Original Research Article

Assessing the impact of co-fertilization of silicon with macronutrient fertilizers on yield, nutrient uptake, use efficiency and grain quality of ricein sandy clay loam soil

Abstract

This study wantedtoclarify the impact of silicon (Si) fertilization on nutrient uptake, silicon use efficiency, yield and quality of rice and to find out the rate and mode of application of Si fertilizer in silicon deficient soil. Thefield experiment was conducted with ten treatment combinationsof100% NPK,100% NPK + potassium silicate (PS)@ 0.25%,0.50% and 1.0% Foliar spray (FS) at tillering stage,100% NPK + PS@ 0.25% ,0.50% and 1.0%FS at tillering and panicle initiation stages,100% NPK + PS@ 50,100 and 150 kg Si ha^{-1}soil application (SA). Soil application of 50 kg Si ha^{-1} through PS recorded the highest grain (6183 kg ha^{-1}) and straw (6740 kg ha^{-1}) yield, and caused the maximum uptake of nitrogen, phosphorus and potassium in rice and it was on par withfoliar spray of 1% Si. Silicon uptake increased linearlywithSilevels and the maximum uptake was recorded with 150 kg Si ha^{-1} and foliar spray at 1% Si. Foliar spray recorded higher Si use efficiency compared to soil application and rice grain quality viz., protein, amylose and carbohydrate were significantly influenced by silicon addition. The results proved that both foliar and soil application of Si through potassium silicate in sandy clay loam soil could enhance the rice yield, nutrient uptake and grain quality by means of improving nutrient use efficiency.

Key words: Amylase, potassium silicate, silicon use efficiency, sandy clay loam, true protein content, yield

1. Introduction

Soil is definitely the most important resources among the natural resources as it performs incrediblycountlessvital functions(ref). The modern farming grown with high yielding varieties has led to rise of multiple nutrient deficiencies owing to heavy withdrawal of nutrients by crops without replenishing(ref). Tropical and sub-tropical soils are associated with low plant available silicon (Meena*et al*., 2014). Rice crop demand more silicon for its growth, and Ma and Takahashi (2002) reported that for every 100 kg brown rice, 20 kg SiO_2 ha^{-1} is removed. Soils of tropical and sub-tropical regions are considered low in plant available silicon and crops grown in these soils respond to silicon fertilization significantly (Meena*et a*l., 2014). Silicon is present in different forms either alone or in complex with organic and inorganic constituents, but the plant available silicon taken up by the crops has primary influence on growth of crops. Mitani and Ma (2005) have observed that rice is greater accumulator of silicon owing to prolific nature of rice roots to extract silicon from soiland hence silicon is beneficial element for cereal crops more so for rice(Brunings *et al.*, 2009). Ma (2004) and Ahmad *et al.* (2013) reported that besides N, P and K, silicon plays an important role in balancing the macronutrients for rice cultivation to improve quality and yield of crops. Silicon plays a significant role in not only promoting growth and yield of crops, but also improves nutrient availability and helps to mitigate biotic and abiotic stresses in several crops. In the soil solution, Si is present as monosilicic acid and polysilicic acid as well as complexes with organic and inorganic compounds such as aluminium oxides and hydroxides. While it is the plant available silicon (PAS) that is taken up by the plants and has a direct influence on crop growth.Beneficial nutrients are equally important as macronutrients like nitrogen and phosphorus (Ahmad *et al.*, 2013), and balancing these nutrients in rice cultivation can enhance the quality and yield of the crop (Ma, 2004). Silicon plays an important role in the mineral nutrition of plants. Interestingly, silicon is the only one non-essential nutrient that is included in the guidelines for rice fertilization (Si), besides all plant-essential nutrients already have established fertilization programs for rice (Doberman and Fairhurst, 2000).Besides rice yield increase, Si has many fold advantages of increasing nutrient availability (N, P, K, Ca, Mg, S, Zn), decreases nutrient toxicity (Fe, Mn, P, Al) and minimizing biotic and abiotic stress in plants and improving fertilizer use efficiency (Ma *et al.*,2007). Si fertilizer has been used in many countries for improving rice yield (Guntzer*et al.*, 2012).Considering the contribution of Si to rice grain yield and quality especially reduces the chalkiness(Siregar et al.,2021), Si is now considered as an important determinant in rice

Comment [CM1]: Incredibly countless vital functions in crop farming/production….? Then the next sentence can connect perfectly.

