Si fertilizer has increased the total chlorophyll content by 35–65% over the control, and the maximum was recorded in 125 kg SiO_2/ha treated plants. However, it was not significantly different from 100 kg SiO_2 /ha treated plants.

Effect of Different Rates of Silicon on Tissue Silicon Concentration

The significant differences ($p < 0.05$) in Si concentration were observed in tissues

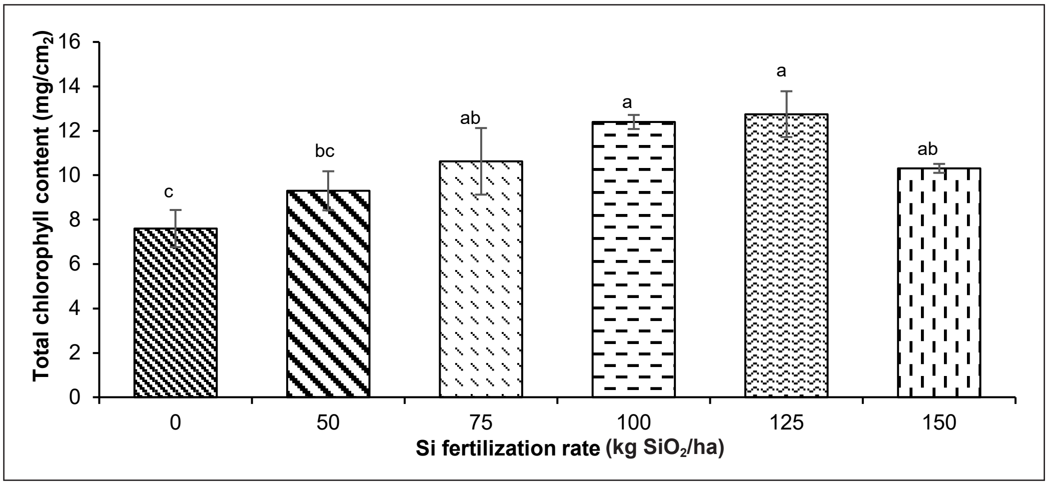


Figure 3. Total chlorophyll content at the flowering stage with different rates of Si fertilization
Note. Means with the same letters are not significantly different ($p < 0.05$) using DMRT

raised with different Si rates (Figure 4). There were no significant differences between Si rates of 100 and 125 kg SiO_2/ha as well as between 50 kg SiO_2/ha and control on tissue Si concentrations. The lowest Si concentration of 54.5 µg/100 mg was observed in the control, while the highest Si concentration of 395.3 µg/100 mg was observed at the Si rate of 100 kg SiO_2/ha, which was statistically similar to the rate of 125 kg SiO_2/ha. Almost 2, 3.4, 7.25, 6.7, and 5.2 folds more Si was accumulated in the shoot tissues of plants grown under 50, 75, 100, 125, and 150 kg SiO_2/ha treatments, respectively when compared to the control.

Effects of Different Silicon Rates on Silicon Uptake

In Bw 367, significant differences were observed under Si uptake in varied levels of Si fertilization (Figure 5). The Si uptake ability of a plant is a genotypic character

