Identifying suitable source and optimum rate of silicon in rice at Ganges Delta Coastal Zone Soils

Mohammad Asadul Haque
Patuakhali Science and Technology University
Md Jahiruddin
Bangladesh Agricultural University
Md. Islam (msaifulpstu@yahoo.com)
Patuakhali Science and Technology University
Md Fazlul Hoque
Patuakhali Science and Technology University
Md Baktear Hossain
Bangladesh Agricultural Research Council
Md Abdus Satter
Bangladesh Agricultural Research Council
Md Enamul Haque
Murdoch University
Richard William Bell
Murdoch University

Research Article

Keywords: Calcium silicate, chlorophyll, grain yield, silicon uptake, silicon use efficiency

Posted Date: June 27th, 2022

DOI: https://doi.org/10.21203/rs.3.rs-1723369/v1

Abstract

Purpose: Silicon established as a beneficial nutrient element especially for cereals, however it's suitable source and optimum rate of application as a chemical fertilizer still not recommended. The purpose of the study was to identify the suitable source and optimum rate of silicon for growing rice at Ganges delta coastal zone soils.

Methodology: Two similar succeeding field experiments: one at early monsoon season with T. Aus rice and another at monsoon season with T. Aman rice in 2021 were carried out using a two factor split plot design having replicated thrice. The first factor was three different sources of silicon (silicic acid, sodium meta silicate and calcium silicate) and second factor was seven rates of silicon (0, 1, 2, 5, 10, 20 and 40 kg Si ha^{-1}).

Results: Using a quadratic model the optimum rate of silicic acid, sodium meta silicate and calcium silicate were 32.2, 25.7 and 23.6 kg Si ha^{-1} for T. Aus rice, and 42.9, 25.8 and 24.5 kg Si ha^{-1} for T. Aman rice, respectively. Calcium silicate was the best source of silicon as it shows best response with smaller rates of silicon. Sodium meta silicate had the second and silicic acid had the lowest performance. Increasing Si rates progressively increases the Si content, Si uptake and chlorophyll content of rice.

Conclusion: Calcium silicate with 24 kg Si ha^{-1} is recommended for rice at Ganges delta coastal zone soils.

1. Introduction

Rice (*Oryza sativa* L.) next to wheat, the second most widely cultivated cereal crop in the globe (Rajamoorthy et al., 2015). It is the staple food for over half of the world's population. Despite recent increase in world rice production, another 25% increase in rice production would be needed to meet the foods of the flourished global human population by 2030, especially in the case of the inhabitants of the Ganges Delta. Although a difficult target to increase yield, rice production frequently hampered by adverse climatic conditions, soil and water salinity, tidal water flooding, drought, pest and disease incidence etc. Exogenous application of silicon (Si) might be a potential alternative for healthy and competitive growth of rice as well as sustainable food security (Ma & Yamaji, 2006; Singh et al., 2020).

Rice is considered as a strong accumulator of Si and it requires a considerable amount of Si for its growth, development and high production (Ma & Takahashi, 2002; Meena et al., 2014). Plants can accumulate Si with a range of 0.1 and 10% of their dry weight, but it vary considerably with species (Ma and Takahashi, 2002; Kuhla et al., 2021). Due to non-involvement in the plant metabolism, Si was not considered to be essential for growth of higher plants. Epstein and Bloom (2005) described new criteria for essentiality of nutrients for plant, thereafter Si was considered essential for higher plants.

Silicon fertilizer improves uptake efficiency of essential nutrients and alleviates mineral toxicity (Sahebi et al., 2015), aiding photosynthesis (Lavinsky et al., 2016), preventing lodging due to stress (Epstein, 1999), alleviating water stress (Agarie, 1998), enhancing tolerance of rice against diseases and insect pests (Cooke and Leishman, 2011; Liang et al., 2007). Moreover excess accumulation of Si don't interfere the growth and development of plants. It keeps the leaves, stems, and culms of plants more erect which facilitate the light distribution within the canopy (Epstein, 1999). Earlier study reported the beneficial role of Si for the increment of rice yield (Agostinho et al., 2017; Cuong et al., 2017; de Oliveira et al., 2019; Li et al., 2020; Siregar et al., 2021).

Next to oxygen, Si is the second most abundant element in the earth's crust (Haynes, 2014; Bhatt and Sharma, 2018). Silicon remains in the soil as mineral quartz and clay, but its concentration in available form (silicic acid; H_4O_4Si) is very low (Schaller et al., 2021). Rather readily plant available soil Si can transform to the intricate form of polymers (Epstein, 1999; Ma & Takahashi, 2002). Furthermore plant can't utilize total elemental percentage of Si present in the soil (Abdullah et al., 2021). Therefore, continuous cropping of land, high cropping intensity, inherently deficient soils or natural weathering can be causes of Si deficiency. The tropical and subtropical soils showed less Si availability; therefore, artificially applied Si to the soil will benefit for growth and development of rice crops (Abdullah et al., 2021).

Most of the research work on Si has been done under pot culture condition, in Ganges delta there was found no evidence of Si use for crop cultivation. A very few studies have been done to evaluate the suitable source and application rate of Si in rice at field condition. Some industrial byproducts with extremely high rates are used as a source of Si; chemical fertilizer source is ignored. There might have differences among different sources of Si for plant uptake. We hypothesized that application of Si in suitable source and optimum rate will improve crop yield, Si uptake and Si use efficiency in rice. The objective of the study was therefore, to identify the suitable source and rate of Si in improving crop yield and Si use efficiency in rice at Ganges delta coastal zone soils.

2. Materials And Methods

2.1 Location

Two similar field experiments: one at early monsoon season with T. Aus rice and another at monsoon season with T. Aman rice in 2021 were carried out at Ganges delta coastal zone soils. The T. Aus rice experiment has been carried out at farmer's field of Dumki upazila of Patuakhali district, Bangladesh which is typical of tidal non-saline area which located at 22.463042° north latitude and 90.396890° east longitude. The T. Aman rice experiment was conducted at Amtali upazila of Barguna district, Bangladesh located at 22.13141° north latitude and 90.22386° east longitude which represented the exposed saline coast (Sup. 1).

Sup. 1 Map of the study area: D-Dumki site (T. Aus rice) and A-Amtali site (T. Aman rice)

2.2 Field characteristics

The experimental field was medium high land in Agro-Ecological Zone (AEZ) 13, the Ganges Tidal Floodplain (FRG. 2018). The T. Aus rice field soil (0-10 cm) was silty clay loam (135 sand:525 silt:340 clay, g kg^{-1}) with pH (water) 6.1, EC (dS/m) 1.12, Walkley& Black organic carbon 5.5 g kg^{-1}, total N (Kjeldahl N) 0.47 g kg^{-1}, Olsen P 4.13 mg kg^{-1}, NH_4OAc exchangeable K 0.31cmol (+) kg^{-1} and $CaCl_2$ extractable S 17.5 mg kg^{-1}. The T. Aman rice field soil was loam (118 sand:646 silt:236 clay, g kg^{-1}) having soil characteristics such as pH 5.5, EC (dS m^{-1}) 2.37, organic carbon 4.71 g kg^{-1}, total N 0.49 g kg^{-1}, Olsen P 3.04 mg kg^{-1}, NH_4OAc exchangeable K 0.28 cmol (+) kg^{-1} and $CaCl_2$extractable S 43.5 mg kg^{-1}). Soil analysis was done following the methods outlined by Page et al. (1982).

2.3 Growing season weather condition

The maximum monthly average air temperature in the month of January was 31ºC (Sup. 2). From January maximum air temperature progressively increased with time. The month of May was the warmest month (35ºC); thereafter the maximum air temperature declined gradually. Similar trend was also found for minimum air temperature. The month of January, February, March and November was relatively rain free month. Although the month of December was supposed to be rain free but 87 mm rainfall was recorded. Maximum rainfall was occurred in the month of June (Sup. 2).

Sup. 2 Monthly climatic variables at the study site

2.4 Crop variety

The variety of T. Aus rice was BRRI dhan48 and T. Aman rice was BRRI dhan73. Both the rice varieties were released by Bangladesh Rice Research Institute (BRRI).

