Pak. J. Bot., 44(3): 891-897, 2012.

SILICON TREATMENT TO RICE (*ORYZA SATIVA* L. cv 'GOPUMBYEO') PLANTS DURING DIFFERENT GROWTH PERIODS AND ITS EFFECTS ON GROWTH AND GRAIN YIELD

YOON-HA KIM[1], ABDUL LATIF KHAN[1,2], ZABTA KHAN SHINWARI[3], DUCK-HWAN KIM[1], MUHAMMAD WAQAS[1], MUHAMMAD KAMRAN[1] AND IN-JUNG LEE[1]*

[1]*School of Applied Biosciences, Kyungpook National University, Daegu, 702-701, Korea*
[2]*Department of Botany, Kohat University of Science and Technology, Kohat Pakistan*
[3]*Department of Biotechnology, Qauid-e-Azam University, Islamabad, Pakistan*
**Corresponding author: e-mail: ijlee@knu.ac.kr*

Abstract

Silicon (Si) has been considered a beneficial element for plant growth. We have assessed the effects of Si application on rice (*Oryza sativa* L.) growth and its grain yield at field level. For this, we performed two experiments. In experiment 1, we applied Si of three different concentrations (liquid Si-10, 25 and 36%) to the seedbed of rice before transplantation into paddy field. The results of this experiment showed that Si application to rice seedbeds did not affected the rice plant height and shoot fresh weight but its application significantly increased the pushing resistance of rice plants from 12.2~16.7% as compared with water applied control plants. The lodging index of Si treated rice plants significantly decreased (13.7% on LS-25) as compared with control. Similarly, Si treated plants had significantly higher yield. Upon Si treatment (LS-36), the grain yield per 10 acre and panicles per plant were 15.1% and 6.3% higher than the water treated control plants respectively. The best concentration (LS-36%) revealed in the first experiment was foliar applied at 10 days before heading stage, initial tilling stage and panicle initiation stage to the rice leaves and we observed that shoot biomass was not significantly different between control and Si treated plants. However, significantly higher pushing resistance (10.5%~13.8%) and plant height (12.2%~16.7%) were observed while lower lodging index (7.6~7.8%) was recorded for Si treated plants as compared to control plants. Similarly, Si application increased the number of panicles per plant as well as the grain yield per 10 acre as compared to control. In conclusion, the Si application can significantly regulate plant growth and yield if applied at proper time with feasible concentration.

Introduction

In Asia, rice is one of the three most important food crops. Especially, in the vast monsoonal areas of tropical Asia, rice gives the highest food-staple cereal yield from a fixed land area of arable land (Datta, 1986; Köster *et al.,* 2009). Rice (*Oryza sativa* L.) is classified a typical monocotyledon plant and also separated as semi-aquatic plant because of its growing at both the seedling and adult stages (Kende *et al.,* 1998). Rice is known to accumulate high amount of silicon approximately 10% of its dry weight (Epstein, 1994, 1999). Silicon (Si) is second abundant element in soil and is an essential element for animals and has been implicated in optimal bone and connective tissue growth and development in the human body (Mitani *et al.,* 2008). In higher plants, Si is consumed from the rhizosphere through root in the form of $Si(OH)_4$ and SiO_2 while its uptake and accumulation varies greatly among different plant species (Kim *et al.,* 2011; Parveen & Hussain, 2008; Takahashi *et al.,* 1990). Through recent studies, uptake and transport of Si in plants have revealed by two ways i.e., (i) from apoplast into symplast and (ii) loading of Si into xylem (Hattori *et al*., 2008). Rice has both types of transporter, and their high activity allows rice to take up considerable amounts of silicon from soil solution (Hattori *et al.,* 2008; Mitani & Ma, 2005). After Si uptake in plants, Si has various physiological actions to plants in its regulation of biotic and abiotic stresses.