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production (Gong *et al.*, 2012;Meharg and Meharg, 2015;Jinger et al.,2020).Recent studies shown that effect of applying Si fertilizers on rice productivity without clarifying the soil silicon supply in different soil types especially different textural classes. Thus, it is necessary to understand the response of rice to Si fertilizers and establish an optimized silicon fertilizer and application mode at critical stages. Till now, scanty information available on soil Si supply level and suitable Si fertilizer application rate for different soils. Hence, this field experiment was conducted to identify the influence of co-fertilization silicon with macronutrient fertilizers in sandy clay loam textured soil on rice yield, nutrient uptake, and quality and silicon use efficiency especially to find out the potassium silicate fertilizer rate and suitable mode application for enhancing nutrient use efficiency.

2. Materials and Methods

2.1.Experimental site

The field experiment was conducted in the farmer's holding located at Rajagopalapuram village under Kuttalam taluk, Mayiladuthurai district, Tamilnadu, India. The experimental field is geographically situated 11.10°N and 79.67°E at an altitude of 16 m above mean sea level.The experimental soil identified as sandy clay loam soil belonging to Padugai series (TypicUstifluvent).The soil pH-7.25, EC-0.15 dSm^{-1}, soil organic carbon-3.5 g kg^{-1}, $KMnO_4$-N- 265 kg ha^{-1}(low), Olsen P- 18.4 kg ha^{-1}(medium), NH_4OAc-K- 228 kg ha^{-1}(medium) and available silicon- 25 mg kg^{-1}.

2.2. Treatment structure and Design

The treatment structure includes T_1 - NPK (RDF), T_2 - NPK + Potassium silicate (FS) - 0.25%, T_3- NPK + Potassium silicate (FS) - 0.50%, T_4 - NPK + Potassium silicate (FS) - 1.00%, T_5-NPK + Potassium silicate (FS) - 0.25%, T_6 -NPK + Potassium silicate (FS) - 0.50%, T_7- NPK + Potassium silicate (FS) - 1.00%, T_8 - NPK + Potassium silicate (SA) - 50 kg ha^{-1}, T_9 - NPK + Potassium silicate (SA) - 100 kg ha^{-1} and T_{10} - NPK + Potassium silicate (SA) – 150 kg ha^{-1}. From T_2 to T_4 foliar spray was done at tillering stage and from $T_{5\ to}\ T_7$, foliar spray was done at tillering and panicle initiation stage.The experiment was conducted in randomized block design (RBD) design with three replications.

