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IMPACTS OF SILICON FOLIAR SPRAYING AND NITROGEN APPLICATION TECHNIQUES ON QUANTITATIVE AND QUALITATIVE PARAMETERS OF RICE AT DIFFERENT PLANTING SPACES

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ABSTRACT

The silicon (Si) foliar application along with timely application of nitrogen (N) can be help to increase the quantity and quality of crops. Also, planting spaces is an agronomic technique that can affect yield and quality of rice. The objective of this study was to evaluate the effects of Si foliar application and N application techniques on yield components, grain yield and accumulation of Si and N in rice grains at different planting spaces. The experiment was conducted as a split-split-plot in a randomized complete block design with three replications during two crop years of 2018 and 2019. The experimental treatments included the main plot assigned to planting spaces (25×10 cm, 20×10 cm), the sub-plot assigned to N application techniques (N application as 33.3% at basal + 33.3% at panicle initiation + 33.3% at full heading, N application as 40% at basal + 40% at panicle initiation + 20% at full heading), and the sub-sub-plot assigned to foliar application of Si (control or non-use of Si, Si foliar application). The results indicated that the reducing planting space (20×10 cm) resulted in an increase in the number of panicle number m^{-2} by 9.3%, followed by an improvement in grain yield by 9.7% compared with planting distance of 25×10 cm. The plants that received N in three equal splits had higher grain yield (6993.1 $kg.ha^{-1}$). The Si-treated plants showed both higher yield parameters and greater physiological characteristics when compared with control plants. We observed an increase in grain yield (10%), N concentration (7%) and uptake (14.3%) in grain, protein content (6.8%), and nitrogen use efficiency (7.1%) by supplying Si fertilizer. Overall, our results revealed that foliar application of Si could be an effective technique for increasing rice grain yield and improving rice nutritional quality.

Keywords: rice yield, nutritional quality, silicon foliar application, planting space, plant nutrition.

INTRODUCTION

Rice (*Oryza sativa* L.) is one of the most important staple food crops in the world and is consumed by more than 50% of the word population (Zhou et al., 2018). Nitrogen (N) is one of the most important nutrients for the rice production and its deficiency or excess reduces the grain yield (Zhou et al., 2019). Proper management of N fertilizer usage in rice fields increases N use efficiency and improves grain yield in paddy fields and thus enhances the farmers' incomes in the regions (Faraji et al., 2012). N fertilizer should be applied at the right time to achieve the optimum grain yield (Thu et al., 2014). Therefore, N fertilization and optimal technique of N application are important for higher grain production (Sathiya and Ramesh, 2009). Proper application of N fertilizer is one of the most important agronomic techniques that affect the yield and quality of rice (Lampayan et al., 2010). The increase in rice yield depends greatly on the N regulation at different growth stages (Pan et al., 2012). Optimal management of N application at different growth phases by regulating the source-sink relationship increases rice grain yield (Sui et al., 2013). Jafari Kelarijani et al. (2021) observed that efficient management of N fertilizer in paddy fields can be help to increase rice production potential. Kamruzzaman et al. (2013) suggested that N application in three equal splits at 15, 30 and 45 days after transplanting (DAT) would be essential for the production of high grain yield. In another study, Djaman et al. (2018) revealed that N application in four splits could be recommended to improve rice production and food security. Anil et al. (2018) found that the application of N (180 kg ha^{-1}) in four equal splits (basal, 20, 40 and 60 DAT) increased significantly

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the number of tillers m^{-2} and rice grain yield. Dahipahle and Singh (2018) reported that when N (150 kg ha^{-1}) was supply to rice in three splits as 33.3% at 15-20 days after sowing (DAS) + 33.3% at active tillering stage + 33.3% at panicle initiation stage enhanced significantly the crop growth and yield.