Numerous studies have elucidated its beneficial effects on plant growth and development under biotic (diseased and pests) and abiotic stresses (salinity, metal toxicity, drought, radiation damage, nutrient imbalances, high temperature, freezing, etc.) conditions (Kim *et al.,* 2011). Si has many effect which Si improve cell wall thickness below the cuticle and it also improves leaf angle, making leaves more erect, thus reducing self-shading, especially under high nitrogen rate (Mauad *et al.,* 2003). Si treatment has acted as effective improvements of leaf water status by decreasing excess transpiration *via* modification of stomatal action and reduction in cuticular transpiration during abiotic stress conditions (Agarie *et al.,* 1999; Hattori *et al.,* 2008; Matoh *et al.,* 1991). The beneficial effect of Si application other than rice plants has also been reported. Studies have revealed that Si is a beneficial element to higher plants, particularly for grasses and various cultivated crops like rice, wheat, tomato, cucumber (Ahmed *et al*., 2011; Chen *et al*., 2011; Epstein, 1994, 1999; Hamayun *et al*., 2010; Hattori *et al*., 2005; Kim *et al*., 2011; Liang *et al*., 1996, 1999, 2002; Parveen & Ashraf, 2010). In last decade or so, various studies have revealed the mitigating role of Si under various biotic (plant diseases and pests) and abiotic stresses (heavy metals, drought and salinity) to crop plants (Ahmed *et al*., 2011; Chen *et al*., 2011; Epstein, 1994, 1999; Hamayun *et al*., 2010; Hattori *et al*., 2005; Liang *et al*., 1996, 1999, 2002; Parveen & Ashraf, 2010). In mitigation of abiotic stress, according to many research reports, Si has beneficial effects to be applied during cultivation of rice (Ando *et al*., 2002; Savant *et al*., 1997; Yoshida *et al*., 1962). However, few reports also suggest that applying Si-containing fertilizers to paddy fields can suppress both leaf and panicle blast in irrigated rice (Datnoff *et al.,* 1991; Seebold *et al.,* 2000). Further studies are needed at field levels to elucidate the effects on the economically important agronomics. The effects of different concentration of Si application to seedbeds and different rice growth stages and grain yield components have not been well understood and sparsely investigated (Nwugo & Huerta, 2008). In the present study, we aimed to assess the effect of different Si application with different methods (seed bed and foliar) on the growth and yield of rice plants.

Materials and Methods

Plant material and cultivation method: Rice seeds (130 g/seedbed) sowed in a seedbed cover with nursery bed soil and grown in nursery for thirty days. Rice seeding was planted to paddy field in Gun-wi (36° 06´ N, 128° 38´ E, altitude 129 m), Kyungsangbuk-do, Republic of Korea with the help of rice-planting machine on 11 June, 2009. In our research, chemical fertilizer N, P_2O_5, and K_2O was applied as 90-45-57 kg/ha in paddy field before rice transplanting. N was applied three times during cultivation period (land preparation; 50%, tillering stage; 30%, panicle initiation stage; 20%). P_2O_5 was applied as basal @ 45 kg/ha, and K_2O was applied as 70%-0%-30% @ 57 kg/ha. The fertilizer application time of each stage was depending on rice growing and weather conditions.

Si application concentration, method and time: In the present study, we used three kinds of different Si viz., liquid Si 10% (LS 10, SiO_2 10%), liquid Si 25% (LS 25, SiO_2 25%) and liquid Si 36% (LS 36, SiO_2 16% + Calcium phosphate 20%). On the basis of these concentrations, we performed two different of experiments.

Experiment 1: LS 10, LS 25 and LS 36 were 10 fold dilutions (100 ml/1 L) using sprayer. Si treated to each of 10 rice seedbeds on rice transplanting date (11 June, 2009). Rice seeding treated with Si was planted by 6 row rice-planting machine as shown in Fig. 1A.

Experiment 2: On the transplanting date (11 June, 2009), Si was not treated to seedbed and rice seeding transplant to paddy field by a rice-planting machine. Through the experiment 1, a suitable Si application concentration (LS 36) to plant growth characteristics and yield component was revealed. We used LS 36 treatment as 500 fold dilutions (2 ml/1L) in experiment 2. Si (LS 36) was treated to leaf of growing rice at different growth stages such as initial tilling stage (IS; 10 July, 2009), panicle initiation stage (PS; 28 July, 2009) and 10 days before heading stage (10 BHS; 13 August, 2009) (Fig. 1B).