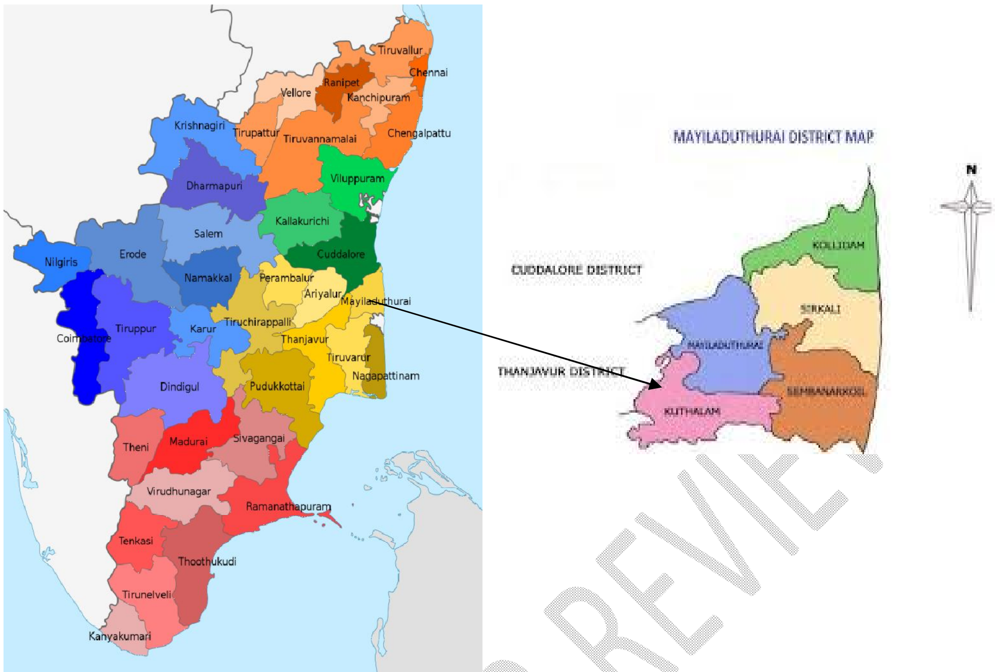

Figure 1. location of the study area (11.10°N and 79.67°E at an altitude of 16 m amsl)

2.3. Crop husbandry

The main field was puddle~~th~~rice to bring the soil to a satisfactory colloidal condition. After levelling the plots were laid out as per the specification of plot size (5 m x 4m), treatments and replications. The bunds of the plots were raised and strengthened in between the replications to prevent seepage of water nutrients from one plot to another. Rice crop var. ADT 43 of ~~twenty five~~twenty-five days old seedlings weretransplanted in the main field. Transplanting was done at the rate of two seedlings $hill^{-1}$. The spacing adopted was 15 x 10 cm. Gap filling was done at 7(days after transplanting~~)~~(DAT) with seedlings of same age. The recommended dose of 150:50:50 N, P_2O_5 and K_2O ha^{-1} through urea, superphosphate and muriate of potash was added uniformly to all the plots. The potassium silicate contains 22 per cent Si and 11 per cent K_2O. Foliar and soil application of silicon was applied as per the treatment schedule and amount of potassium silicate based on treatment was calculated. The amount of potassium supplied through potassium silicate was taken out while applying in recommended dose of potassium to all the plots.

2.4.Data collection and analysis

At the time of harvest, grain and straw yield was recorded separately from each plot and expressed as kg ha^{-1}. Grain and straw samples were analysed for nitrogen wet digestion of 0.5 g plant material with 12 ml of diacid mixture(H_2SO_4:$HCLO_4$-5:2) (Humphries, 1956), phosphorus by Vanadomolybdate phosphoric yellow colour method (Jackson,1973),,potassium by flame photometric method (Jackson, 1973), and silicon(Dai et al.,2005)content and respective nutrient uptake was computed. Grain samples were analysed for its quality viz.,Carbohydrate (Victor *et al.*, 1921), Amylose (McReady*et al.,* 1950) and true protein (Lowry *et al.*, 1951). The data were subjected to anova analysis using SPSS version 28.0.0.0 (190) and wherever the treatment differences were found significant (F test), critical differences were worked out at five per cent probability level and the values are furnished. Treatment differences which were not significant are denoted as “NS”.