2.5 Treatment and design

The experiments were laid out in two factor split plot randomized complete block design model having replicated thrice. The first factor (Factor-a) was three different sources of silicon and second factor (factor-b) was seven rates of silicon. The sources of Si were distributed in the main plot and rates of Si were distributed in the sub plot. The sources of Si were silicic acid (H_2SiO_3), sodium meta silicate ($Na_2O_3Si\ 9H_2O$) and calcium silicate ($CaSiO_3$). The laboratory grade chemicals were used for each sources of Si. The rates of Si for each source were 1, 2, 5, 10, 20 and 40 kg ha^{-1} along with a control (no Si added). Therefore, there were sixty three unit plots in each experiment. The size of each experimental plot was 4´3m. The plots were surrounded by 30cm wide and 10cm high earthen bunds. One meter space was kept between adjacent blocks.

2.6 Experiment setup

Three ploughing and two leveling operations were done to prepare the experimental fields. The T. Aus and T. Aman rice were transplanted in puddle soil on 28 May 2021 at Dumki site and 02 September 2021 at Amtali site, respectively. For both the crops plant spacing was 20´20 cm. The twenty and thirty days old seedlings were transplanted for T. Aus and T. Aman rice, respectively. For both the rice crops 2-3 seedlings were transplanted per hill. Ten days after transplanting Furadan (5g) was applied in each crop to control stem borer infestation.

2.7 Fertilizer application

The rates of N, P and K were 75, 15 and 45 kg ha^{-1} in T. Aus rice and 80, 15 and 50 kg ha^{-1} in T. Aman rice, respectively. Fertilizer rates were obtained from Fertilizer Recommendation Guide (FRG 2018). The sources of N, P and K were urea, triple super phosphate (TSP) and muriate of potash (MoP), respectively. During final land preparation the TSP and MoP fertilizers were applied in each plot of the experimental field. Urea was applied in three equal splits at final land preparation, 20 and 32 days after transplanting (DAT) in T. Aus rice, and 10, 25 and 40 DAT in T. Aman rice. During urea fertilizer top dressing weeding was done in rice crops.

2.8 Irrigation

The T. Aus and T. Aman rice were grown under rainfed conditions. During growth period the T. Aus rice enjoyed tidal water flooding to some extent.

2.9 Data collection

The T. Aus rice was harvested on 22 August 2021 and T. Aman rice was harvested on 04 December 2021 at 80% maturity of grains. The grain and straw yield data was recorded by harvesting the central $4m^2$ area from each plot. Grain yield was expressed at 14% moisture content basis whereas straw yield was expressed on a sun-dry basis.

The crude silica content in grain, straw and flag leaf was determined following method described by Yoshida et al. (1976). Plant samples were digested in tri acid mixture of HNO_3, $HCLO_4$ and H_2SO_4 at a ratio of 5:2:1. One gram of dried and ground plant material was taken into a 50 ml Pyrex conical flask. Ten ml acid mixture was taken in the conical flask and allowed over night for predigestion. The samples were then digested in a hot plate. First few minutes the samples were digested at 100°C until frothing stops, then the samples were digested at 200°C until the mixture becomes clear. After cooling around 10 ml distilled water was added in conical flask. The content in the conical flask was filtered using an ashless Whatman42 filter paper. The filter paper and residue of the sample extract was dried in an oven at 80°C. The filter paper was charred in a muffle furnace for 2 hours at 550°C. After cool in a desiccator for at least 2 hours the weight of ash was determined. The crude silica content in the plant sample is then calculated using the following formula.

The leaf chlorophyll concentrations were determined at maximum growth stage of each crop. The third leaf from the top was used for chemical analysis of plant samples. Both chlorophyll-a and chlorophyll-b concentrations were determined following the method described by Coombs et al. (1985).

2.10 Statistical analysis

Statistical analyses were done using STAR (Statistical Tool for Agricultural Research) software version 2.0.1. The effects of different sources and rates of Si on grain yield, straw yield, yield components, and grain, straw and flag leaf crude silica content and leaf chlorophyll concentration were determined using a two-way analysis of variance (ANOVA) model (Split plot Randomized Complete Block Design). The differences between means were tested using the least significant difference (LSD) at the 95% confidence level. Microsoft Office Excel Worksheet software was used to prepare the graphs.

3. Results

3.1 Grain yield

The grain yield of T. Aus rice (early monsoon rice) was significantly influenced by sources and rates of Si application but the interactions between sources and rates were not significant (Table 1). Regarding sources of Si, the calcium silicate, sodium metasilicate and silicic acid recorded mean grain yield of 4.70, 4.58 and 4.44 t ha^{-1}, respectively (n=21) and all are significantly different with each other. Regarding the rates of Si, grain yield progressively increased with increase of the rate of Si and it varied from 4.20 to 4.82 t ha^{-1} over the treatments. The 20 kg Si ha^{-1} had the highest grain yield of 4.82 t ha^{-1} (n=9) although it was statistically similar with 5, 10 and 40 kg Si ha^{-1} rate.

The T. Aman rice (var. BRRI dhan73) grain yield was significantly influenced by different rates of silicon and the interactions between sources and rates of Si, but the single effect of sources of silicon was not significant. Over the rates of the Si the grain yield of T. Aman rice varied from 4.00 to 4.72, 3.78 to 4.37, and 3.81 to 4.81 t/ha in silicic acid, sodium meta silicate and calcium silicate, respectively (Table 1). The mean grain yield data of both T. Aus rice and T. Aman rice of each sources of Si against different rates of silicon were fitted well to the quadratic regression model of crop response curve (Fig. 1).

Table 1. Grain yield of T. Aus (var. BRRI dhan48) and T. Aman (var. BRRI dhan73) rice as influenced by different sources and rates of silicon

Fig. 1 Determination of optimum rate of Si for different sources of Si using quadratic equation in T Aus (var. BRRI dhan48) and T. Aman rice (var. BRRI dhan73)

3.2 Straw yield

Straw yield of both T. Aus and T. Aman rice didn't significantly influenced by different sources but in case of rates it was significant. However, none of the rice crops were significantly influenced by the interaction effect of sources and rates of Si. Increasing Si rate progressively increased the straw yield of both rice crops. The straw yield of T. Aus rice varied from 4.47 t ha^{-1} in control to 5.36 t ha^{-1} in 40 kg Si ha^{-1} rate. Regarding T. Aman rice straw yield varied from 4.18 to 4.94 t ha^{-1}; lowest was in control treatment and highest was in 20 kg Si ha^{-1} rate.

3.3 Number of grains $panicle^{-1}$

The number of grains $panicle^{-1}$ of T. Aman rice was significantly influenced by different sources of Si but it was not in T. Aus rice. In T. Aman rice calcium silicate had the highest number of grains $panicle^{-1}$, although it was statistically similar with sodium meta silicate. Regarding Si rates both the crops were positively responded with increasing rates of Si. Over the Si rates, number of grains panicle varied from 111 to 128 in T. Aus rice and 113 to 131 in T. Aman rice (Table 2). In T. Aus and T. Aman rice the highest number of grains $panicle^{-1}$ were produced in 20 and 40 kg Si ha^{-1} rate, respectively; although both the crops had statistically similar number of grains in 5 to 40 kg Si ha^{-1}. The interaction effects on this parameter were not significant.

Table 2. Effects of different sources and rates of Si on yield and yield parameters of T. Aus (var. BRRI dhan48) and T. Aman (var. BRRI dhan73) rice

3.4 Silicon content in plant

The Si content in grain, straw and flag leaf in both T. Aus and T. Aman rice were significantly varied by different sources and rates of Si but their interactions were not significant. Among the sources highest Si contents in T. Aus rice whole grain was found in calcium silicate (2.45%), second highest in sodium meta silicate (2.33%) and lowest in silicic acid (2.08%), respectively (Table 3). Similarly in T. Aman rice the whole grain Si content was found as 2.49, 2.15 and 1.86% in calcium silicate, sodium meta silicate and silicic acid, respectively (Table 3). Similar trend was also found in straw and leaf where calcium silicate, sodium meta silicate and silicic acid recorded straw Si content of 7.76, 8.21 and 8.50 % in T. Aus rice and that of 4.92, 5.81 and 6.00% in T. Aman rice, respectively; the same sources had leaf Si content of 11.5, 11.3 and 11.9 % Si in T. Aus rice, and 5.45, 7.95 and 8.26 % in T. Aman rice, respectively.

Across the sources of silicon, increasing rate of Si progressively increased the concentration of Si in grain, straw and flag leaf. Over the rates of the Si, at T. Aus and T. Aman rice the Si content varied from 2.09-2.50 % and 1.78-2.58 % in whole grain, 7.39-8.71% and 4.90-6.19% in straw, and 10.33-12.30% and 6.43-8.18% in flag leaf, respectively (Table 3). Every cases control treatment had the lowest and 40 kg Si

ha^{-1} treatment had the highest performance. Although most of the cases 20 and 40 kg Si ha^{-1} treatments had statistically similar Si contents.