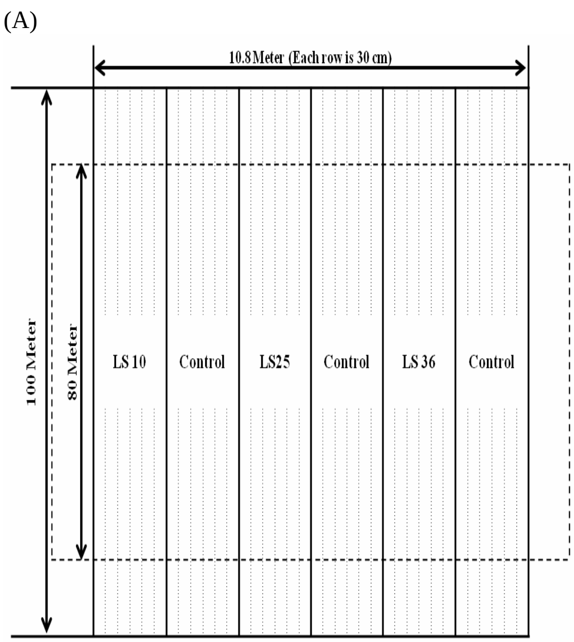

Fig. 1. Shows the field layout of the experiment. Dotted line shows the rice plants to be assessed for Si application and its effects on plant growth characteristics and grain yield. Each row is individual rice planting area. (A) Si of different concentration applied to the rice plant in seed bed stage. Three Si concentrations were used. LS-10 is liquid Si 10%; LS-25 is liquid Si 25%; LS-36 is liquid Si 36% with Calcium phosphate. (B) Shows the LS-36 applied to rice plants at different stages of the rice growth viz. initial tilling stage (IS), panicle initiation stage (PS) and 10 days before heading stage (10 BHS).

Survey of growth characteristics, lodging index and grain quantity data

Experiment 1: After Si application to seedbed on rice transplanting date, concerning the lodging index and growth characteristics data were surveyed on 20 days after heading date (18 September, 2009) through harvesting in each treatment of 20 samples. Determination of lodging index was used by Force gauge (AD-4932A-59N, A&D, Japan) from 3rd internodes of rice. Rice grain quantity-related data like spikelet panicle number per square meter, number per panicle, ripened grains rate, 1,000 grain weight and yield in rice per 10a surveyed on 50 days after heading date (18 October, 2009).

Experiment 2: Rice growth characteristics data, lodging index data and grain quantity-related data were measured on same period as equal methods in mentioned at experiment 1.

Climate data collection: During cultivation period, weather data (minimum, maximum and average of temperature and relative humidity) is showed in Table 1. All the data was collected by datalog (MicroLogPRO EC750, Fourier Systems Ltd. USA). During the experiments, we couldn't find any specific difference about temperature, relative humidity and total rainfall (Table 1).

Statistical analysis: Duncan Multiple Range Test (DMRT) was carried out to determine whether significant ($p<0.05$) differences occurred between individual treatments. To analyze the data SAS version 9.1 (SPSS Inc) was used.

Results

Experiment 1: After Si application to the rice during growth in seed bed, the plant height and shoot fresh weight data was recorded and shown in Fig. 2. Rice plant height data showed that the plant height of control, LS 10, LS 25 and LS 36 were 94.4, 92.1, 90.5 and 93.3 cm respectively. Though the rice plant height was slightly lower than control plants however, this was not significantly different between control and Si applied plants. A similar effect was also observed for the shoot fresh weight. The shoot biomass of Si treated rice plants was significantly not different than the control plants. The shoot fresh weight after Si treated to seedbeds was ranging from 10.0 g~10.3 (Fig. 2).

Pushing resistance and lodging index after Si treatments to rice seedbeds before rice transplanting date shown in Fig. 3. In the control, pushing resistance was 900 g/plant while the pushing resistance of Si treated plants was 1010~1050 g/plant. Thus, Si application to rice seedbeds before rice transplanting date significantly increased the pushing resistance from 12.2 to 16.7% as compared to control plants. Among Si treatments, pushing resistance was significantly increased upon LS25 treatment than LS10 and LS 36 (Fig. 3A). Lodging index, on the other hand, was significantly decreased upon Si treatments to rice seedbeds before as compared with control. It decreased approximately13.7% in LS 25 as compared to control and lodging index in the different Si application concentration indicated that it has a little difference among Si treatment as from 89.7% to 93.1% however; these results were not significantly different among Si treatments as statistical analysis (Fig. 3B).

Si treated rice plants in seedbeds were transplanted to the paddy field and we recorded the grain yield and yield components of the rice (shown in Table 2). Panicles number per square meter before rice seeding transplanting showed 344.8~397.0 ea/plant upon Si treatments. Thus, LS10 and LS25 treatments were not significantly different than control while in the LS 36, panicles number per square meter was significantly different in comparison with control (Table 2). The Si treatments to rice seedbeds before rice seeding transplanting, value of spikelets per panicle, spikelet filling and grain weight per 1000 seeds revealed similarity among treatments. Grain yield (polished rice) per 10a recorded as 510.1~542.7 kg/10a, grain yield of LS10 and LS25 increased about 0.3% to 1.1% respectively however, statistically, these results were not different in comparison with control. Grain yield in LS36 also increased approximately 6.3% as comparison with control and it was significantly different (Table 2). To conclude, spikelets per panicle, spikelet filling and grain weight were regulated by Si application but value of panicles per square meter was considerably increased by Si application of the rice plants in seedbeds and hence the grain yield was increased (Table 2).