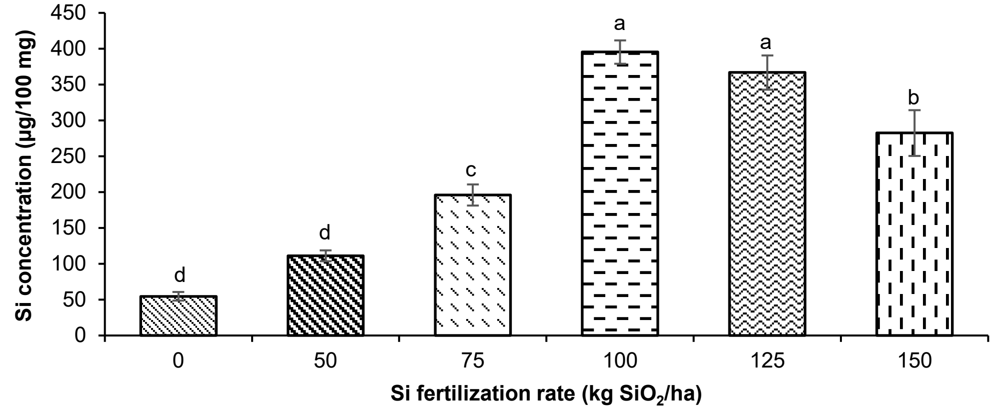


Figure 4. Silicon concentration in tissues at the harvesting stage with different rates of Si fertilization
Note. Means with the same letters are not significantly different ($p < 0.05$) using DMRT

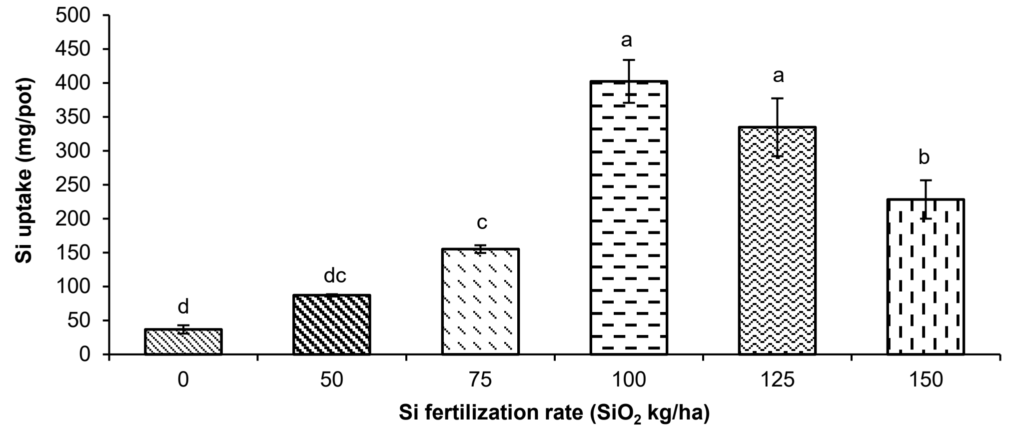


Figure 5. Total silicon uptake at the harvesting stage with different rates of Si fertilization
Note. Means with the same letters are not significantly different ($p < 0.05$) using DMRT

(Rupasinghe et al., 2021; Swain et al., 2016). A gradual and several folds increase in relative Si concentration was observed in shoots with increasing rates of Si supplied in the root medium. However, Si uptake was significantly decreased when applying the highest rate of Si. The highest amount of Si uptake (402.4 mg/pot) was observed in plants treated with 100 kg SiO_2/ha, and it was statistically similar to plants treated with 125 kg SiO_2/ha.

Effects of Different Silicon Rates on Phosphorous Uptake

The current results found that the P uptake in rice plants significantly varied depending upon the variation of Si application (Figure 6). It was noticed that P accumulation was significantly higher in Si fertilized plants than in Si non fertilized plants. Further, a significant increase in P accumulations was observed with the increased level of Si application. Compared to the control, plants treated with the 100 kg SiO_2/ha treatment resulted in a 107% increase in P uptake, indicating that rice crops in Si-fertilized soil had a greater response to P nutrition.

The present study showed that plants grown using 100 and 125 kg SiO_2/ha Si treatments recorded a significantly high yield have enhanced accumulation of Si and P in their tissues.

Effects of Different Silicon Rates on Potassium Uptake

Different Si rates had a significant ($p < 0.05$) effect on K uptake by rice shoots (Figure 7). An increase in applied Si rate resulted in increased K absorption and accumulation in shoots, consequently increasing the dry weight. However, K was mostly accumulated in the shoots of Si-treated plants when applied at a rate of 100 kg SiO_2/ha, which was approximately 1,912 mg/pot and was twofold higher than in Si-untreated plants. However, an increase of Si at 125 and 150 kg SiO_2/ha rates tend to decrease the K uptake but is not significantly different with 100 kg SiO_2/ha application.