Among the agronomic techniques used to help rice plants to improve the grain yield and quality, is the foliar application of an abundant macro-element such as silicon (Si). Si is the second most abundant element in the Earth's crust after oxygen (Liao et al., 2020). Si is one of the beneficial elements for rice plants which can be increase the plant growth and productivity (Kheyri et al., 2019a). Si plays a vital role for rice plants by enhancing size and strength of sink (Lavinsky et al., 2016). It is documented that addition of Si to plant enhances the accumulation of nutrients such as Si, N, P and K in rice tissue (Cuong et al., 2017). The higher rice grain yield by Si foliar application could be attributed to greater nutrient accumulation in plant tissue (Kheyri et al., 2019b). Zia et al. (2017) found that the application of Si significantly increased the Si concentration in rice plants. Agostinho et al. (2017) demonstrated that the Si application can be an effective way for improving yield and increasing Si accumulation in rice. Patel et al. (2017) reported that Si nutrition helped to enhancing macronutrients and micronutrients content in rice grain and straw.

Choosing the right planting space (PS) is one of the vital factors in increasing the plant population (Tian et al., 2017). Reducing PS leads to an increase in plant density and ultimately affects the yield and quality of rice grains (Hu et al., 2020). Appropriate increase of plant population enhances the grain yield by balancing the yield components factors (Yang et al., 2019). Reduction of hill density leads to poor grain filling and thus reduces rice grain yield (Ao et al., 2019). Alipour Abookheili and Mobasser (2021) reported that the number of panicle m^{-2} and grain yield in 30×10 cm^2 PS were higher than 20×20 cm^2 and 25×25 cm^2 PS. In their 2-yr study, Sandhu et al. (2015) indicated that decreasing the planting distance increased grain yield. In a previous study on rice Kheyri et al. (2016) suggested the 20×20 cm PS as the suitable distance for Tarom Amrolahi variety. Therefore, determining the proper PS is necessary to improve grain yield and increase nitrogen use efficiency (NUE) (Zheng et al., 2020).

The aim of the present study was to investigate the effects of Si foliar application and N application time on yield components, grain yield, nutrient accumulation, protein content and N use efficiency in rice at different planting spaces.

MATERIAL AND METHODS

Experimental site

This experiment was performed at the farmer's field in Sari, Mazandaran Province, Iran (36°56′N, 53°01′E; 15 m above sea level) during the two crop years of 2018 and 2019. The meteorological data of the experimental site during growth and development of rice for both crop years were provided from the nearest synoptic meteorological station to the paddy field and presented in Table 1. The soil of experimental site was classified as a Loam-textured. Soil sampling was performed at the experimental site at depths of 0-30 cm before the initiating experiment. Physical and chemical analyses of the soil included analysis of soil texture by hydrometric method (Bouyoucos, 1962), soil EC and pH by preparation of soil suspension (soil/water 1:5), organic matter using the volumetric method (Walkley and Black, 1934), total N by Kjeldahl method (Bremner and Mulvaney, 1982), extractable P by extraction sodium bicarbonate (Olsen et al., 1954), and extractable K by flame photometer techniques (Toth and Prince, 1949). Table 2 shows the soil physical and chemical properties of the experimental site.

Table 1. Meteorological parameters of the experimental site consisted of minimum (Min), maximum (Max) and average (Avg) temperature, total precipitation (TP) and total sunny hours monthly (TSHM) for both years (2018 and 2019)

Months	Average temperature (°C)						TP (mm)		TSHM (h)	
	Min		Max		Avg					
	2018	2019	2018	2019	2018	2019	2018	2019	2018	2019
Apr	10.3	10.6	21.3	18.8	15.8	14.7	38.3	78.2	148.7	131.5
May	15.1	15.3	25.7	25.8	20.4	20.6	18.6	51.1	194.5	200.6
Jun	20.0	21.4	28.3	31.7	24.1	26.5	12	1	171.2	272.4
Jul	24.5	24.0	34.5	32.0	29.5	28.0	7.4	69.9	255.4	202.4
Aug	25.2	23.3	32.9	32.3	29.0	27.8	72.6	22.3	142.8	184.2
Sep	24.5	20.6	31.7	29.4	28.1	25.0	11.9	45	182.8	160.3

Table 2. Physical and chemical characteristics of the experimental soil prior to experiment

Parameters	Unit	Concentration	
		2018	2019
Sand	%	39	42
Silt	%	36	32
Clay	%	25	26
Textural class		Loam	Loam
pH		7.04	7.54
EC	ds m^{-1}	0.86	1.41
Organic matter	%	2.82	2.70
Total N	%	0.18	0.16
Available P	mg kg^{-1}	7.9	8.1
Available K	mg kg^{-1}	165	181

Experimental design and treatments

The experiment was carried out as a split-split-plot in a randomized complete block design with three replications. The experimental treatments included the main plot assigned to planting space (25×10 cm, 20×10 cm), the sub-plot assigned to N application techniques (N application as 33.3% at basal + 33.3% at panicle initiation + 33.3% at full heading, N application as 40% at basal + 40% at panicle initiation + 20% at full heading), and the sub-sub-plot assigned to foliar application of Si (control or non-use of Si, Si foliar application).