Experiment 2: Experiment 2 was conducted by using LS 36 (SiO_2 16% + Calcium phosphate 20%) treatment to rice plant at initial tilling stage (IS; 10 July, 2009), panicle initiation stage (PS; 28 July, 2009) and 10 days before heading stage (10 BHS; 13 August, 2009). Plant height and shoot fresh weight was recorded and shown in Fig. 4. Shoot height was increased by different Si application during rice growth stages as compared with the control (Fig. 4A). In case of Si treatment (LS36), at PS and 10 BHS, the shoot height was significantly increased (7.6~7.8%) than control while upon Si application at IS, the height was not significantly different in comparison with control (Fig. 4A). Shoot fresh weight of rice was 10.1 ~ 10.3g per plant. Contrarily, the shoot biomass was not significantly different upon all Si application during different rice growth stage (Fig. 4B).

Table 1. Condition of weather during cultivation period of rice plant. All the data means were recorded on monthly basis.

Cultivation period	Weather conditions				
	T[1)] (°C)	HT[2)] (°C)	LT[3)] (°C)	RH[4)] (%)	TRF[5)] (mm)
May	18.0	27.0	9.5	61.9	117.4
June	22.2	29.4	15.6	65.5	63.6
July	24.1	29.4	19.7	78.0	288.9
August	24.1	30.0	19.3	75.9	88.8
September	20.4	27.7	14.5	74.6	69.9
October	13.2	23.0	5.6	71.5	9.4
November	6.1	13.2	0.5	70.1	31.4

[1)]T= Average temperature, [2)]HT= High temperature, [3)]LT= Low temperature, [4)]RH= Relative humidity, [5)]TRF= Total rainfall

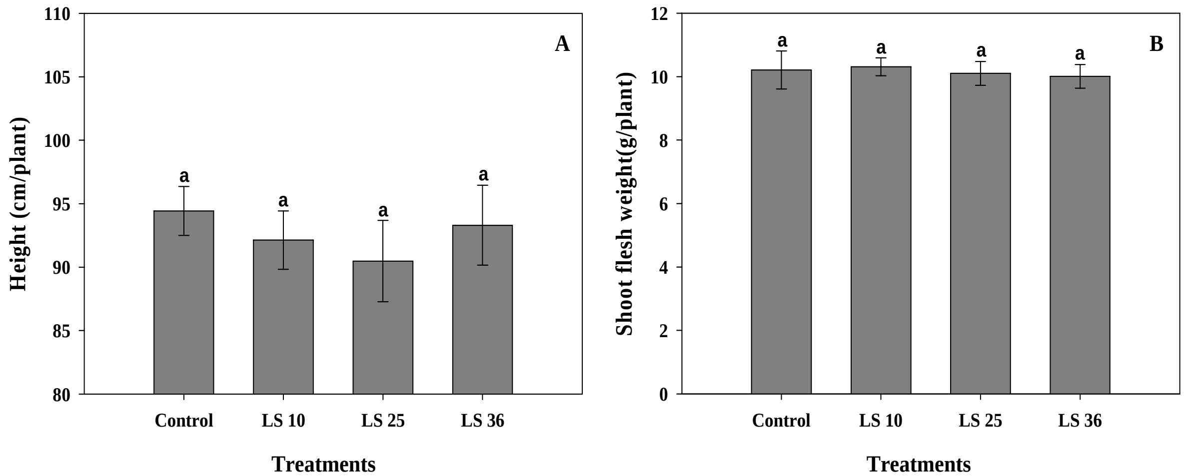

Fig. 2. Effect of different Si treatments concentration on plant height and shoot fresh weight of rice plants. Si treated to seeding seedbeds on rice transplanting date (11 June, 2009) and rice height and shoot fresh weight measured on 20 days after heading date (18 September, 2009). Error bars indicated standard error (*n*=20).