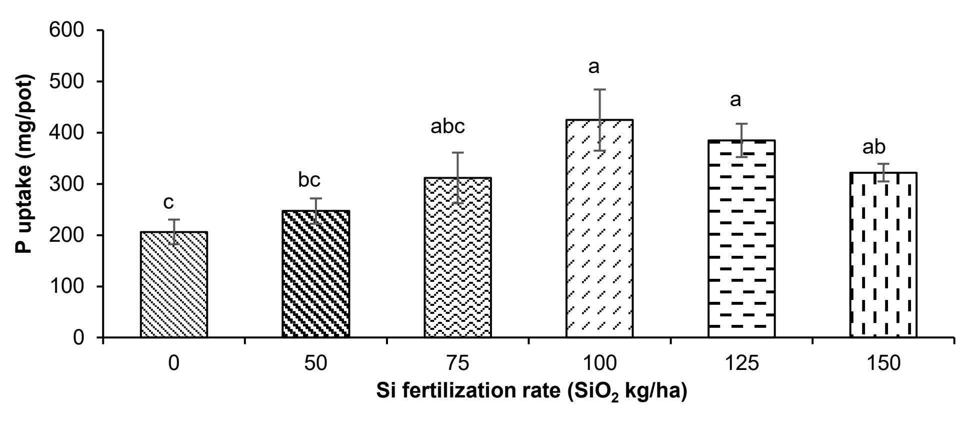


Figure 6. Total phosphorous uptake at the harvesting stage with different rates of Si fertilization
Note. Means with the same letters are not significantly different ($p < 0.05$) using DMRT

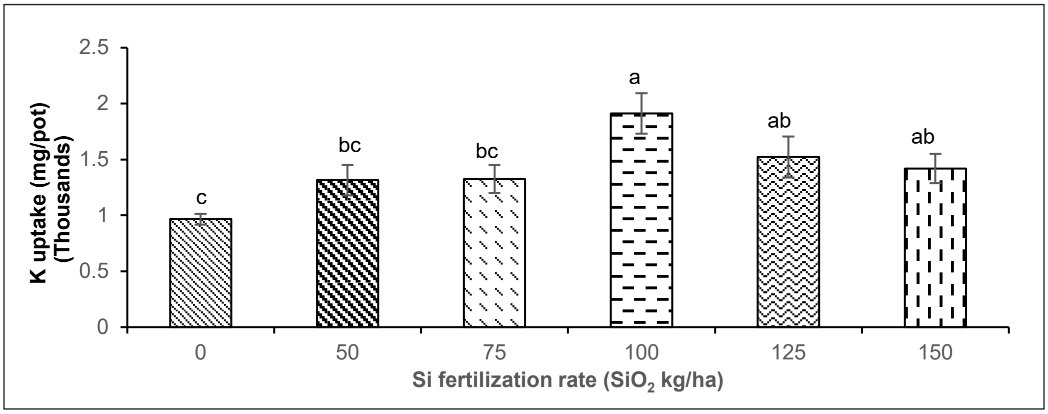


Figure 7. Total potassium uptake at the harvesting stage with different rates of Si fertilization
Note. Means with the same letters are not significantly different (p < 0.05) using DMRT

Effects of Different Silicon Rates on Magnesium Uptake

Magnesium uptake of rice plants exposed to the different rates of SiO_2 (50-150 kg SiO_2/ha) was significantly increased (p < 0.05) in comparison to the control. Applied Si rate increased Mg uptake gradually but then decreased at the highest rate of Si concentration applied (Figure 8). Mg uptake increased from 11% to 75% in Si fertilized plants compared to the control. The highest amount, 291.72 mg/pot of Mg, was accumulated in plants, which received Si at the rate of 100 kg SiO_2/ha, and it was statistically similar to the rate of 125 and 150 kg SiO_2/ha.