Table 3. Effects of different sources and rates of Si on Si content of T. Aus (var. BRRI dhan48) and T. Aman (var. BRRI dhan73) rice

3.5 Silicon uptake

The grain, straw and total (grain + straw) Si uptake was significantly influenced by both source and rates of Si, but their interaction was not significant. Among the sources calcium silicate had the highest grain, straw and total Si uptake both in T. Aus (115, 434 and 549 kg ha^{-1}, respectively) and T. Aman rice (109, 279 and 388 kg ha^{-1}, respectively) (Table 4). Silicic acid had the significantly lowest Si uptake, whereas sodium meta silicate had intermediate Si uptake of silicic acid and calcium silicate.

For both T. Aus and T. Aman rice increasing Si rate progressively increased the grain, straw and total Si uptake of rice. At lower rates of Si (viz. 0-5 kg Si ha^{-1}) the rate of increment is higher than higher rate of Si application (viz. 10-40 kg Si ha^{-1} rate). At higher rates of Si application the Si uptake was rather statistically similar. In T. Aus rice over the rates of the Si application the Si uptake varied from 88 to 119 kg ha^{-1} in grain, 330 to 469 kg ha^{-1} in straw, and 418 to 588 kg ha^{-1} in total Si uptake (Table 4). Regarding T. Aman rice these values are ranged from 68.7 to 119.8 kg ha^{-1} in grain, 205.4 to 304.6 kg ha^{-1} in straw and 274.1 to 424.3 kg ha^{-1} in total uptake of Si (Table 4).

Table 4. Effects of different sources and rates of Si on Si uptake (kg ha^{-1}) of T. Aus (var. BRRI dhan48) and T. Aman (var. BRRI dhan73) rice

3.6 Agronomic Si use efficiency

Generally agronomic use efficiency was higher in lower rates of Si and was lower in higher rates. The agronomic Si use efficiency of sodium meta silicate had the highest in 1 kg Si ha^{-1} rate both in T. Aus rice and T. Aman rice; thereafter increasing Si rate the Si use efficiency was gradually decreased (Fig. 2). However, upto 5 kg Si ha^{-1} rate in T. Aman rice the performance of sodium meta silicate was better than other two sources of Si. Regarding silicic acid and calcium silicate up to 2 kg Si ha^{-1} rate agronomic efficiency increased and attained at it's peak, thereafter increasing Si rate agronomic use efficiency gradually decreased. Regarding silicic acid and calcium silicate highest use efficiency was found in 2 kg ha^{-1} rate, and thereafter, increasing Si rate the agronomic use efficiency was gradually decreased. The results clearly evidenced that sodium meta silicate had higher efficiency at 1-5 kg Si ha^{-1} rate but for calcium silicate higher efficiency was found in 2-10 kg Si ha^{-1} rate.

Fig. 2 Agronomic Si use efficiency of different Si-sources (kg grain kg^{-1} added Si) in T. Aus (var. BRRI dhan48) and T. Aman (var. BRRI dhan73) rice (Vertical bar indicates standard error of means; n=3)

3.7 Recovery efficiency

The recovery efficiency of silicic acid, sodium meta silicate and calcium silicate at 1 kg Si ha^{-1} rate in both T. Aus and T. Aman rice was highest; which gradually decreased with the increase of the rate of Si application (Fig. 3). In T. Aus rice among three sources of Si, calcium silicate had the higher recovery efficiency at all the Si rates. Silicic acid had higher recovery efficiency than sodium meta silicate only at 1 and 2 kg Si ha^{-1} rate; rather in 5, 10, 20 and 40 kg ha^{-1} rate the sodium meta silicate had higher recovery efficiency than silicic acid. Over the sources of silicon the recovery efficiency varied from 36.7 to 65.0, 25.5 to 46.7, 15.8 to 22.0, 9.6 to 12.6, 6.2 to 7.9 and 3.5 to 4.7 kg Si uptake kg^{-1} added Si in 1, 2, 5, 10, 20 and 40 kg Si ha^{-1}, respectively.

In T. Aman rice higher recovery efficiency was found in sodium meta silicate only at 1, 2 and 5 kg Si ha^{-1} rate, but in 10, 20 and 40 kg Si ha^{-1} rate calcium silicate had the higher recovery efficiency of Si. In 5, 10, 20 and 40 kg Si ha^{-1} rate the silicic acid had the lowest recovery efficiency. At 1, 2, 5, 10, 20 and 40 kg Si ha^{-1} rate over the sources of Si recovery efficiency varied from 24.6 to 48.0, 19.8 to 31.9, 13.7 to 16.9, 8.3 to 14.2, 5.8 to 7.0 and 3.2 to 4.5 kg Si uptake kg^{-1} added Si, respectively (Fig. 3).

Fig. 3 Recovery efficiency of different sources of Si (kg Si uptake kg^{-1} added Si) in T. Aus (var. BRRI dhan48) and T. Aman (var. BRRI dhan73) rice

(Vertical bar indicates standard error of means; n=3)

3.8 Chlorophyll content

The chlorophyll-a, chlorophyll-b and total chlorophyll content of T. Aus and T. Aman rice were generally not significantly influenced by sources of silicon excepting chlorophyll-a in T. Aus rice where calcium silicate had the highest performance. The rates of Si significantly influenced the chlorophyll-a and total chlorophyll content of T. Aus rice, and chlorophyll-a, chlorophyll-b and total chlorophyll content of T. Aman rice. Chlorophyll content progressively increased with the increase of the rates of Si application. Table 5 shows that over the rates of the Si, the total chlorophyll content varied from 3.99 to 4.50 mg g^{-1} fresh leaf in T. Aus rice, and 3.62 to 4.01 mg g^{-1} fresh leaf in T. Aman rice. It was also found that the 10, 20 and 40 kg Si ha^{-1} rate had no remarkable difference on total chlorophyll production in both T. Aus and T. Aman rice.

Table 5. Effects of different sources and rates of Si on chlorophyll content of T. Aus (var. BRRI dhan48) and T. Aman (var. BRRI dhan73) rice

3.9 Pearson correlation co-efficient

The Pearson correlation co-efficient of grain yield with different plant parameters has been given in Table 6. It was found that grain yield of both T. Aus and T. Aman rice was significantly and positively correlated with straw yield (r= 0.452 and 0.674), number of grains panicle (r= 0.622 and 0.627), grain Si content (r= 0.637 and 0.564), straw Si content (r= 0.707 and 0.481) and total chlorophyll content (r= 0.527 and 0.376), respectively.

Table 6. Pearson correlation co-efficient of grain yield with different plant parameters (n=63)

4. Discussion

A significant yield increase by Si amendment was consistently found in both T. Aus and T. Aman rice. The significant yield increase by Si amendment was also reported by some other scientists (Babu Rao and Sushmitha, 2017; Siam et al., 2018; Mahendran et al., 2021). However, we found few variations among different sources to the extent of yield increase. In the experiment silicic acid, sodium meta silicate and calcium silicate had maximum grain yield increase by 15.5 and 18%, 15.9 and 16%, and 15.3 and 26% in T. Aus and T. Aman rice, respectively. Overall 15.6% and 20% yield increase was achieved in T. Aus and T. Aman rice, respectively through amendment of Si in soil. Berahim et al. (2021) and Jinger et al. (2021) reported 39% yield increase with top dressing of Si in soil. Cassola et al. (2021) reported 43% increased shoot growth in Si amended treatment compared to control having cultivar to cultivar differences under a pot culture experiment. In T. Aus season no remarkable variation was observed among three sources to increase yield, but in T. Aman season (BRRI dhan73) calcium silicate source was found as the best source of Si.

In the experiment BRRI dhan73 had better yield increase than BRRI dhan48 in Si amended treatments over control. It was probably happened due to varietal difference of crop response to Si. Thorne et al. (2022) reported that there was significant variation among the cultivars for enhancement of crop growth under Si fertilized condition in rice.

Increasing Si rate progressively increased the grain yield of rice. But the regression relation was not linear, rather it follows the quadratic model which indicates that in a certain level of Si application grain yield reaches it's maximum then declined. The quadratic relationship of Si application and grain yield of rice was also described by Cassola et al. (2021) and de Souza et al. (2021). From quadratic regression model it was found that the optimum rate of silicic acid, sodium meta silicate and calcium silicate were 32.2, 25.7 and 23.6 kg Si ha^{-1} for T. Aus rice, and 42.9, 25.8 and 24.5 kg Si ha^{-1}, respectively for T. Aman rice (Fig. 1). The results clearly evidenced that calcium silicate was the best source of silicon as it shows best response with smaller rates of silicon. Silicic acid had the lowest performance as it's optimum rate was the highest (32.2 kg ha^{-1} for T. Aus rice and 42.9 kg Si ha^{-1} for T. Aman rice). However, other researchers reported higher rates of Si application than the present study. For example, Babu Rao and Sushmitha, (2017) reported that calcium silicate at a rate of 100 kg ha^{-1} to 250 kg ha^{-1} improve rice yield. Jinger et al.