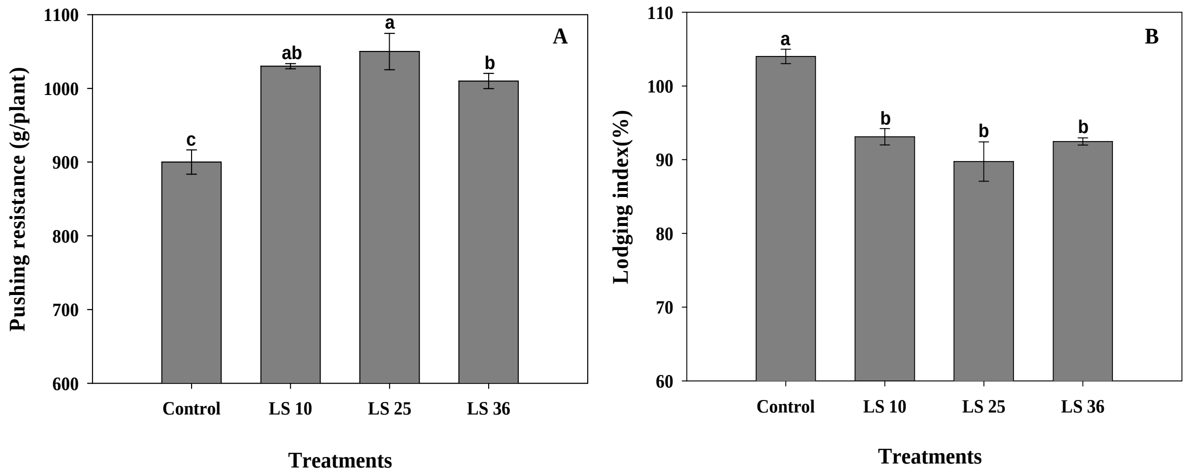

Fig. 3. Effect of different Si treatments concentration on plant height and shoot flesh weight of rice plant. Si treated to seeding seedbeds on rice transplanting date (11 June, 2009) and pushing resistance and lodging index measured on 50 days after heading date (18 October, 2009). Error bars indicated standard error (*n*=20).

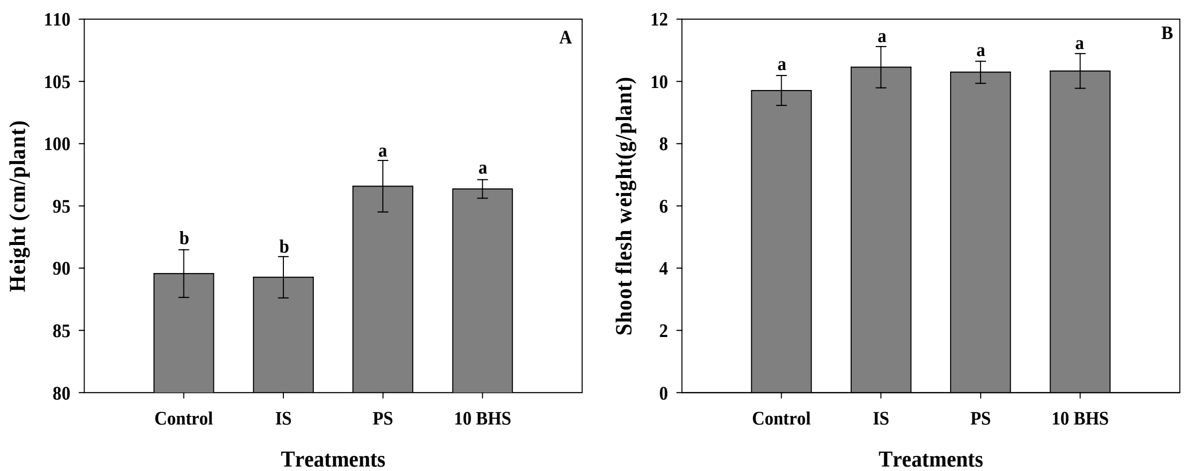

Fig. 4. Effect of Si treatments in different rice growth stage on plant height and shoot flesh weight of rice plant. Si treated to plants leaf by high pressure sprayer. IS, PS and 10 BHS indicated the rice growth stage such as initial tilling stage (10 July, 2009), panicle initiation stage (28 July, 2009) and 10 days before heading stage (13 August, 2009) respectively. Rice plants height and shoot flesh weight measured on 20 days after heading date (18 September, 2009). Error bars indicated standard error (*n*=20).

Table 2. Effect of Si application to seedbeds on grain yield and yield components of rice.

Treatments	Panicles/m^2 (ea/plant)	Spikelets/panicle (ea/plant)	Spikelet filling (%)	Grain weight (g/1000 seeds)	Grain yield/10a (kg)
Control	344.8 ± 16.5b	78.4 ± 13.5a	81.8 ± 3.5a	21.8 ± 1.2a	510.1 ± 18.9b
LS 10	364.8 ± 15.8b	80.1 ± 7.8a	82.5 ± 4.1a	21.4 ± 0.7a	511.8 ± 23.6b
LS 25	355.2 ± 21.6b	77.3 ± 9.6a	82.9 ± 3.3a	21.6 ± 1.8a	515.8 ± 10.8b
LS 36	397.0 ± 9.7a	76.9 ± 10.4a	82.1 ± 3.7a	21.4 ± 1.7a	542.7 ± 19.7a