Rice cultivation and management

A local rice (*Oryza sativa* L.) cultivar Tarom Hashemi was used as plant material in the present study. The rice seeds were pregerminated by soaking in water for 24 h and incubated for 48 h in the dark. Germinated seeds were sown in nursery beds. The nursery land was prepared one week before sowing. Land preparation was performed by puddling, harrowing and leveling the soil in the field. The plots size was 10 m^2 (2×5 m). The plots boundaries were enclosed with a plastic cover up to a depth of 30 cm to prevent the outflow of water and fertilizers between plots. All the experimental plots received phosphorus and potassium as basal at the rate of 130 kg P_2O_5 ha^{-1} as triple superphosphate and 150 kg K_2O ha^{-1} as potassium sulfate, respectively. N (urea 46%) was applied at the rate of 150 kg ha^{-1} based on the treatments defined in the experimental plots. Si fertilizer from the source of potassium silicate (produced by AgriTecno Company) was sprayed on plants at a rate of 5 per thousand. To control weeds, Butachlor herbicide was applied at a concentration of 3.5 L ha^{-1} one week after transplanting, and the manual weeding was performed in week 2 and 4 after transplanting. In order to control *Chilo suppressalis*, diazinon insecticide (10% Granule) was applied at a rate of 15 kg ha^{-1} at the maximum tillering and heading stages.

Sampling and measurement

At physiological maturity, plant samples were randomly selected from each plot after removing the border rows. The panicle length was determined by measuring 20 panicles in each plot. The number of total tillers hill^{-1} was determined from 15 hills plot^{-1}. The number of panicles m^{-2} was obtained by harvesting and counting all panicles from a 2 m^{2} area in each plot. The Percentage of filled spikelets panicle^{-1} was obtained from the ratio of the number of filled spikelets panicle^{-1} to the total number of spikelets panicle^{-1}. The 1000-grain weight was recorded by counting and weighing 10 samples of 100 seeds. The grain yield were measured by manually harvesting an area of 4 m^{2} (2×2 m) in the middle of each plot and based on 14% moisture content. The determination of accumulation of Si and N in rice grains was performed according to the methods described by Fallah et al. (2004) and Emami (1996), respectively. The N uptake in grain of rice was calculated by multiplying the dry matter accumulation in grain yield of rice with their respective concentrations expressed in kg ha^{-1}. The protein content in grain was calculated by total nitrogen multiplied by 5.95 (Lopez et al., 2010). The nitrogen use efficiency (NUE) was derived using the following formulae:

$$\text{NUE (kg.kg}^{-1}) = \frac{\text{grain yield } (\text{kg.ha}^{-1})}{\text{nitrogen uptaked by the plant } (\text{kg.ha}^{-1})}$$

Statistical analysis

Statistical analysis of data was performed using SAS software. Combined analysis of variance was conducted as split-split-plot in a randomized complete block design with three replications. Mean values were compared using least significant difference (LSD) test at 5% probability level.

RESULTS AND DISCUSSION

Growth parameters and grain yield

The results of combined analysis of variance showed that the main effect of year was significant on all the yield components. The grain yield was not affected by the year. The number of total tillers hill^{-1}, number of panicles^{-2}, and grain yield were significantly affected by the effect of planting space. The panicle length and grain yield were affected by the main effect of nitrogen application techniques. The simple effect of silicon was significant only on grain yield. Also, the 1000-grain weight was significantly (P≤0.05) affected by the three-way interaction between planting space × nitrogen application techniques × silicon foliar application (Table 3).