3. Results and Discussion

3.1.Rice yield

Perusal of data furnished in Fig.1a showed significant impact of graded dose of foliar and soil application of silicon through potassium silicate on grain and straw yield over control. The grain yield ranged from 5283 to 6183 kg ha^{-1} and straw yield ranged from 5653 to 6740 kg ha^{-1}.Soil application of 50 kg Si ha^{-1} recorded the highest grain yield (6183 kg ha^{-1}) and straw yield (6740 kg ha^{-1}). Foliar spray of silicon increased the grain yield from 5530 to 6133 kg ha^{-1} over control (5283 kg ha^{-1}) and straw yield from 6028 to 6747 kg ha^{-1} over control (5653 kg ha^{-1}). Twice foliar spray of silicon recorded higher rice yield compared to single spray except foliar spray @ 1%. Among the foliar spray, application @ 0.5 and 0.25% twice recorded higher rice yield compared to their single spray. But when 1.0% Si foliar spray was applied twice, it reduced the yield. Soil application of 50 kg Si ha^{-1} was comparable with foliar spray of Si @ 1% applied at tillering stage. Per cent increase in grain yield ranged from 4.7 to 17 and straw yield ranged from 6.6 to 19.4 due to various treatment and the highest per cent increase in grain yield was noticed with soil application of 50 kg Si ha^{-1} (17.0) followed by single spray @ 1% Si applied at tillering stage (16.1). The lowest response was noticed with foliar spray of Si @ 0.25 per cent applied at tillering stage.Nitrogen fertilization can influence rice response to silicon fertilizer. Ke*et al.* (1993) reported that adequate supply of N can enhance rice yield response to silicon fertilization. In the present study, silicon application either through soil or foliar was accompanied by recommended dose of N fertilizer. This has improved N status of the soil and nitrogen uptake in rice. The observed increase in grain yield with silicon application to plants would have the potential to enhance the roots adsorptive capacity and nutrient uptake in nature and agricultural ecosystem (Korndofer*et al*., 1999). Method of fertilizer application used has very large effect on Si uptake. When silicon in soil solutions is higher (soluble Si), the plant content of the element is generally greater (Korndofer*et al*., 1999). DMP is linearly related to plant Si uptake. In the present study, addition of silicon either through soil or foliar enhanced the leaf Si concentration and silicon in the soil which would have contributed to higher grain yield. This was supported by significant positive correlation between grain yield with Si content ($r = 0.621^{**}$), Si uptake ($r = 0.687^{**}$) and available Si ($r = 0.78^{**}$). This was further confirmed by regression equation (Fig.2) where grain silicon content accounted 69.2 per cent variation in grain yield and Si uptake accounted for 38.3 per cent, 45.6 per cent and 49.5 per cent variation in grain yield at tillering, panicle and harvest stage respectively. The improvement in both grain and straw yields due to silicon might be attributed to enhancing the pollen viability and photosynthetic activity (Detmann*et al.,* 2012) and improving nutrient uptake (Pati*et al*., 2016, Crooks and Prentice, 2017, Cuong*et al.*, 2017). In the present study, higher uptake of nutrients by grain and straw was witnessed due to application of silicon. Prakash *et al*. (2010) reported increase in rice yield on additions of calcium silicate at 3-4 t ha^{-1} in coastal and hilly soils of Karnataka. Yogendra*et al*. (2014), Jawahar*et al*. (2015), Nagula*et al.* (2016), Malav*et al.* (2018) and Ali *et al*. (2020) reported that individual application of silicon produced the highest grain and straw yield in rice. Foliar spray at different concentration increased the grain yield. It is likely to play active role in biochemical processes of the plant. Okamoto (1993) and Hooda and Srivastava (1996) found that spray of soluble Si at 0.1 to 0.2 mg lit^{-1} solution as sodium silicate or 1% soluble as sodium silicate on the leaves of the rice plant increased plant growth and yield and the effect was attributed to a reduced rate of transpiration. Mobasser*et al.* (2008) and GhanbariMalidarreh*et al.* (2011) reported increase in rice yield on foliar applied silicon. The reproductive stage in the most affected by absence of silicon with reduction of up to 40 per cent in the number of grain bearing spikelet and 10 per cent on the total number of spikelet $panicle^{-1}$ (Ma *et al*., 1989). In the present study, foliar spray of 0.25 and 0.5% sprayed at tillering and panicle initiation stage recorded higher grain yield compared to application of same concentration at tillering stage only. Ahmad *et al*. (2013) reported higher rice yield with 1% Si foliar spray.