(2021) reported 80 kg Si ha^{-1} for optimum yield of rice. Swe et al. (2021) found that the optimum grain yield was achieved from the application of Si 200 kg ha^{-1}. Mahendran et al. (2021) applied 150 kg Si ha^{-1} as calcium silicate to rice field and they observed high growth and grain yield. de Souza et al. (2021) recommended 2 ton ha^{-1} of silicon to control blast disease and higher yield of rice. Probably different researchers used different kinds of Si and their nutrient release capacity may differ considerably. In our experiment we used reagent grade chemical sources of Si, therefore lower rate probably had the higher impact. Other factors may contribute were tidal water flooding, lower cropping intensity having only a single T. Aman rice crop in a year, etc. Tidal water may have dissolved Si, which needs to identify through future research. Due to low cropping intensity Si mining is relatively low in the coastal region compared to intensive cropping area of the country, especially double rice growing area.

In the present study although 40 kg Si ha^{-1} treatment had the highest straw yield, but 20 kg Si ha^{-1} had statistically similar result. Silicon amendment increases straw yield by 20% and 18% in T. Aus and T. Aman rice, respectively. These results are agreement with the findings of Mahendran et al. (2021) who observed highest straw yield in the treatment with application of calcium silicate @ 150 kg Si ha^{-1} which clearly indicated that Si application in soil had a positive impact on straw yield of rice. Sultana et al. (2021) reported higher straw yield in Si treated plants under pot culture condition. The enhanced straw yield with Si at higher levels may be attributed to leaf erectness which facilitated better penetration of sunlight leading to higher photosynthetic activity of plant and higher production of carbohydrates (Prakash et al., 2011; Buck et al., 2018).

A progressive increase of the number of grains $panicle^{-1}$ was observed with the increase of the rate of Si application. Silicon application in soil increases the number of grains $panicle^{-1}$ by 15.3 and 17.0% in T. Aus and T. Aman rice, respectively. Some other reports also described that soil application of Si increased the shoot weight of rice, productive tillers, filled grains per panicle, thousand grain weight and grain yield of rice (Rautaray, 2005; Sreya et al., 2014; Elshayb et al., 2021). The sufficient Si supply promotes the production of photosynthetic products which ultimately help to develop filling of storage tissues which might be the reason for enhanced number of filled grains in the spikelets (Gholami and Falah, 2013).

Exogenous application of Si significantly improves the Si content of rice. It was observed that Si amendment increases grain Si content by 19.6 and 44.9 %, straw Si content by 17.9 and 26.3 %, and flag leaf Si content by 19.1 and 27.2% in T. Aus rice and T. Aman rice, respectively. Generally the T. Aman rice (var. BRRI dhan73) had relatively better response than T. Aus rice (var. BRRI dhan48) in relation to increase the Si content of rice. Regarding straw and flag leaf Si content the T. Aus rice (var. BRRI dhan48) had higher Si content than that of T. Aman rice (var. BRRI dhan73). Probably it was happened due to genetic makeup of the varieties. Mahendran et al. (2021) reported Si content of 1.27 and 4.12% in grain and straw under Si added treatment (as calcium silicate) which was 104 and 29% higher than respective control treatment. Jinger et al. (2021) found that the different levels Si increased the Si concentration in hulled rice grain and straw by 25 and 64 %, respectively. According to Ma and Yamaji (2006), the content of Si in rice was 8.05% in hulls, and 4.21% in leaves, while rice with low levels of Si only had 1.44% and

0.48% in the hull and leaves, respectively. Calcium silicate increased the availability of soil Si which might have contributed for higher Si in plant parts namely grain, straw and flag leaf. Singh et al. (2002) observed higher Si in straw than grain and concluded 3.5% of Si in straw for the optimum growth and yield of rice. With the application of large quantity of Si fertilizers, rice can accumulate Si in the stem and leaves up to 10–15% of its dry weight (Siam et al. 2018).

Higher Si content in grain and straw had a positive reflection on Si uptake by the plant parts. Silicon application in the soil increased grain, straw and total Si uptake by 35.2, 42.1 and 40.1 % in T. Aus rice, and 74.3, 48.3 and 54.8% in T. Aman rice, respectively than the respective Si control treatment. In the experiment total Si uptake in T. Aus rice (var. BRRI dhan48) was higher than T. Aman rice (var. BRRI dhan73), because of higher Si content in straw of T. Aus rice. The significant increase in Si uptake by Si application in rice was also reported by Pan et al. (2021), Swe et al. (2021) and Tao-wen et al. (2021). Increased concentration of silicon in the shoots indicated that source of silicon used was reactive and very effective in providing silicon in the soil and the plant. The increased, Si uptake with the application of Si fertilizer might be due to the increased Si availability in soil and enhanced root system, which might in turn stimulate the plant to uptake more Si from the soil solution (Kumar et al. 2021).

The nutrient use efficiency parameters including agronomic use efficiency and physiological use efficiency was higher in lower doses of Si and was decreased gradually with increasing doses of Si. Jinger et al. (2021) also reported agronomic and physiological Si use efficiency in a pattern of 40>80>120 kg Si ha^{-1} rate. The greater nutrient use efficiency at lower rate is common because of efficient utilization of nutrients at lower level (Fageria and Baligar, 2001). Higher silicon use efficiency in rice could be due to higher uptake of silicon in rice grain or addition of silicon through fertilizers. Among three sources sodium meta silicate had comparatively higher use efficiency in lower dose but calcium silicate had higher efficiency in higher dose. Probable cause may be easy dissociation in soil solution. Sodium meta silicate instantly dissolved in soil solution, along with it’s sodium content which may act as plant nutrition in lower dose. When sodium meta silicate applied at higher dose it’s higher sodium level may create negative impact on crops (Akter et al. 2021).

In the present study three different sources of Si were tested but found no significant difference among them for accumulation of chlorophyll (except chlorophyll a in T. Aus rice). The results are quite similar with the findings of Cassola et al. (2021), who also found no significant difference between the sources of Si for chlorophyll a and b contents. Increasing rates of Si supplementation steadily increases the chlorophyll a and b content both in T. Aus and T. Aman rice. With the addition of Si the levels of chlorophyll a and b increased in both T. Aus and T. Aman rice, possibly because Si boosts pigment levels (Souza, 2008). Furthermore, Si is related to adjustments in the chloroplast ultrastructure, and is beneficial in maintaining chlorophyll levels (Ahmed et al., 2014). Silicon application in soil increases leaf area and keeps leaves erect, which improve crop photosynthesis (Gerami and Rameeh, 2012; Patil et al., 2017; Sharma et al., 2021; Elshayb et al., 2021). The chlorophyll a contents were found higher than those of chlorophyll b. This is usually the case in the majority of plants, since chlorophyll b is an integral part of antenna pigments only, whereas chlorophyll a is an integral part of antenna pigments and photosystem reaction centers (Taiz et al., 2017). Application of Si improves chlorophyll a, b and total chlorophyll by 13.8, 12.6 and 12.8% in T. Aus rice, and 9.8, 14.6 and 10.8% in T. Aman rice. Gong et al. (2005) reported that sodium metasilicate increases chlorophyll a by 30 and 47% in two water regimes.

5. Conclusions

In Ganges delta coastal zone soils Si had a significant effect to increase rice yield. Among three tested sources calcium silicate was identified as the best source of Si at a rate of 24 kg Si ha^{-1} as optimum dose for sustainable productivity of T. Aus and T. Aman rice due to its positive influence on grain production, Si concentration and uptake, chlorophyll content and eventually grain and straw yield of rice. The present study results will be useful in formulating efficient nutrient management practices for the rice growing soils of the Ganges delta coastal zone soils. However, the results could be validated using more rice varieties in double or triple crop areas of the Ganges delta.

Declarations

Acknowledgements

We would like to thank the project entitled “Nutrient Management for Diversified Cropping in Bangladesh”, co-funded by Australian Centre for International Agricultural Research, Australia (LWR/2016/136) and Krishi Gobeshona Foundation, Bangladesh (ICP-II) to support the expense of the study.