Table 3. Combined analysis of variance for PS, NAT and Si as well as their interactions on yield components and grain yield of rice

Source of variation	df	Panicle length	No. of total tillers per plants	No. of panicle m^{-2}	Percent of filled spikelet panicle^{-1}	1000-grain weight	Grain yield
Year (Y)	1	10.82**	210.50**	632272.52**	131.27*	14.08**	1208088.02^{ns}
Replication (Y)	4	6.29	6.00	13820.83	16.13	1.16	1734897.39
Planting space (PS)	1	0.80^{ns}	78.79**	27888.52*	18.32^{ns}	0.75^{ns}	5559004.68*
Y×PS	1	3.21^{ns}	5.89^{ns}	20708.52^{ns}	0.41^{ns}	0.75^{ns}	1471750.52^{ns}
Error	4	2.63	2.86	4276.33	40.81	4.00	1671977.60
Nitrogen application techniques (NAT)	1	12.31**	2.91^{ns}	623.52^{ns}	20.38^{ns}	0.75^{ns}	3799688.02*
Y×NAT	1	13.83**	4.38^{ns}	999.18^{ns}	13.04^{ns}	0.08^{ns}	2937825.52^{ns}
PS×NAT	1	0.53^{ns}	1.87^{ns}	10296.02^{ns}	5.86^{ns}	10.08**	174604.68^{ns}
Y×PS×NAT	1	0.03^{ns}	20.64*	667.52^{ns}	43.01*	0.75^{ns}	306400.52^{ns}
Error	8	0.94	4.08	4217.87	17.04	1.91	1151534.37
Silicon (Si)	1	0.11^{ns}	0.33^{ns}	325.52^{ns}	8.45^{ns}	0.75^{ns}	5751213.02*
Y×Si	1	0.05^{ns}	0.75^{ns}	4780.02^{ns}	2.86^{ns}	0.08^{ns}	519792.18^{ns}
PS×Si	1	1.05^{ns}	0.002^{ns}	20542.68^{ns}	46.49^{ns}	0.75^{ns}	400588.02^{ns}
Y×PS×Si	1	0.29^{ns}	2.53^{ns}	16762.68^{ns}	6.64^{ns}	0.75^{ns}	1838875.52^{ns}
NAT×Si	1	4.56^{ns}	4.28^{ns}	13.02^{ns}	3.95^{ns}	2.08^{ns}	17442.18^{ns}
Y×NAT×Si	1	0.33^{ns}	0.39^{ns}	7326.02^{ns}	20.38^{ns}	0.08^{ns}	129688.02^{ns}
PS×NAT×Si	1	0.74^{ns}	1.12^{ns}	1598.52^{ns}	2.52^{ns}	4.08*	88.02^{ns}
Y×PS×NAT×Si	1	0.002^{ns}	0.08^{ns}	5963.02^{ns}	27.63^{ns}	0.08^{ns}	1807692.18^{ns}
Error	16	1.15	4.50	4662.81	29.21	0.58	817706.77
CV (%)	-	4.56	16.39	13.83	6.15	2.86	13.47

^{ns}, *, and ** are non-significant and significant at the 5 and 1% probability levels, respectively.

As shown in Table 4, the panicle length in the first year of the experiment was 4% higher than the second year. There was no significant difference in panicle length between two planting spaces, as well as between the foliar application and non-application of Si. Our results indicated that the panicle length increased by 4.2% when rice plants received the N fertilizer as 33.3% at basal + 33.3% at panicle initiation + 33.3% at full heading compared with N application as 40% at basal + 40% at panicle initiation + 20% at full heading. These findings are in agreement with Kamruzzaman et al. (2013) and Alipour Abookheili et al. (2020), who reported that the N application in three equal splits significantly improved the rice panicle length. In this study, the panicle length was not affected by Si treatment. Similar to our results, the foliar application of Si had no significant effect on panicle length of rice (Sheykhzadeh et al., 2022).