3.2. Macro nutrient uptake

Accumulation of other nutrients (N, P and K) by rice was significantly improved on addition of soil and foliar application of silicon over control (table1). In all cases, grain and straw accumulated lower N, P, K and Si in RDF alone compared to silicon supplementation. The highest uptake of N, P and K was noticed with 50 kg Si ha^{-1} and foliar spray at 1% applied attillering stage. But silicon uptake increased with silicon levels and foliar concentrations. The percent improvement in uptake of nutrients due to silicon fertilization ranged from (10.2 to 49.5, 13.1 to 27.8- nitrogen), (12.1 to 48.6, 42.5 to 99.4 – phosphorus), (3.9 to 37.0, 11.9 to 29.2- potassium) and (17.9 to 61.7, 44.2 to 75.3- silicon) in grain and straw, respectively. Singh et al (2005) reported that Si application has the potential in enhancing the availability of N in soil, resulting in an enhanced N uptake due to ample N availability. Siliconapplication enhanced more optimum use of nitrogen applied to rice (Savant et al., 1997). Meena*et al.* (2014) reported that with adequate Si, the uptake of N was increased. Silicon increased P content in grain and straw, which caused higher P uptake, which is attributed to enhanced translocation of P from root to shoot.Patra and Neue (2010) reported that silicon content of soil solution influenced P concentration in the plant at different stages of crop growth and uptake of P.Singh *et al.* (2006) also reported increase in K concentration and uptake in rice grain and straw on addition of 180 kg Si ha^{-1}. The improved the uptake of N, P and K in above-ground rice biomass(fig.3) is consistent with previous findings (Pati*et al.*, 2016, Crooks and Prentice, 2017 and Cuong et al., 2017). 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 (Pati*et al.*, 2016). Throughout the crop growth, there was close agreement between the expected uptake of Si and available silicon in soil. Regression analysis as shown (Fig.4) showed very good relationship between available silicon with silicon uptake at all stages. It indicated that 78.0 per cent, 82.0 per cent and 66.0 per cent variation in silicon uptake in grains at tillering, panicle initiation and harvest stage respectively was accounted by available silicon in soil.

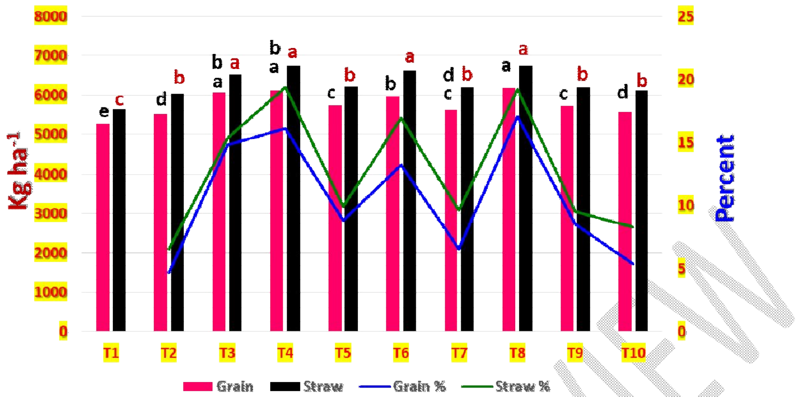

Fig.1a. Effect of potassium silicate on rice yield and percent increase over control

Different letters in each treatment and each column show significant difference at P 0.05 by least significant difference (LSD)