Effect of Silicon on Yield Attributes of Rice

A productive tiller is one of the important yield-determining parameters in rice. However, in this research, regardless of

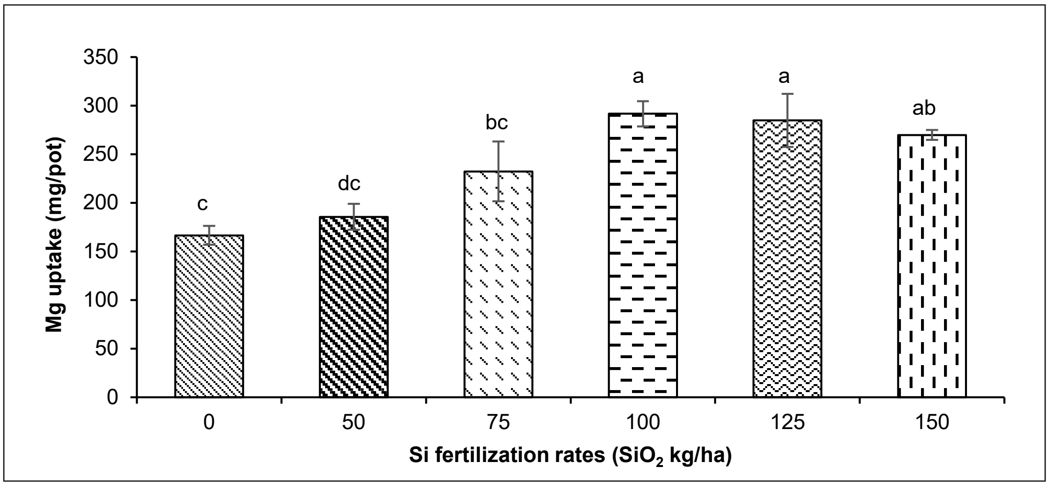


Figure 8. Total magnesium uptake at the harvesting stage with different rates of Si fertilization
Note. Means with the same letters are not significantly different (p < 0.05) using DMRT

the six different Si fertilizer treatments, rice plants produced the statistically same number of productive tillers (Table 2).

The number of filled grains/panicle is another yield-determining component in rice, and it was significantly affected by the application of Si (Table 2). All the Si-treated rice plants yielded a significantly higher amount of filled grains than the control plants. This study showed that filled grains/panicle increased with increasing of Si rate up to 125 kg SiO_2/ha. The highest mean number of filled grains/panicle (343) was produced by applying Si at the rate of 100 kg SiO_2/ha, closely followed by the rate of 125 kg SiO_2/ha (340). The filled grains/panicle increased with the application of Si fertilizer at 100 kg SiO_2/ha over the control (0 kg SiO_2/ha) was about 51%, and it was a remarkable improvement in Si application which impressively indicated the yield improvement.

Silicon has a positive effect on the grain filling of rice, resulting in a reduced number of unfilled grains/panicle. According to the results, 30% of unfilled grain reduction was observed by applying Si fertilizer at the rate of 100 kg SiO_2/ha, which was statistically similar to 125 kg SiO_2/ha. The highest number of unfilled grains/panicle of 70 was developed in the Si untreated plants confirming the positive effect of Si on the formation of filled grains. Among the applied levels of Si, 50, 100, and 125 kg SiO_2/ha recorded the lowest number of unfilled grains, while filled grains were highest only in the rates of 100 and 125 kg SiO_2/ha.

Significant differences in the total number of grains/panicle were seen in response to the enforced Si treatments. Total grains/panicle of 100 and 125 kg SiO_2/ha fertilized plants recorded the significantly highest number of grains, amounting to 392, following the same pattern as the number of filled grains/panicle. Another important yield component in rice is the 1,000-grain weight. However, it is more specific to the genotype than a response to fertilization (Cox & Smith, 2019). As demonstrated in Table 2, this study also found that the applied Si on 1,000-grain weight was non-significant over the control.