Table 4. Mean comparison of main effects of Y, PS, NAT and Si on yield components and grain yield of rice

Experimental treatments	Panicle length (cm)	No. of total tillers per plants	No. of panicle m^{-2}	Percent of filled spikelets $panicle^{-1}$	1000-grain weight (g)	Grain yield ($kg.ha^{-1}$)
Year						
First	24.05a	10.8b	378.7b	86.2a	26.08b	6553.1a
Second	23.10b	15.03a	608.2a	89.5a	27.16a	6870.4a
Planting space						
25×10 cm	23.7a	14.2a	469.3b	87.2a	26.7a	6371.5b
20×10 cm	23.4a	11.6b	517.5a	88.4a	26.5a	7052.1a
Nitrogen application techniques						
NAT1	24.08a	12.6a	489.8a	88.5a	26.7a	6993.1a
NAT2	23.07b	13.1a	497.0a	87.2a	26.5a	6430.4b
Silicon application						
Control	23.6a	12.8a	490.8a	87.4a	26.7a	6365.6b
Silicon	23.5a	13.02a	496.1a	88.3a	26.5a	7057.9a

Means in columns followed by the same letter(s) are not significantly different at $P \leq 0.05$;
NAT1: nitrogen application technique as 33.3% at basal + 33.3% at panicle initiation + 33.3% at full heading;
NAT2: nitrogen application technique as 40% at basal + 40% at panicle initiation + 20% at full heading.

Our findings showed that the number of total tillers per plants in the second year was 28% higher than in the first year of the experiment. The higher growth parameters in the second year of this study could be attributed to improvement of environmental conditions, especially temperature and sunny hours (Table 1) during rice growing season compared with first year. It has been reported that there is a direct relationship between the yield components of rice and environmental factors such as light and temperature (Deng et al., 2015).

The results indicated that the increase in planting space (25×10 cm) led to an increase in number of total tillers by 18.3% compared with planting space of 20×10 cm (Table 4). The reduction in planting space followed by an increase in planting density reduced the number of tillers due to more competition between rice seedlings for nutrient absorption (Alipour Abookheili and Mobasser, 2021). Our findings are further strengthened by the findings of Koireng et al. (2019), who reported that the number of tillers m^{-2} significantly increased by enhancing planting spaces and reducing planting density. These findings are in agreement with Halder et al. (2018) and Kheyri et al. (2016). There was no significant difference between application and non-application of Si in terms of total tillers number. However, the Si foliar application had better positive impacts on number of total tillers than control plants. In similar results, Kheyri et al. (2019a) reported that the plants treated with both nano-Si and calcium silicate produced significantly higher total tillers when compared to control plants.

In the present study, the number of panicle m^{-2} was higher in the second year than first year by 37.7%, which was due to the increase in the total tillers number in the second year compared with first year. The Higher panicle m^{-2} results in greater grain yield and vice versa. We observed that the number of panicle m^{-2} significantly increased by decreasing planting space. The plants grown at 20×10 cm planting spacing showed higher panicle number m^{-2} (9.3%) when compared to plants grown at 25×10 cm spacing (Table 4). Our results are confirmed by Chen et al. (2019), who found that the number of panicle m^{-2} significantly increased by reduces in planting spaces and enhances in planting density. The findings in our study that the number of panicle m^{-2} exhibited a significant increase at 20×10 cm planting spacing was consistent with Kheyri et al. (2016) who reported that the number of panicle m^{-2} in rice significantly increased in response to decreasing planting spaces due to enhancing number of stems m^{-2}. Previous studies revealed that the panicle number m^{-2} plays a vital role in increasing rice grain yield (Kheyri et al., 2016; Chen et al., 2020). The Si treated plants had slight higher panicle number m^{-2} (496.1 panicles) over control plants (490.8 panicles), although there was no significant difference between application and non-use of Si. In another study, Sheykhzadeh et al. (2022) found that foliar application of Si at critical growth stages of rice helps to increase the total number of spikelets panicle^{-2} and improve the rice grain yield.

Our results showed that there was no significant difference between various experimental treatments in terms of the percent of filled spikelets panicle^{-1}. However, the plants grown at 20×10 cm planting spacing, N application in three equal splits (NAT1) and Si foliar application had positive effects on percent of filled spikelets panicle^{-1} (Table 4). Alipour Abookheili et al. (2020) were observed the higher number of filled spikelets when N fertilizer applied in three equal splits. Kheyri et al. (2019a, b) demonstrated that Si-treated plants had higher number of filled grains panicle^{-1} when compared with plants did not receive Si fertilizer. Lavinsky et al. (2016) reported that the Si application (2 mM) at reproductive growth phase of rice enhanced the number of filled grains panicle^{-1}.