LS 10= SiO_2 10%; LS 25= SiO_2 25%; LS 36= SiO_2 16% + Calcium phosphate 20%
Mean ± standard error (*n*=20) and same letter in each column indicated insignificantly different at *p<0.05%* by DMRT

Our results showed that pushing resistance and lodging index were found higher in Si-treated rice growth stage (Fig. 5). The effect of Si application to IS, PS and 10 BHS on pushing resistance were significantly different in comparison with control and among the Si treatments, pushing resistance showed difference between Si treatments. Pushing resistance reveled as 900 g/plant in control while, it was 1050 g/plant at IS, 1030 g/plant at PS and 1010 g/plant at 10 BHS. Thus, Si treated to IS, PS and 10 BHS increased about 12.2%~16.7% (Fig. 5A). Lodging index after Si application to different rice growth stage showed that Si-treated rice growth stage found lower than control. Especially, Lodging index was highly suppressed approximately 13.8% in the IS compare to control and it also suppressed from 10.5% to 11.1% in PS and 10 BHS comparison with control (Fig. 5B).

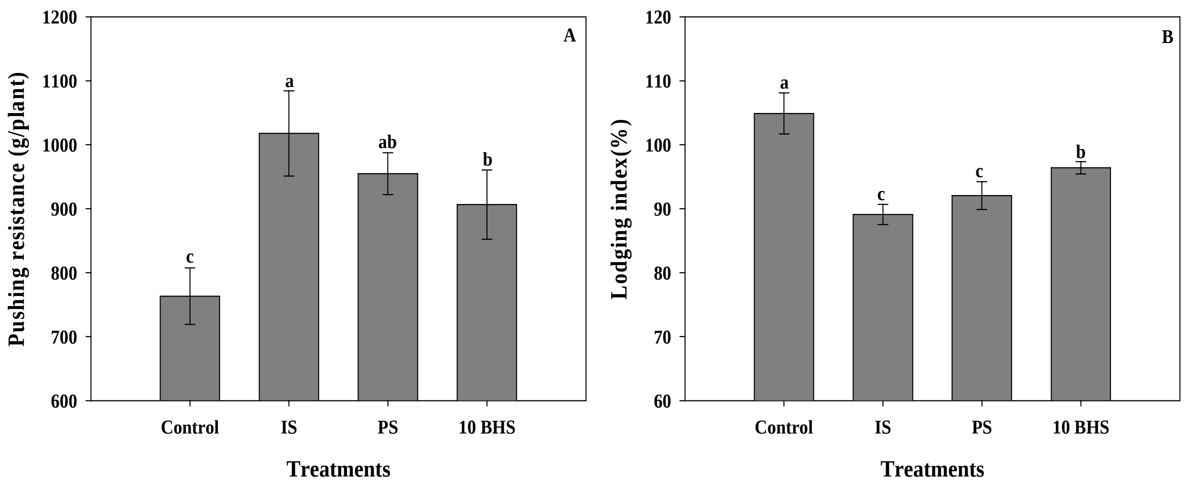

Fig. 5. Effect of Si treatments in different rice growth stage on pushing resistance and lodging index of rice plant. Si treated to plants leaf by high pressure sprayer. IS, PS and 10 BHS indicated the rice growth stage such as initial tilling stage (10 July, 2009), panicle initiation stage (28 July, 2009) and 10 days before heading stage (13 August, 2009) respectively. Rice plants height and shoot flesh weight measured on 20 days after heading date (18 September, 2009). Error bars indicated standard error (*n*=20).

Si treatments to different rice growth stages have increased the panicles per square meter and grain yield per 10a (Table 3). Especially, Si applications when it applied to PS stage of rice were most effectively acted at panicle per square meter and grain yield per 10a and also in the treatments when Si treated to IS and 10 BHS, panicles per square meter and grain yield per 10a were slightly increased about 5.9%~6.3% in panicles per square and 6.8%~7.1% in grain yield per 10a compare to control (Table 3) however, spikelets per panicle, spikelet filling and 1,000 grain weight were not affected by Si application to IS, PS and 10 BHS in comparison with the control (Table 3).

Table 3. Effect of Si treatments in different rice growth stage on grain yield and yield components of rice.