Funding: This work was supported by Australian Centre for International Agricultural Research (grant number-LWR/2016/136) and Krishi Gobeshona Foundation, Bangladesh (grant number- ICP-II).

Financial interests: The authors have no relevant financial or non-financial interests to disclose.

Ethics approval: Not applicable

Consent to participate: Not applicable

Consent for publication: Not applicable

Data availability: The analyzed datasets are available from the corresponding author on reasonable request.

Code availability: Not applicable

Authors’ contributions:

All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by Mohammad Asadul Haque and Md Jahiruddin. The first draft of the manuscript was written by Mohammad Asadul Haque and Md Fazlul Hoque. Mohammad Asadul Haque, Md Saiful Islam, Md Baktear Hossain and Md Abdus Satter analysed the data, wrote, revised, and improved the manuscript. Md Jahiruddin, Md Baktear Hossain, Md Abdus Satter, Md Enamul Haque and Richard William Bell accomplish funding for the study work. All authors read and approved the final manuscript.

References

1. Abdullah EHE, Misran A, Yaapar MN, Yusop MR, Ramli A. (2021) The potential of silicon in improving rice yield, grain quality, and minimising chalkiness: A review. Pertanika J Trop Agric Sci 44(3):655-672
2. Agarie S, Uchida H, Agata W, Kubota F, Kaufman PB (1998) Effects of silicon on transpiration and leaf conductance in rice plants (Oryza sativa L.). Plant Prod Sci 1(2): 89–95
3. Agostinho FB, Tubana BS, Martins MS, Datnoff LE (2017) Effect of different silicon sources on yield and silicon uptake of rice grown under varying phosphorus rates. Plants 6:35 https://doi.org/10.3390/plants6030035
4. Ahmed M, Asif M, Hassan FU (2014) Augmenting drought tolerance in sorghum by silicon nutrition. Acta Physiol Plant 36(2):473-483. http://dx.doi.org/10.1007/ s11738-013-1427-2.
5. Akter N, Haque MA, Hoque MF (2021) Improvement of growth of maize by application of silicon through its suppressing effect on sodium uptake under salt stress condition. J Bangladesh Acad Sci 45(2); 251-253. https://doi.org/10.3329/jbas.v45i2.57213
6. Babu Rao G, Sushmitha P (2017) Silicon uptake, transportation and accumulation in rice. J Pharmacogn Phytochem 6(6):290-293
7. Berahim Z, Omar MH, Zakaria NI, Ismail MR, Rosle R, Roslin NA, Che'Ya NN. (2021) Silicon improves yield performance by enhancement in physiological responses, crop imagery, and leaf and culm sheath morphology in new rice line, PadiU Putra. BioMed Res Int 6679787, 17 pages. https://doi.org/10.1155/2021/6679787.
8. Bhatt D, Sharma G (2018) Role of silicon in counteracting abiotic and biotic plant stresses. Int J Chem Stud 6(2):1434-1442
9. Buck GB, Korndorfer GH, Nolla A, Coelho L (2018) Potassium silicate as foliar spray and rice blast control. J Plant Nutr 31:231– 237
10. Cassola JC, Sponchiadoa D, Dornellesa SHB, Tabaldia LA, Barretoa EPM, Pivettaa M, Lopesa SJ (2021) Silicon as an attenuator of drought stress in plants of *Oryza sativa* L. treated with dietholate. Braz J Biol 81(4):1061-1072
11. Cooke J, Leishman MR (2011) Is plant ecology more siliceous than we realize? Trends Plant Sci 16(2): 61-68. https://doi.org/10.1016/j. tplants.2010.10.003
12. Coombs J, Hind G, Leegood RC, Tieszen LL, Vonshak A (1985) Analytical Techniques, In: Techniques in Bioproductivity and photosynthesis 2nd edition. p. 219–220.
13. Cuong TX, Ullah H, Datta A, Hanh TC (2017) Effects of Silicon-Based Fertilizer on Growth, Yield and Nutrient Uptake of Rice in Tropical Zone of Vietnam. Rice Sci 24: 283-290

https://doi.org/10.1016/j.rsci.2017.06.002

14. de Oliveira LM, Marchesan E, de David R, Werle IS, Aramburu BB, Donato G, da Silva AL, da Costa IFD (2019) Occurrence of rice blast on and grain quality of irrigated rice fertilized with nitrogen and silicates. Pesqui Agropecu Bras 54: e00295. https://doi. org/10.1590/S1678-3921.pab2019.v54.00295
15. de Souza ACA, de Filippi MCC, Nascente AS, Prabhu AS, Alves E (2021) Silicon rates and beneficial microorganism on blast suppression and productivity of upland rice. J Plant Sci Phytopathol 5:020-027. https://doi. org/10.29328/journal.jpsp.1001057
16. Elshayb OM, Nada AM, Ibrahim HM, Amin HE, Atta AM (2021) Application of silica nanoparticles for improving growth, yield, and enzymatic antioxidant for the hybrid rice EHR1 growing under water regime conditions. Materials 14:1150. https://doi.org/ 10.3390/ma14051150
17. Epstein E (1999) Silicon. Annu Rev Plant Biol 50:641-664. https://doi.org/10.1146/annurev.arplant.50.1.641
18. Epstein E, Bloom A (2005) Mineral nutrition of plants: Principles and perspectives. Sunderland, MA: Sinauer Associates. Inc
19. Fageria NK, Baligar YC (2001) Lowland rice responses to nitrogen fertilization. Commun Soil Sci Plant Ann 32:1405-1429
20. FRG (Fertilizer Recommendation Guide) (2018) Bangladesh Agricultural Research Council. Dhaka-1215, Bangladesh.
21. Gerami M, Rameeh V (2012) Study of silicon and nitrogen effects on yield components and shoot ions nutrient composition in rice. Agriculture (Poľnohospodárstvo), 58(3):93–98
22. Gholami Y, Falah A (2013) Effects of two different sources of silicon on dry matter production, yield, and yield components of rice, Tarom Hashemi variety and 843 lines. Int J Agric Crop Sci 5:227-231
23. Gong H, Zhu X, Chen K, Wang S, Zhang C (2005) Silicon alleviates oxidative damage of wheat plants in pots under drought. Plant Sci 169(2):313-321 http://dx.doi.org/10.1016/j.plantsci.2005.02.023.
24. Haynes RJ (2014) A contemporary overview of silicon availability in agricultural soils. J Plant Nutr Soil Sci 177(6):831-844 https://doi.org/10.1002/jpln.201400202
25. Jinger D, Dhar S, Dass A, Sharma VK, Paramesh V, Parihar M, Joshi E, Singhal V, Gupta G, Prasad D, Vijayakumar S (2021) Co-fertilization of silicon and phosphorus influences the dry matter accumulation, grain yield, nutrient uptake, and nutrient-use efficiencies of aerobic rice. Silicon. https://doi.org/10.1007/s12633-021-01239-5
26. Kuhla J, Pausch J, Schaller J (2021) Effect on soil water availability, rather than silicon uptake by plants, explains the beneficial effect of silicon on rice during drought. Plant Cell Environ 44(10): 3336-3346 https://doi.org/10.1111/pce.14155
27. Kumar PA, Sriramachandrasekharan MV, Muthukumararaja T (2021) Int J Appl Pure Sci Agric 7(6):38-49. https://doi.org/10.22623/IJAPSA.2021.7006.WEDX8