The results presented in Table 5 indicated that the 1000-grain weight had higher value (27.66 g) at planting distance of 25×10 cm by Si foliar spraying and N application as 33.3% at basal + 33.3% at panicle initiation + 33.3% at full heading, whereas the plants grown at planting spaces of 20×10 cm showed higher thousand-grain weight (TGW) (27.33 g) when Si foliar sprayed and N fertilizer applied as 40% at basal + 40% at panicle initiation + 20% at full heading. This result reveals that at planting distance of 20×10 cm, more N fertilizer application at the vegetative growth stage along with Si application can be help to ameliorate TGW weight. However, the greatest TGW in both planting spaces was observed in Si-treated plants. Kheyri et al. (2019a, b) also observed that Si application via either nano-Si or calcium silicate improved growth and yield of rice plants compared with control plants. In a 2-yr study, Dahipahle and Singh (2018) found that the N application in three equal splits at the vegetative and reproductive growth phases resulted in highest TGW.

Table 5. Mean comparison of interactions between PS, NAT and Si on 1000-grain weight of rice

Planting space	25×10 cm		20×10 cm	
Treatments	NAT1	NAT2	NAT1	NAT2
Control	27.00abc	26.00cd	26.66abcd	26.33bcd
Silicon application	27.66a	26.33bcd	25.66d	27.33ab

Means in columns followed by the same letter(s) are not significantly different at P ≤ 0.05;
NAT1: nitrogen application technique as 33.3% at basal + 33.3% at panicle initiation + 33.3% at full heading;
NAT2: nitrogen application technique as 40% at basal + 40% at panicle initiation + 20% at full heading.

The assay of grain yield revealed that the plants grown at planting distance of 20×10 cm had highest grain yield (7052.1 kg.ha^{-1}), whereas the increase in planting space (25×10 cm) resulted in the yield reduction of 9.7% (Table 4). The higher yield at planting space of 20×10 cm could be attributed to greater panicle number m^{-2}. Alipour Abookheili et al. (2020) indicated that reducing planting space form 25×25 cm to 30×10 cm enhanced rice grain yield by 20.3% by increasing number of panicles m^{-2}. Similar findings were confirmed by Zhou et al. (2019), Zheng et al. (2020) and Chen et al. (2019), who reported that higher grain yield was observed in lower planting spaces followed by higher planting density.

In this research, the application of N fertilizer in three equal splits (NAT1) significantly increased the grain yield by 8% when compared with NAT2 treatment (Table 4). Optimal splitting of N fertilizer at different growth stages improves rice grain yield by enhancing N uptake by the plant (Esmaeilzadeh Moridani et al., 2011). Faraji et al. (2011) documented the increase in grain yield of rice by N splitting application in appropriate doses.

We also observed that the plants untreated with Si showed the lower yield (6365.6 kg.ha^{-1}), whereas the Si-treated plants had 10% higher grain yield than control plants (Table 4). Foliar application of Si increases the rice grain yield by facilitating the nutrients uptake by the plant (Kheyri et al., 2018). Cuong et al. (2017) reported that the Si-treated rice plants showed higher grain yield due to increasing yield attributes and ameliorating nutrients accumulation. Kheyri et al. (2019a) found that the application of calcium silicate and nano-Si increased rice grain yield compared with control plants by 6.9% and 9.6%, respectively, which is consistent with the results of the present study.

Physiological parameters

The results of combined analysis of variance revealed that the all physiological parameters were significantly affected by the simple effects of year. The main effects of planting spaces and nitrogen application techniques were not significant on physiological characteristics of rice. Among physiological traits, only nitrogen uptake in grain was significantly ($P<0.05$) affected by silicon foliar application. The physiological parameters were not affected by the three-way interaction between planting space × nitrogen application techniques × silicon foliar application (Table 6).