Treatments	Panicles/m^2 (ea/plant)	Spikelets/panicle (ea/plant)	Spikelet filling (%)	Grain weight (g/1000 seeds)	Grain yield/10a (kg)
Control	347.2 ± 17.1c	78.4 ± 9.7a	81.9 ± 1.4a	21.2 ± 1.3a	502.3 ± 22.4c
IS	367.8 ± 13.2b	80.2 ± 6.8a	82.8 ± 2.6a	21.5 ± 0.8a	537.9 ± 19.8b
PS	371.5 ± 18.4a	81.7 ± 10.2a	83.4 ± 3.6a	22.9 ± 1.5a	559.2 ± 13.1a
10 BHS	369.1 ± 19.4b	79.7 ± 9.2a	81.5 ± 3.1a	21.7 ± 2.0a	536.5 ± 25.7b

IS=Initial stage (10 July, 2009); PS=Panicle initiation stage (28 July, 2009); 10 BHS=10 days before heading stage (13 August, 2009).
Mean ± standard error (n=20) and same letter in each column indicated insignificantly different at *p<0.05%* by DMRT

Discussion

The rice plant uptake the soil silicon along with the essential elements such as nitrogen, phosphorus and potassium. The endogenous Si has been known to improve the plant growth and mitigates environmental stresses (Epstein, 1999; Kim *et al.*, 2002; Ma *et al.*, 2001; Parveen & Hussain, 2008; Kim *et al*., 2011). These effects were confirmed through several previous studies (Ahmed *et al*., 2011; Chen *et al*., 2011; Epstein 1994, 1999; Hamayun *et al*., 2010; Hattori *et al*., 2005; Kim *et al*., 2011; Liang *et al*., 1996, 1999, 2002; Parveen & Ashraf 2010) which state that Si plays a favorable role in plant growth, mineral nutrition, mechanical strength, and resistance to fungal diseases. The physiological studies suggests that silicon increases defense response and cell silicification of rice leaves completely contribute to the silicon-induced rice resistance against disease and herbivore insect (Chen *et al.*, 2011). In agricultural pestology, Si has a very important role which Si accumulation of rice plant reduces the severity of important diseases of rice such as blast, brown spot, sheath blight, stem rot and leaf scald (Datnoff *et al.*, 1991; Elawad & Green, 1979).

Our results showed that Si application to rice seedbeds and Si treated to different growth stage affect the pushing resistance and lodging index of rice. According to research of Mobasser *et al*., (2009), Terashima *et al*., (1994) and Won *et al*., (1998), pushing resistance and lodging index in rice are determined by morphometric characteristics of rice such as root morphology; stem bending strength and other characteristics. Other factors like accumulation of lignin, cellulose, hemicelluloses and carbohydrate contents of rice stems are related to pushing resistance and also high amount of Si accumulation in rice affect to pushing resistance, lodging index and physical strength (Jones *et al.*, 2001; Kashiwagi *et al.*, 2006; *Li et al*., 2003; Ma *et al.*, 2002; Mobasser *et al.*, 2009; Tanaka *et al.*, 2003; Yang *et al.*, 2001). Especially, Si accumulation in rice directly increase epidermal cell wall thickness of rice (Kim *et al.*, 2002) therefore, in our results, pushing resistance and lodging index of increasing or decreasing have been induced because Si treatment to rice seedbeds and different rice growth stage in rice plant induced epidermal cell wall thickness. Thus, effects of Si application to rice seedbeds and IS, PS and 10 BHS are in conformity with previous studies (Kim *et al.*, 2002; Tanaka *et al.*, 2003; Yang *et al.*, 2001).

Panicles number, spikelet number, spikelet filling and grain weight are important components of rice yield therefore improvement of these components ultimately caused the increase of rice production. In rice cultivation, promotion technique for panicles number, spikelet number, spikelet filling and grain weight have been known to trigger the increase in rice productivity. In our experiments, Si application to seedbeds and rice plants on different growth stage increase the panicles number comparison with non-Si treatment so our results suggested that grain yield per square meter was increased by Si application. Those results can be accessed from two aspects. First, due to Si application, form for light-interception of rice leaf was improved so photosynthetic capacity also increased. Second, increased-photosynthetic capacity induce the increase of anabolite in rice plant as well as, increased-anabolite in rice plant was affected to panicles number of rice through various metabolic process. This phenomenon was confirmed by many researches. According to Matoh *et al*., (1991), if high amount of Si accumulate in plant tissue it helps to alleviate the water stress in the plant through reducing transpiration and also high accumulation of Si causes the photosynthetic capacity by keeping the leaf blade erect thereby improving form for light interception of plant. Hattori *et al*., (2005) showed that Si application to sorghum induced plant dry matter and also induced nutrient assimilation rate and photosynthesis rate. Zuccarini (2008) showed that Si application to the irrigation water can mitigate negative effects NaCl on growth and on important ecophysiological parameters connected with it, such as stomatal conductance, photosynthetic rate and relative water content, as well as reduce mineral absorption such as Na^+ and Cl^- in plant tissues under various concentrations of salt stress conditions. As above, most of experiment about Si concentrated on effect of Si application on plant growth and photosynthetic rate under stress conditions however, appropriate Si treatment concentration and treatment period has been an important preposition to be studied for further assertion of Si role at field levels.