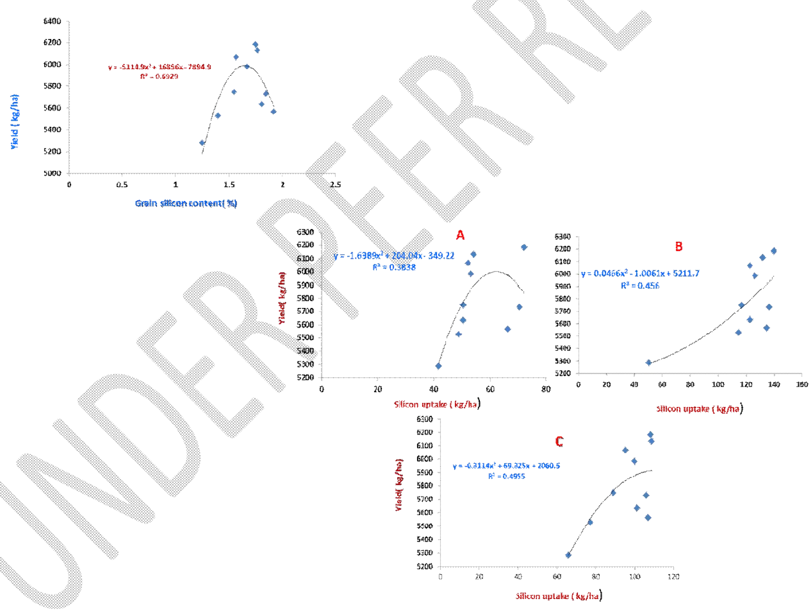

Fig.2. Quadratic relationship between grain yield with grain Si content and with Si uptake at a) Tillering stage b) Panicle initiation c) Harvest

Table 1. Effect of potassium silicate application on nutrient uptake (kg ha^{-1}) by grain and straw

Treatments	Nitrogen		Phosphorus		Potassium		Silicon	
	Grain	Straw	Grain	Straw	Grain	Straw	Grain	Straw
T_1 – RDF (Control)	20.6	37.3	7.40	3.39	18.1	39.4	66.1	96.1
T_2 – RDF + PS (FS) - 0.25% @ TS	22.7	42.2	8.29	4.83	18.8	44.1	77.4	138.6
T_3 – RDF + PS (FS) - 0.50% @ TS	26.1	46.9	10.3	5.87	22.0	48.3	95.2	157.2
T_4 – RDF + PS (FS) - 1.0% @ TS	27.6	50.6	11.1	6.74	22.7	50.6	108.6	171.3
T_5 – RDF + PS (FS) - 0.25% @ TS & PI	24.1	43.2	9.08	4.82	20.2	45.3	89.1	144.7
T_6 – RDF + PS (FS) - 0.5% @ TS & PI	26.5	49.2	10.5	6.62	22.1	51.1	99.9	163.3
T_7 – RDF + PS (FS) - 1.0% @ TS & PI	24.2	44.5	8.83	5.57	20.1	45.3	101.2	163.5
T_8 – RDF + PS (SA) - 50 kg ha^{-1}	30.8	47.7	11.0	6.76	24.8	50.9	108.2	157.9
T_9 – RDF + PS (SA) - 100 kg ha^{-1}	26.9	44.5	9.14	5.47	21.2	47.2	106.1	158.6
T_{10} – RDF + PS (SA) - 150 kg ha^{-1}	24.5	44.1	8.33	4.90	19.8	47.4	106.9	168.5
SE_d	2.55	2.19	0.42	0.47	2.14	2.80	1.21	1.38
CD @ 5%	3.36	4.61	0.89	0.98	4.51	5.89	3.58	4.10

[RDF- Recommended dose of fertilizer; PS- Potassium silicate; FS- Foliar spray; SA-Soil application; TS-tillering stage; PI-Panicle initiation; SEd-Standard error deviation ; CD- critical difference]

3.3. Silicon Use efficiency

Nutrient use efficiency has been extensively used as a measure of capacity of a plant to acquire and utilize nutrients for biological and grain yield (Gill et al., 2004).Silicon fertilization either through soil or foliar application significantly improved various silicon use efficiency viz., response ratio, physiological efficiency and apparent Si recovery. Foliar applications of silicon recorded higher silicon use efficiency compared to soil application. Response ratio, physiological efficiency and apparent Si recovery decreased with Si levels and maximum value was noticed with 50 kg Si ha^{-1}. Similarly foliar spray of 0.5% Si at tillering stage recorded higher silicon use efficiency compared to 0.25 and 1% Si. Further silicon use efficiency was higher when foliar spray was done at once compared to twice, irrespective of silicon concentration. (table2).Higher silicon use efficiency in rice could be due to higher uptake of silicon in rice grain.Greater nutrient use efficiency at lower level is common because of efficient utilization of nutrients at lower level (Fageria, 1992).