Table 6. Combined analysis of variance for PS, NAT and Si as well as their interactions on Si and N accumulation in grain, protein content in grain and nitrogen use efficiency of rice

Source of variation	df	Si concentration in grain	N concentration in grain	N uptake in grain	Protein content in grain	N Use Efficiency
Year (Y)	1	0.229**	0.569**	1708.10*	20.30**	868.45**
Replication (Y)	4	0.012	0.096	1073.81	3.42	8.48
Planting space (PS)	1	0.016^{ns}	0.048^{ns}	276.16^{ns}	1.74^{ns}	253.12^{ns}
Y×PS	1	0.001^{ns}	0.011^{ns}	53.19^{ns}	0.42^{ns}	21.10^{ns}
Error	4	0.039	0.034	515.85	1.22	32.14
Nitrogen application techniques (NAT)	1	0.010^{ns}	0.084^{ns}	3.66^{ns}	2.99^{ns}	242.82^{ns}
Y×NAT	1	0.006^{ns}	0.065^{ns}	1197.15^{ns}	2.29^{ns}	19.01^{ns}
PS×NAT	1	0.003^{ns}	0.035^{ns}	372.63^{ns}	1.25^{ns}	54.53^{ns}
Y×PS×NAT	1	0.007^{ns}	0.036^{ns}	58.60^{ns}	1.29^{ns}	143.77^{ns}
Error	8	0.018	0.032	262.37	1.14	40.28
Silicon (Si)	1	0.002^{ns}	0.089^{ns}	1951.80*	3.15^{ns}	60.23^{ns}
Y×Si	1	0.011^{ns}	0.312*	2814.65**	11.06*	60.62^{ns}
PS×Si	1	0.006^{ns}	0.002^{ns}	89.21^{ns}	0.08^{ns}	2.18^{ns}
Y×PS×Si	1	0.001^{ns}	0.222^{ns}	275.61^{ns}	7.93^{ns}	111.59^{ns}
NAT×Si	1	0.038^{ns}	0.062^{ns}	373.49^{ns}	2.20^{ns}	8.48^{ns}
Y×NAT×Si	1	0.30^{ns}	0.000^{ns}	55.61^{ns}	0.001^{ns}	6.50^{ns}
PS×NAT×Si	1	0.004^{ns}	0.000^{ns}	1.55^{ns}	0.01^{ns}	10.76^{ns}
Y×PS×NAT×Si	1	0.000^{ns}	0.007^{ns}	117.27^{ns}	0.25^{ns}	64.15^{ns}
Error	16	0.024	0.065	328.45	2.32	68.24
CV (%)	-	15.80	20.67	21.91	20.68	27.35

^{ns}, *, and ** are non-significant and significant at the 5 and 1% probability levels, respectively.

In this study, the Si grain concentration in the second year (1.05%) was higher than first year (0.91%). Our findings showed that the different experimental treatments did not have a significant effect on Si concentration in rice grains. However, the plants grown at planting space of 20×10 cm, N application as 40% at basal + 40% at panicle initiation + 20% at full heading and foliar application of Si on plants produced higher Si concentration in grain (Table 7). Razavipour et al. (2018) observed the positive impacts of N application at different growth phases of rice plants on nutrients uptake in grain. The correct technique of using N fertilizer during the rice growing season can be helps to enhancing plant growth, improving photosynthesis, and increasing N concentration in grain (Moslehi et al., 2016). Our results are in agreement with Kheyri et al. (2019a) who documented that addition of Si to rice plants enhanced the grain Si accumulation. Cuong et al. (2017) also observed the higher Si content in rice grains by application of Si fertilizer.

Table 7. Mean comparison of main effects of Y, PS, NAT and Si on N and Si accumulation in grain, protein content in grain and nitrogen use efficiency of rice

Experimental treatments	Si concentration in grain (%)	N concentration in grain (%)	N uptake in grain ($kg.ha^{-1}$)	Protein content in grain (%)	N Use Efficiency ($kg.kg^{-1}$)
Year					
First	0.91b	1.34a	88.67a	8.01a	25.95b
Second	1.05a	1.12b	76.74b	6.71b	34.45a
Planting space					
25×10 cm	0.96a	1.27a	80.30a	7.55a	27.90a
20×10 cm	1.00a	1.20a	85.10a	7.17a	32.50a
Nitrogen application techniques					
NAT1	0.96a	1.19a	82.98a	7.11a	32.45a
NAT2	0.99a	1.28a	82.43a	7.61a	27.95a
Silicon application					
Control	0.97a	1.19a	76.33b	7.10a	29.08a
Silicon	0.98a	1.28a	89.08a	7.62a	31.32a

Means in columns followed by the same letter(s) are not significantly different at $P \leq 0.05$;
NAT1: nitrogen application technique as 33.3% at basal + 33.3% at panicle initiation + 33.3% at full heading;
NAT2: nitrogen application technique as 40% at basal + 40% at panicle initiation + 20% at full heading.