Table 2
Yield components of rice with different rates of silicon fertilization

Si fertilization rate (kg SiO_2/ha)	Productive tillers/panicle	Filled grains/ panicle	Unfilled grains/ panicle	Total grains /panicle	1,000-grain weight (g)
0	9 ± 0a*	226 ±11c	70 ± 5a	296 ± 12d	14.7 ± 0.27a
50	8 ± 0.57a	259 ± 11bc	49 ± 3c	308 ± 8dc	14.23 ± 0.23a
75	8 ± 1.2a	292 ± 6b	63 ± 4ab	356 ± 4ab	14.15 ± 0.52a
100	8 ± 0.33a	343 ± 10a	49 ± 8c	392 ± 11a	14.57 ± 0.03a
125	8 ± 0.88a	340 ± 10a	49 ± 5c	389 ± 14a	14.23 ± 0.43a
150	9 ± 0.33a	293 ± 15b	52 ± 6bc	345 ± 16bc	14.87 ± 0.28a

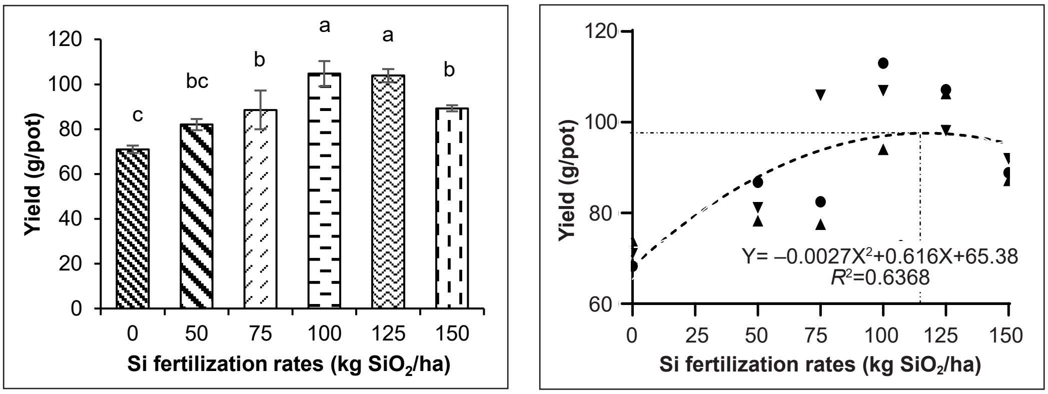
Note. Means with the same letters across the column are not significantly different ($p < 0.05$) using DMRT
* ± value indicates the standard error of the mean (n=3)

Effect of Silicon on Grain Yield of Rice

The grain yield of the Bw 367 genotype was significantly affected by the varied level of the added Si (Figure 9a). The highest pot yield (104.6 g/pot) was recorded in the plants fertilized with 100 kg SiO_2/ha, and it was on par with the pot yield of plants fertilized with 125 kg SiO_2/ha rate. The relative grain yield of 100 kg SiO_2/ha treatment was 47% higher than the control. Same as the other tested parameters, the highest rate of Si yielded a significantly lower yield than that of the 100 and 125 kg SiO_2/ha treatments.

Correlation Analysis

The correlation study was used to find out the relationship between the tested parameters (Table 3). Plant available Si in the soil was increased with the applied Si rates (Figure 1), and rice plants adsorbed more Si when Si fertilizer was supplied



(a) (b)

Figure 9. Grain yield with different rates of Si fertilization: (a) Yield at different Si rates; and (b) Si rate required for the optimum level of the yield of Bw 367 genotype

Note. Means with the same letters are not significantly different ($p < 0.05$) using DMRT

Table 3

Correlation between available silicon in soil and other parameters

Parameter	SiU	PU	KU	MgU	Chl	SDW	AvSi
PU	0.46						
KU	0.59*	0.92**					
MgU	0.49*	0.89**	0.82**				
Chl	0.77**	0.88**	0.82**	0.80**			
SDW	0.63*	0.81**	0.90**	0.68**	0.83**		
AvSi	0.57**	0.73**	0.64**	0.74*	0.78**	0.62*	
Y	0.71**	0.82**	0.86**	0.83**	0.88**	0.84**	0.76**