28. Lavinsky AO, Detmann KC, Reis JV, Ávila RT, Sanglard ML, Pereira LF, Sanglard LMVP, Rodrigues FA, Araújo WL, DaMatta FM (2016) Silicon improves rice grain yield and photosynthesis specifically when supplied during the reproductive growth stage. J Plant Physiol 206:125-132 https://doi.org/10.1016/j.jplph.2016.09.010
29. Li N, Feng A, Liu N (2020) Silicon application improved the yield and nutritional quality while reduced cadmium concentration in rice. Environ Sci Pollut Res 27(11): 20370-79. https://doi.org/10.1007/s11356-020-08357-4
30. Liang Y, Sun W, Zhu YG, Christie P (2007) Mechanisms of silicon-mediated alleviation of abiotic stresses in higher plants: A review. Environ Pollut 147(2):422-428 https://doi.org/10.1016/j.envpol.2006.06.008
31. Ma JF, Takahashi E (2002) Soil, fertilizer, and plant silicon research in Japan. Amsterdam, The Netherlands: Elsevier.
32. Ma JF, Yamaji N (2006) Silicon uptake and accumulation in higher plants. Trends Plant Sci 11(8): 392-397 https://doi.org/10. 1016/j.tplants.2006.06.007
33. Mahendran PP, Gowthamraj K, Balasubramaniam P, Chandramani P, Yuvaraj M (2021) Status and Distribution of Plant Available Silicon in Relation to Some Soil Properties and Response of Rice (Oryza sativa L.) to Silicon Nutrition in the Intensively Rice Growing Soils of Kanyakumari District, Tamil Nadu, India. Silicon. https://doi.org/10.1007/s12633-021-00947-2.
34. Meena VD, Dotaniya ML, Coumar V, Rajendiran S, Ajay, Kundu S, Subba Rao A (2014) A case for silicon fertilization to improve crop yields in tropical soils. Proc Natl Acad Sci India Sect B Biol Sci, 84(3):505-518 https://doi. org/10.1007/s40011-013-0270-y
35. Page AL, Miller RH, Keeney DR. 1982. Methods of Soil Analysis. American Society of Agronomy, Inc. and Soil Science Society of America, Inc. Madison, Wisconsin.
36. Pan T, Zhang J, He L, Hafeez A, Ning C, Cai K (2021) Silicon Enhances Plant Resistance of Rice against Submergence Stress. Plants. 10:767 https://doi.org/ 10.3390/plants10040767
37. Patil AA, Durgude AG, Pharande AL, Kadlag AD, Nimbalkar CA (2017) Effect of calcium silicate as a silicon source on growth and yield of rice plants. Int J Chem Stud 5(6):545 -549
38. Prakash NB, Chandrashekar N, Mahendra C, Patil SU, Thippeshappa GN, Laane HM (2011) Effect of foliar spray of soluble silicon acid on growth and yield parameters of wetland rice in hilly and costal zone soils of Karnataka, South India. J Plant Nutr 34:1883–1893 https://doi.org/10.1080/01904167.2011.600414
39. Rajamoorthy Y, Abdul Rahim K, Munusamy S (2015) Rice industry in Malaysia: Challenges, policies and implications. Procedia Econ Finan 31(15):861-867. https://doi. org/10.1016/s2212-5671(15)01183-1
40. Rautaray SK (2005) Nutrient dynamics, dehydrogenase activity, and response of the rice plant to fertilization sources in an acid lateritic soil. Acta Agric Scand Sect B 55:162-169
41. Sahebi M, Hanafi MM, Siti Nor Akmar A, Rafii MY, Azizi P, Tengoua FF, Nurul Mayzaitul Azwa J, Shabanimofrad M (2015) Importance of silicon and mechanisms of biosilica formation in plants.

BioMed Res Int 396010. https://doi. org/10.1155/2015/396010

42. Schaller J, Puppe D, Kaczorek D, Ellerbrock R, Sommer M (2021) Silicon cycling in soils revisited. Plants 10(2):295 https://doi.org/10. 3390/plants10020295
43. Sharma PP, Jawahar S, Kalaiyarasan C, Sriramachandrasekharan MV (2021) Effect of silicon on vegetative growth and root characteristics of rice. Int J Botany Stud 6(4):09-12
44. Siam HS, Abd El-Moez MR, Holah SS, Abou Zeid ST (2018) Effect of silicon addition to different fertilizer on yield of rice (Oryza sativa L.) plants. I- macro nutrients by different rice parts. Middle East J Appl Sci 8(1):177-190
45. Singh KK, Singh K, Ragevendra S, Yogeshwar S, Singh CS (2002) Efficiency of various organic residues for enhancing Rice-Wheat production under normal soil conditions. Indian J Agric Sci 40:2107–2113
46. Singh V, Virendra Singh, Singh S, Khanna R (2020) Effect of zinc and silicon on growth and yield of aromatic rice (*Oryza Sativa*) in North - Western Plains of India. J Rice Res Develop 3(1):82-86
47. Siregar AF, Sipahutar IA, Anggria L, Yufdi MP (2021) Improving rice growth and yield with silicon addition in Oxisols. In IOP Conference Series: Earth Environ Sci 648(1):012202 https://doi.org/10.1088/1755-1315/648/1/012202
48. Souza JV (2008) Aplicação de silicato de potássio via foliar no milho: fotossíntese, crescimento e produtividade. Uberlândia: Universidade Federal de Uberlândia, 33 p. Monografia.
49. Sreya U, Parvathi, Mahendran PP (2014) Delineation of silicon deficient areas in the intensively rice growing soils of Periyar Vaigai Command area, Tamil Nadu. National conference on emerging challenges and opportunities in biotic and abiotic stress management, Dec 13–14. Directorate of Rice research, Rajendranagar, Hyderabad, pp 51–52
50. Sultana N, Haque MA, Hoque MF, Hossain MB, Satter MA, Jahiruddin M (2021) Effect of silicon application on growth and biomass yield of rice under salinity stress. J Bangladesh Agril Univ 19(4):429-436. https://doi.org/10.5455/JBAU.117294
51. Swe MM, Mar SS, Naing TT, Zar T, Ngwe K (2021) Effect of Silicon Application on Growth, Yield and Uptake of Rice (Oryza sativa L.) in Two Different Soils. Open Access Lib J 8: e7937 https://doi.org/10.4236/oalib.1107937
52. Taiz L, Zeiger E, Mller IM, Murph A (2017) Fisiologia e desenvolvimento vegetal. 6ª ed. Porto Alegre: Artmed Editora S.A., 120p.
53. Tao-wen P, Yu C, Kun-zheng C (2021) Effect of nitrogen and silicon fertilizer on plant nutrient content, yield and quality of high quality rice. J Ecol Rural Environ 37(1):120-126
54. Thorne SJ, Stirnberg PM, Hartley SE, Maathuis FJM (2022) The ability of silicon fertilisation to alleviate salinity stress in rice is critically dependent on cultivar. Rice 15(8):1-10 https://doi.org/10.1186/s12284-022-00555-7
55. Yoshida S, Forno DA, Cock JH, Gomez KA (1976) Laboratory Manual for Physiological Studies of Rice. International Rice Research Institute, Philippines, 3rd ed. pp 17-22.

Tables

Table 1. Grain yield of T. Aus (var. BRRI dhan48) and T. Aman (var. BRRI dhan73) rice as influenced by different sources and rates of silicon

Silicon rates	Sources of silicon			Mean
(kg ha^{-1})	Silicic acid	Sodium meta silicate	Calcium silicate	(n=9)
Grain yield of T. Aus rice (t ha^{-1})				
0	4.13	4.16	4.31	4.20 d
1	4.16	4.47	4.45	4.36 cd
2	4.31	4.54	4.71	4.52 bc
5	4.53	4.54	4.84	4.64 ab
10	4.47	4.77	4.83	4.69 ab
20	4.67	4.82	4.97	4.82 a
40	4.77	4.76	4.79	4.77 a
Mean (n=21)	4.44 b	4.58 ab	4.70 a	
Significance level: Sources- P≤0.05, Rates- P≤0.001, Sources:Rates interaction- not significant %CV(a)- 4.76; %CV(b)- 3.47				
Grain yield of T. Aman rice (t ha^{-1})				
0	4.00 c	3.78 b	3.81 b	3.83
1	4.10 bc	4.21 ab	3.87 b	4.06
2	4.16 bc	4.33 a	3.98 b	4.15
5	4.21 abc	4.32 a	4.24 b	4.25
10	4.29 abc	4.35 a	4.81 a	4.48
20	4.55 ab	4.34 a	4.80 a	4.56
40	4.72 a	4.37 a	4.78 a	4.62
Mean (n=21)	4.29	4.24	4.33	
Significance level: Sources- not significant, Rates- P≤0.001, Sources:Rates interaction- P≤0.01 %CV(a)- 8.59; %CV(b)- 4.74				

Means with the same letter are not significantly different.

Table 2. Effects of different sources and rates of Si on yield and yield parameters of T. Aus (var. BRRI dhan48) and T. Aman (var. BRRI dhan73) rice

Treatments	Straw yield (t ha^{-1})		No. of grains $panicle^{-1}$	
	T. Aus rice	T. Aman rice	T. Aus rice	T. Aman rice
Si sources (n=21)				
Silicic acid	4.76	4.58	120	118.6 b
Na meta silicate	4.93	4.69	120	122.3 a
Calcium silicate	5.08	4.63	123	123.7 a
Si rates (kg ha^{-1}) (n=9)				
0	4.47 c	4.18 b	111 c	112 c
1	4.74 bc	4.46 ab	115 bc	115 c
2	4.81 bc	4.53 ab	118 abc	119 bc
5	4.95 ab	4.59 ab	122 ab	121 abc
10	5.01 ab	4.83 a	127 a	123 abc
20	5.13 ab	4.94 a	128 a	128 ab
40	5.36 a	4.90 a	126 a	131 a
Significance level				
Si sources	ns	ns	ns	**
Si rates	***	***	***	***
Si sources:Si rates	ns	ns	ns	ns
% CV (a)	14.03	5.64	5.98	3.10
% CV (b)	6.48	7.23	5.48	6.39

**$P \leq 0.01$, ***$P \leq 0.001$, ns= not significant

Means with the same letter are not significantly different.