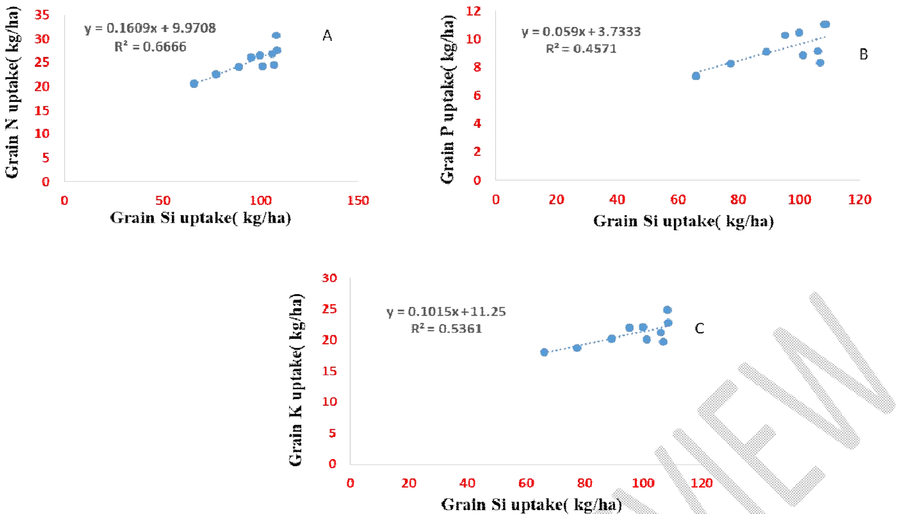

Fig.3. Linear relationship between Si uptake with a) N uptake b) P uptake c) K uptake

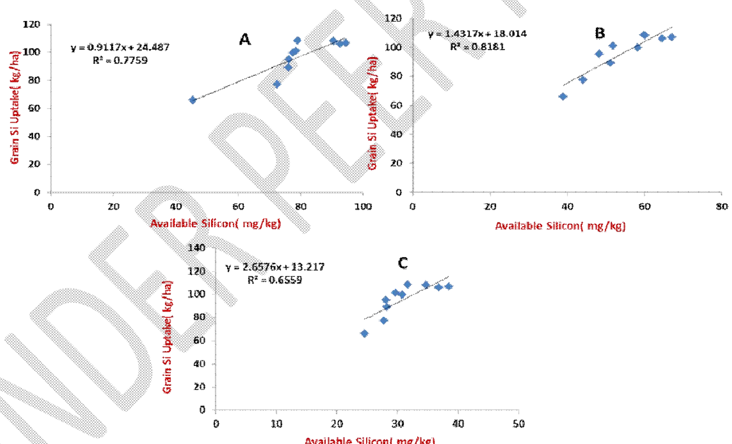

Fig.4. Linear relationship between grain Si uptake with available silicon at a) Tillering b) Panicle initiation c) Harvest

Table 2. Effect of potassium silicate application on silicon use efficiency

Treatments	Response Ratio (kg kg^{-1})	Apparent Si Recovery (%)	Physiological Efficiency (kg kg^{-1})
T_1 – RDF (Control)	-	-	-
T_2 – RDF + PS (FS) - 0.25% @ TS	98.7	452.0	21.8
T_3 – RDF + PS (FS) - 0.50% @ TS	156.7	582.0	26.9I
T_4 – RDF + PS (FS) - 1.0% @ TS	88.30	425.0	20.0
T_5 – RDF + PS (FS) - 0.25% @ TS & PI	110.0	460.0	20.3
T_6 – RDF + PS (FS) - 0.5% @ TS & PI	70.0	338.0	20.7
T_7 – RDF + PS (FS) - 1.0% @ TS & PI	17.5	176.0	9.97
T_8 – RDF + PS (SA) - 50 kg ha^{-1}	18.0	84.2	21.4
T_9 – RDF + PS (SA) - 100 kg ha^{-1}	4.50	40.0	11.3
T_{10} – RDF + PS (SA) - 150 kg ha^{-1}	2.17	27.2	6.95
SE_d	15.5	5.49	0.33
CD @ 5%	32.8	11.63	0.70