Note. * = Significant at p <0.05; ** = Significant at p < 0.01; SiU = Silicon uptake; PU = Phosphorous uptake; KU = Potassium uptake; MgU = Magnesium uptake; Chl = Chlorophyll content; SDW = Shoot dry weight; AvSi = Available silicon; Y = Yield

(Figure 4). Plant available Si in soil was strongly correlated with plant P uptake (0.73**), Mg uptake (0.74**), chlorophyll content (0.78**), and yield (0.76**) and moderately correlated with K uptake (0.64**) and Si uptake (0.57**). It is obvious that Si fertilization increases the available plant Si in the soil, and it improves the soil nutrient uptake as well as biosynthesis of chlorophyll in tissues. All these parameters are strongly correlated with the yield. Moreover, Si uptake was strongly correlated with shoot dry weight (r = 0.63$^{**)}$, yield (0.7**) and chlorophyll content (0.77**). However, the correlation between Si uptake and P uptake was not significant.

DISCUSSION

Various rates of SiO_2 fertilization resulted in a considerable rise in Si concentration in tissues as well as Si uptake. Increased Si uptake with Si fertilizer application could be attributed to the increased level of available Si in the soil and improved root systems, which could encourage the plant to absorb more Si from the soil solution (Pati et al., 2016). Despite the abundance of Si in the soil, plant-available Si in the soil solution is limited (Jawahar & Vaiyapuri, 2013). Therefore, exogenous Si application is required. Silicon fertilizer is applied to enhance the availability of monosilicic acid for plant uptake. However, available Si in soil was not significantly increased with Si fertilization beyond 100 kg SiO_2/ha. Silicon concentration in soil at 2mM Si is potentially the concentration of Si at which polymerization begins even in soil (Fortunato et al., 2015). As the rate of Si addition increases, the monosilicic acid concentration begins to polymerize, forming polysilicic acid, which plants cannot absorb (Fortunato et al., 2015). Similarly, in this study, Si applied rates higher than 100 kg SiO_2/ha may have increased the Si concentration in soil by more than 2mM, leading to polymerization of Si. It could be the reason for no significance of AvSi concentrations even at higher Si application rates. Hence, the application of Si higher than the rate of 100 kg SiO_2/ha seems to be unproductive.

Endogenous Si in rice plants helps to increase the plant growth parameters, including plant height and shoot dry weight, as found in past research evidence (Cuong et al., 2017; Kim et al., 2012; Rupasinghe et al., 2021). The increase in plant height could be attributed to the rapid elongation of the stem caused by Si (Peera et al., 2014). Further, the synthesis of total chlorophyll (chlorophyll *a* and *b*) content was enhanced with the applied Si and thereby increased the photosynthetic capacity of the rice plant. It may be due to the keeping of the leaf blade erect by the accumulated Si, thereby preventing the mutual shading of leaves and improving the light interception (Mauad et al., 2003). In addition, the application of Si significantly improved the uptake of P, K, and Mg alone with Si in the shoots of the rice plant, which is consistent with previous observations as well (Crooks & Prentice, 2017; Pati et al., 2016). Finally, it may be due to the enhanced nutrient availability in the soil. Soil Si enhances the nutrient availability in the soil and stimulates root growth (Swain & Rout, 2018), enabling increased nutrient absorption. With the presence of Si, potassium ions (K^+) are adsorbed onto the silica surface, increasing the availability for plant absorption. The increase in P uptake is due to the increased fertilizer use efficiency, which makes more P available for plant uptake (Subramanian & Gopalswamy, 1991). Accordingly, Si fertilizer improves plant growth caused of enhanced photosynthetic capacity and nutrient uptake. Magnesium is a constituent of chlorophyll molecule as a central atom in the structure. This study observed that the addition of Si improved chlorophyll synthesis, which could be resulted from the increased Mg uptake. In contrast, an inadequate level of Mg in photosynthesis reduces the dry matter assimilation in plant tissues (Tränkner et al., 2018).