Table 3. Effects of different sources and rates of Si on Si content of T. Aus (var. BRRI dhan48) and T. Aman (var. BRRI dhan73) rice

Treatments	Grain Si content (%)		Straw Si content (%)		Leaf Si content (%)	
	T. Aus	T. Aman	T. Aus	T. Aman	T. Aus	T. Aman
Si sources (n=21)						
Silicic acid	2.08 c	1.86 c	7.76 b	4.92 c	11.5	5.45 c
Sodium meta silicate	2.33 b	2.15 b	8.21 a	5.81 b	11.3	7.95 b
Calcium silicate	2.45 a	2.49 a	8.50 a	6.00 a	11.9	8.26 a
Si rates (kg ha^{-1}) (n=9)						
0	2.09 d	1.78 d	7.39 d	4.90 e	10.33 b	6.43 d
1	2.19 cd	1.93 cd	7.80 cd	5.19 de	11.30 ab	6.64 cd
2	2.23 bcd	2.06 bcd	7.94 c	5.35 cd	11.46 a	6.84 bcd
5	2.30bc	2.14 bcd	8.18 bc	5.68 bc	11.52 a	7.28 abcd
10	2.31 bc	2.23 abc	8.42 ab	5.76 bc	11.91 a	7.51 abc
20	2.38 ab	2.41 ab	8.64 a	5.95 ab	12.09 a	7.70 ab
40	2.50 a	2.58 a	8.71 a	6.19 a	12.30 a	8.18 a
Significance level						
Sources of Si	***	**	*	***	ns	***
Rates of Si	***	***	***	***	***	***
Sources:Rates	ns	ns	ns	ns	ns	ns
% CV (a)	3.70	12.16	5.24	3.44	12.33	4.36
% CV (b)	5.61	11.58	3.69	5.25	6.11	8.53

*P≤0.05, **P≤0.01, ***P≤0.001, ns= not significant

Means with the same letter are not significantly different.

Table 4. Effects of different sources and rates of Si on Si uptake (kg ha^{-1}) of T. Aus (var. BRRI dhan48) and T. Aman (var. BRRI dhan73) rice

Treatments	T. Aus rice (var. BRRI dhan48)			T. Aman rice (var. BRRI dhan73)		
	Grain Si uptake	Straw Si uptake	Total Si uptake	Grain Si uptake	Straw Si uptake	Total Si uptake
Si sources (n=21)						
Silicic acid	92 c	370 c	463 b	80 c	226 b	306 c
Sodium meta silicate	107 b	406 b	513 a	92 b	273 a	365 b
Calcium silicate	115 a	434 a	549 a	109 a	279 a	388 a
Si rates (kg ha^{-1}) n=9)						
0	88 e	330 e	418 e	69 e	205 e	274 e
1	96 de	370 de	466 de	78 de	232 de	310 de
2	101 cd	383 cd	484 cd	85 cde	242 cde	327 cde
5	107 bc	405 bcd	512 bcd	91 bcd	261 bcd	352 bcd
10	109 abc	422 bc	531 bc	101 abc	280 abc	381abc
20	115 ab	443 ab	558 ab	110 ab	294 ab	404 ab
40	119 a	469 a	588 a	120 a	305 a	425 a
Significance level						
Sources of Si	***	*	*	***	***	***
Rates of Si	***	***	***	***	***	***
Sources:Rates	ns	ns	ns	ns	ns	ns
% CV (a)	5.55	14.29	10.79	5.25	5.85	4.28
% CV (b)	7.00	7.86	6.69	15.02	10.13	10.36

*P≤0.05, ***P≤0.001, ns= not significant

Means with the same letter are not significantly different.

Table 5. Effects of different sources and rates of Si on chlorophyll content of T. Aus (var. BRRI dhan48) and T. Aman (var. BRRI dhan73) rice

Treatments	T. Aus rice			T. Aman rice		
	Chl-a (mg g^{-1})	Chl-b (mg g^{-1})	Total Chl (mg g^{-1})	Chl-a (mg g^{-1})	Chl-b (mg g^{-1})	Total Chl (mg g^{-1})
Si sources						
Silicic acid	3.33 b	0.821	4.15	3.23	0.679	3.91
Sodium meta silicate	3.34 b	0.843	4.20	3.18	0.734	3.91
Calcium silicate	3.56 a	0.853	4.41	3.05	0.688	3.73
Si rates (kg ha^{-1})						
0	3.19 b	0.808	3.99 b	2.97 b	0.650 b	3.62 b
1	3.19 b	0.839	4.03 b	3.04 ab	0.689 ab	3.73 ab
2	3.31 ab	0.801	4.11 ab	3.10 ab	0.678 ab	3.78 ab
5	3.42 ab	0.814	4.23 ab	3.14 ab	0.692 ab	3.83 ab
10	3.57 ab	0.824	4.40 ab	3.28 a	0.735 a	4.01 a
20	3.54 ab	0.910	4.43 ab	3.26 a	0.745 a	4.00 a
40	3.63 a	0.874	4.50 a	3.26 a	0.716 ab	3.98 a
Significance level						
Sources of Si	*	ns	ns	ns	ns	ns
Rates of Si	**	ns	**	**	**	**
Sources:Rates	ns	ns	ns	ns	ns	ns
% CV (a)	5.99	13.21	6.85	8.77	9.05	8.67
% CV (b)	7.94	10.51	7.47	5.59	7.62	5.51

**P≤0.01, ns= not significant

Means with the same letter are not significantly different.

Table 6. Pearson correlation co-efficient of grain yield with different plant parameters (n=63)

Parameters	Grain yield of T. Aus rice	Grain yield of T. Aman rice
Straw yield	0.452 ***	0.674 ***
Grains panicle^{-1}	0.622 ***	0.627 ***
Grain Si content	0.637 ***	0.564 ***
Straw Si content	0.707 ***	0.481 ***
Leaf Si content	0.545 ***	0.338 **
Chlorophyll-a	0.502 ***	0.378 **
Chlorophyll-b	0.308 *	0.264 *
Total chlorophyll	0.527 ***	0.376 **