[RDF- Recommended dose of fertilizer; PS- Potassium silicate; FS- Foliar spray; SA-Soil application; TS-tillering stage; PI-Panicle initiation; SEd-Standard error deviation ; CD- critical difference]

3.4. Rice grain quality

Application of silicon through potassium silicate influenced carbohydrates(CHS), amylose and true protein content of rice grain compared to control (table 3). Foliar application of silicon at varied concentration and time interval did not improve carbohydrate content over control. However, soil application of silicon at 100 and 150 kg Si/ha did significantly improved carbohydrate content. With regards to amylose content, increasing rate of soil application of silicon reduced amylose content.Foliar spray of silicon from 0.25 to 1% applied once increased amylose content compared to double spray. Soil application of silicon netted higher true protein content than foliar spray. However, different levels of silicon had equal effect on true protein. Foliar spray of silicon from 0.25 to 1% increased true protein. The notional improvement in carbohydrate due to silicon might be attributed to the increments of photosynthetic pigments thereby results in enhancement of carbohydrate synthesis.Manal*et al.* (2014) also reported increase in carbohydrate content of rice grain due to rice seeds pre-treated with silicon. It has been well known that glutamic-pyruvic transaminase is an important enzyme being involved in amino acids and protein synthesis in rice grain (Miflim and Habash, 2002). Some reports demonstrated that the N concentration in rice grains was increased after applying Si, due to the promotion of transportation efficiency of N from leaves to grains induced by the enhancement of the activity of glutamic pyruvic transaminase in rice leaves (Jiang *et al*., 2004; Pati*et al.*, 2016).

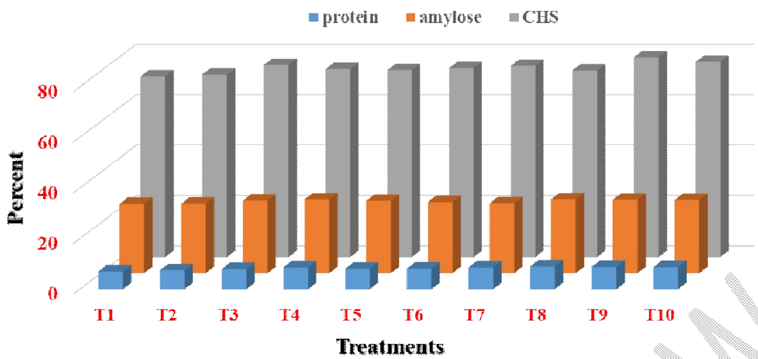

Fig.5. Effect of silicon on rice grain quality

Talebi*et* al. (2015) found that potassium silicate application of exogenous had a positive significant effect by increasing soluble protein and carbohydrate contents in the leaves of potato plants. Liu *et al.* (2017) also reported increase in protein concentration in rice grain due to silicon. Ahmad *et a*l. (2013) and Jawahar*et al.* (2019) reported increase in amylose content in rice with silicon. Present study results coherence with reports of previous studies that silicon application improved the rice grain quality significantly.

4. Conclusions

As rice is considered as silicon accumulator and responds significantly to silicon fertilization, a field experiment was conducted in farmers holding to pronounce the effect of potassium silicate applied as soil and or foliar on rice. Rice responded to silicon addition and soil application of 50 kg Si/ha recorded the maximum rice yield and was on par with foliar spray of Si@1% at critical growth stages of rice crop. The same treatment also showed maximum recovery of N, P and K by rice plant. However silicon uptake was higher with 150 kg Si ha^{-1} and 1% Si foliar sprays. Silicon use efficiency by rice crop was also benefitted by silicon application. Foliar spray registered higher silicon use efficiency than soil application. Also, silicon application found to be improved the grain quality compared to rice plants not received silicon. The optimum Si fertilizer rate both via soil and foliar application at critical stages of rice crop growth in different textured soils should be carried out according to the soil available Si levels.

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Declarations

Data availability Statement The data that support this work are available within the article itself.

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