Rice grain yield is influenced by the tillering capability of the plant, which is associated with the number of panicles per unit area (Efisue et al., 2014). However, Si fertilization did not affect the number of productive tillers per plant, which contradicts Hoseinian et al. (2020) and Pati et al. (2016), who found a considerable increase in productive tillers with Si application. The possible reason for the non-significance effect on a number of tillers is a genetic character, which hardly changed with the environmental effects.

In rice, key yield components are the total number of grains/panicle, the number of filled grains/panicle, the number of unfilled grains/panicle, and the 1,000 grains weight. Therefore, increasing these components and decreasing the number of unfilled grains/panicles have a direct influence on rice production. We discovered a positive response in the number of grains per panicle to applied Si, which agrees with Lavinsky et al. (2016), who mentioned that Si is an important factor in increasing the number of grains per panicle in rice. The grain yield of Si-treated plants was increased due to growth, photosynthesis capacity, and balanced nutrition improvements. Further, Matoh et al. (1991) observed that accumulating a large amount of Si in plant tissue reduces the loss of water, which helps to ease water stress in the plant.

A significant reduction in unfilled grain was observed as well in this study, and it could be attributable to better nutrition, increased metabolic activity, reduction in moisture stress, or a combination of these factors.

A positive response of filled grains per panicle to Si fertilizer was noticed in this study. This finding is consistent with that of Jawahar et al. (2015), who observed that Si fertilizer promotes carbohydrate assimilations in panicles, resulting in a higher number of filled grains per panicle. The number of filled grains in 100 kg SiO_2/ha treated plants was the highest owing to the greatest amount of Si uptake and dry matter assimilation at this Si applied rate.

The weight of 1,000 grains is a genotypic trait (Huang et al., 2013); hence it is less likely to be influenced by other factors. The Si fertilizer also had a non-significant influence on grain weight. These results are comparable to those of Mobasser et al. (2008), who found that adding Si to rice does not affect the 1,000 seed weight;

however, it is contradictory to the findings of Cuong et al. (2017) and Mahendran et al. (2021), who elaborated that using Si fertilizer enhanced rice grain weight. Even at the grain filling stage, Si treatment did not result in a substantial increase in grain size or weight (Kim et al., 2012), which further confirmed our results. With the provision of Si to the rice plant, Si has translocated inside the hull of the seeds as well as the kernel but may not be deposited continuously. Therefore, it would be advantageous to keep the grain size at its specific small size, especially in small grain genotypes like Bw 367, to maintain the consumers' preference. The results were consistent with Pati et al. (2016) and Prakash et al. (2011). The increases in grain yield in this study could be due to the positive effect of Si in increasing growth and yield determining characters, such as number of grains/panicle, number of filled grains/panicle, and reduction in unfilled grains/panicle. Simulation using a quadratic function suggests that the Si fertilization rate for optimum grain yield of rice was 115 kg SiO_2/ha (Figure 9b).

Most of the tested parameters recorded their significantly highest values at the rate of 100 kg SiO_2/ha. Applying Si above this rate was not beneficial for further improvement in growth and yield attributes. However, any toxic effect of Si was also not observed in the excess application of Si fertilization. It could be due to the polymerization of silicic acid. In the xylem, Si presents as silicic acid. However, when the Si concentration is higher than 2mM, silicic acid is polymerized to silica gel. Further, the polymerization process is aggravated by water loss (Ma & Yamaji, 2006).

CONCLUSION

Applied Si improved the tested *indica* rice plant growth, nutrient uptake, and yield. Therefore, all paddy lands need to be fertilized with Si prior to establishing the next crop to maintain the required level of available Si in soil for healthy and high crop production.

It can be recommended that applying Si at the rate of 115 kg SiO_2/ha was the optimum rate of Si fertilizer, which can provide the maximum yield under the glasshouse condition. Furthermore, the different Si fertilizer rates were tested on high-yielding rice genotypes. Thus, the optimal Si rate identified can be included in the general fertilizer recommendation for paddy cultivation. However, this value should be further tested in real field conditions.

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CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

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