*P≤0.05, **P≤0.01, ***P≤0.001

Figures

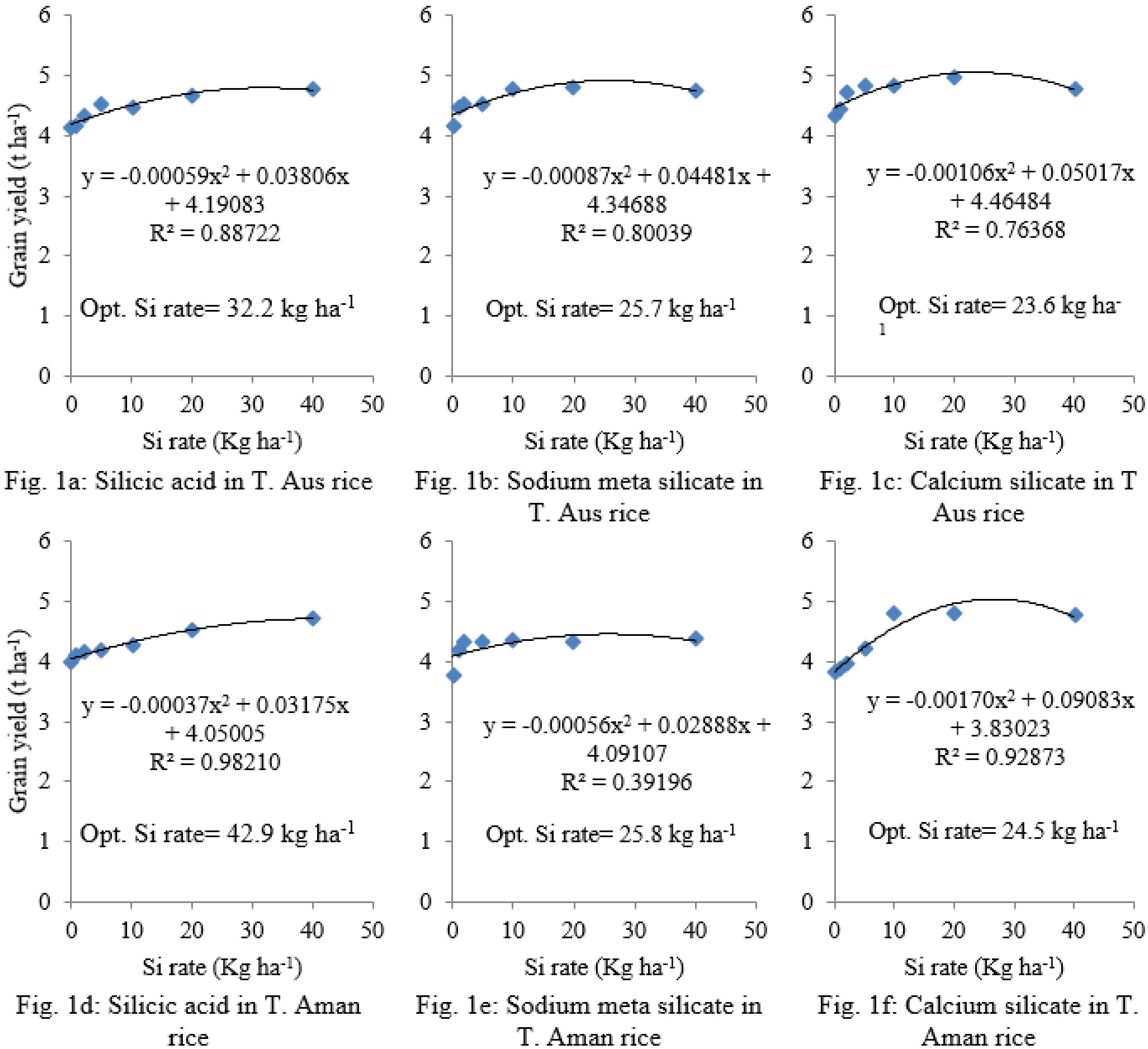

Figure 1

Determination of optimum rate of Si for different sources of Si using quadratic equation in T Aus (var. BRRI dhan48) and T. Aman rice (var. BRRI dhan73)

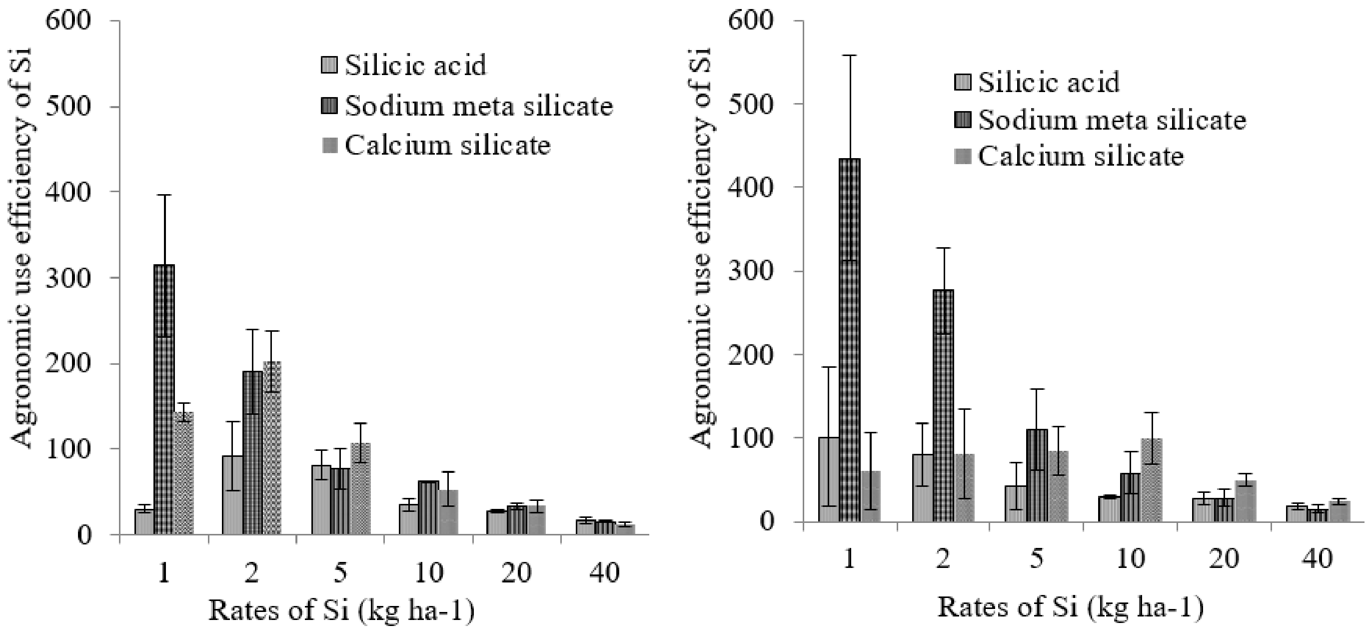

Fig. 2a: T. Aus rice

Fig. 2b: T. Aman rice

Figure 2

Agronomic Si use efficiency of different Si-sources (kg grain kg^{-1} added Si) in T. Aus (var. BRRI dhan48) and T. Aman (var. BRRI dhan73) rice

(Vertical bar indicates standard error of means; n=3)

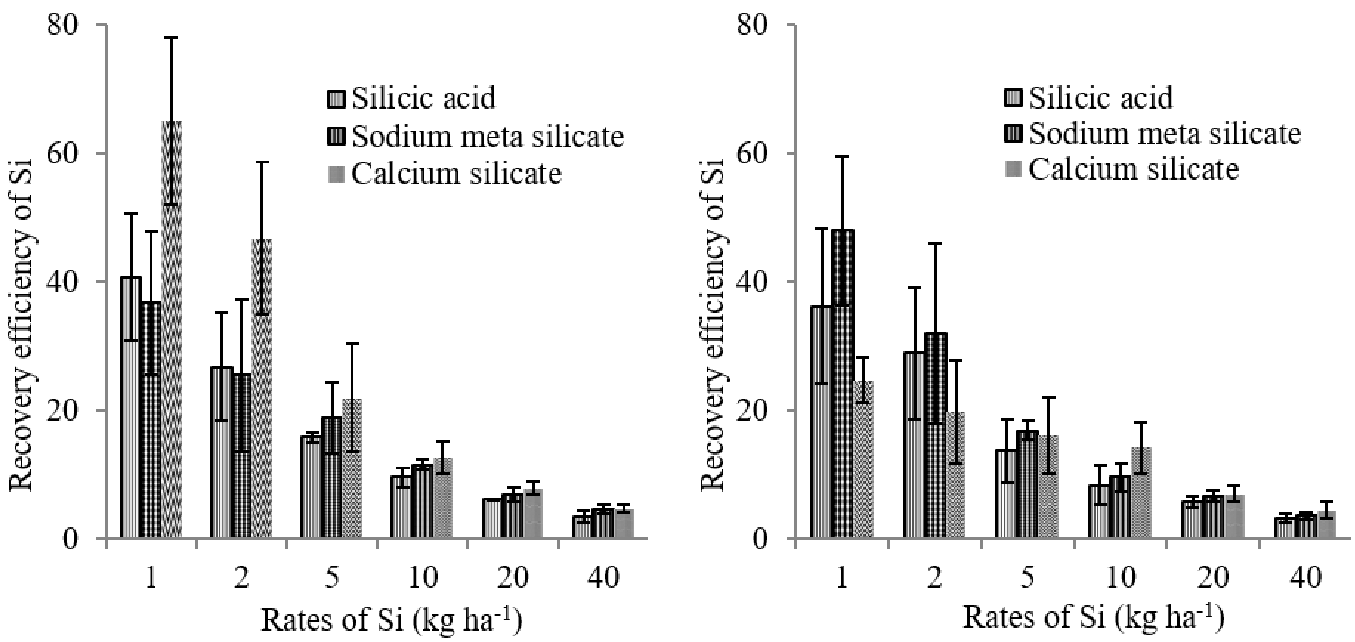

Fig. 3a: T. Aus rice

Fig. 3b: T. Aman rice

Figure 3

Recovery efficiency of different sources of Si (kg Si uptake kg^{-1} added Si) in T. Aus (var. BRRI dhan48) and T. Aman (var. BRRI dhan73) rice

(Vertical bar indicates standard error of means; n=3)

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- Supplimentary.docx