The results presented in Table 7 showed that the N concentration in grain in the first year (1.34%) was significantly higher than the second year (1.12%) of this study. We found that the grain N uptake in plants grown in the first year of the experiment had a similar trend to grain N concentration. The planting space of 20×10 cm resulted in 6% higher N uptake than planting space of 25×10 cm. In this research, the grain N uptake was increased in response to Si fertilization. The Si foliar application enhanced N uptake in rice grains by 14.3% compared with control plants. The augmentation in growth, yield and quality of rice could be attributed to the ameliorating uptake of nutrients such as Si, Zn and N due to the application of Si fertilizer (Kheyri et al., 2019a). Gou et al. (2020) documented the positive impacts of Si on N nutritional processes such as uptake such as uptake, assimilation, and remobilization. Si is able to improve N uptake in rice plants in the situation of non-optimal N supply (Deus et al., 2020). Liang et al. (2021) found that the proper application of Si fertilizer helped to improving N availability for rice plants in paddy fields. Our findings are confirmed by Patel et al. (2017) and Cuong et al. (2017) who demonstrated that Si application increased the N accumulation in rice plant tissue.

The protein content was only affected by the year. Likewise, it was significantly higher in the first year (8.01%) than in the second year (6.71%) (Table 7). The higher protein content in the first year was due to the greater N concentration and uptake in this year compared with second year. N fertilizer affects rice grain quality by increasing protein accumulation (Hao et al., 2007). In this study, the use of Si had slight better impacts on grain protein content compared to non-application of Si. Yazdpour et al. (2014) suggested that foliar application of Si on rice plants significantly increased N concentration and protein content, which is consistent with the results of the present study. Liu et al. (2017) indicated that addition of Si to rice significantly increased the protein content by 6.19% and 5.52% in milled and brown rice, respectively. Our results are further strengthened by the findings of Zeng et al. (2011), Cuong et al. (2017) and Kheyri et al. (2019a), who observed the enhancing protein content and improving grain quality in rice by supplying Si fertilizer.

As shown in Table 7, the nitrogen use efficiency (NUE) in the second year was 24.7% higher than in the first year. The results indicated that the NUE was higher at planting space of 20×10 cm, N application as 33.3% at basal + 33.3% at panicle initiation + 33.3% at full heading, and foliar application of Si by 14.1%, 13.9% and 7.1%, compared with planting space of 25×10 cm, N application as 40% at basal + 40% at panicle initiation + 20% at full heading, and non-use of Si fertilizer, respectively. It has been reported that the N physiological efficiency in rice reduced by the increase of N application rate (Yesuf and Balcha, 2014). Dehpouri et al. (2022) found that the increase in N consumption resulted in the reduction of N efficiency. On the other hand, Asadi et al. (2012) mentioned that the NUE was not affected by N application in different rice growth stages. Si application increases N uptake and NUE by improving source capacity and sink strength (Mohanty et al., 2019). Sabaghnia et al. (2018) reported that the Si-treated plants showed higher fertilizer efficiency compared with control plants. Our results are in agreement with Liao et al. (2020) who documented that Si application could be an effective technique for increasing plant growth and improving N fertilizer efficiency. Increasing NUE at whole-plant level of wheat by using Si fertilizer has also been reported (Neu et al., 2017).

CONCLUSIONS

Our findings illustrated that the plants grown at planting space of 20×10 cm showed the higher panicles number m^{-2}, followed by higher grain yield, and greater N uptake in grain and higher NUE compared with 25×10 cm planting spacing. The NAT1 treatment improved the grain yield and NUE when compared with NAT2 treatment. The addition of Si fertilizer to rice plants ameliorated the yield components, grain yield, and physiological parameters of rice compared with control plants. The foliar application of Si was able to enhance the yield by 10%, improve the N uptake by 14.3%, and increase the NUE by 7.1% in rice plants compared with non-application of Si. Also, an increase in the concentrations of Si and N, and an improvement in the protein content were observed for rice receiving foliar Si. Overall, the results of the present study indicated that the foliar application of Si fertilizer could increase rice grain yield by enhancing yield components and improve rice grain quality by increasing nutrients accumulation and protein content in rice.

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