Acknowledgement

This research work was supported by the Agenda Program (Project No. PJ007522), Rural Development Administration and Brain Korea 21 Project, Republic of Korea.

References

Agarie, S., H. Uchida, W. Agata and P.B. Kaufman. 1999. Effects of silicon on stomatal blue-light response in rice (*Oryza sativa* L.). *Plant Production Sci.*, 2: 232-234.

Ahmed, M., F. Hassen and Y. Khurshid. 2011. Does silicon and irrigation have impact on drought tolerance mechanism of sorghum? *Agric Water Management*, 98: 1808-1812.

Ando, H., K. Kakuda, H. Fujii, K. Suzuki and T. Ajiki. 2002. Growth and canopy structure of rice plants grown under field conditions as affected by Si application. *Soil Sci. Plant Nutr.*, 48: 429-432.

Chen, W., X. Yao, K. Cai and J. Chen. 2011. Silicon alleviates drought stress of rice plants by improving plant water status, photosynthesis and mineral nutrient absorption. *Biol. Trace Elem. Res.*, 142: 67-76.

Datnoff, L.E., R.N. Raid, G.H. Snyder and D.B. Jones. 1991. Effect of calcium silicate on blast and brown spot intensities and yields of rice. *Plant Dis.*, 5: 729-732.

Datta, S.K. 1986. Improving nitrogen fertilizer efficiency in lowland rice in tropical Asia. *Nutrient Cycling in Agroecosystems*, 9: 171-186.

Elawad, S.H. and V.E. Green. 1979. Silicon and the rice plant environment: A review of recent research. *Il Riso.*, 28: 235-253.

Epstein, E. 1994. The anomaly of silicon in plant biology. *Proc Natl Acad Sci USA*, 91: 11-17.

Epstein, E. 1999. Silicon. *Annu. Rev. Plant Physiol. Plant Mol. Biol*., 50: 641-664.

Hamayun, M., E.Y. Sohn, S.A. Khan, Z.K. Shinwari, A.L. Khan and I.J. Lee. 2010. Silicon alleviates the adverse effects of salinity and drought stress on growth and endogenous plant growth hormones of soybean (*Glycine Max* L.). *Pak. J. Bot*., 42(3): 1713-1722.

Hattori, T., K. Sonobe, S. Inanaga, P. An and S. Morita. 2008. Effect of silicon on photosynthesis of young cucumber seedlings under osmotic stress. *J. Plant Nut.,* 31: 1046-1058.

Hattori, T., K. Sonobe, S. Inanaga, P. An, W. Tsuji, H. Araki, A. E. Eneji and S. Morita. 2007. Short-term stomatal responses to light intensity changes and osmotic stress in sorghum seedlings raised with and without silicon. *Environ. Experimental Botany*, 60(2): 177-182.

Hattori, T., S. Inanaga, H. Araki, P. An, S. Morita, M. Luxov´a and A. Lux. 2005. Application of silicon-enhanced drought tolerance in *Sorghum bicolor*. *Physiologia Plantarum*, 123: 459-466.

Jones, L., A.R. Ennos and S.R. Turner. 2001. Cloning and characterization of *irregular xylem4* (*irx4*): a severely lignin-deficient mutant of *Arabidopsis*. *Plant J.,* 26: 205-216.

Kashiwagi, T, Y. Madoka, N. Hirotsu and K. Ishimaru, 2006. Locus *prl5* improves lodging resistance of rice by delaying senescence and increasing carbohydrate reaccumulation. *Plant Physiol. Biochem.,* 44: 152-157.

Kende, H., E. van der Knaap and H.T. Cho. 1998. Deepwater rice: A model plant to study stem elongation. *Plant Physio.*, 118(4): 1105-1110.

Kim, S.G., K.W. Kim, E.W. Park and D. Choi. 2002. Silicon-induced cell wall fortification of rice leaves: A possible cellular mechanism of enhanced host resistance to blast. *Phytopathology,* 92(10): 1095-1103.

Kim, Y.H., A.L. Khan, M. Hamayun, S.M. Kang, Y.J. Beom and I.J. Lee. 2011. Influence of short-term silicon application on endogenous physiohormonal levels of *Oryza sativa* L., under wounding stress. *Biol. Trace Elem. Res.,* 144: 1175-1185.

Köster, J.R., R. Bol, M.J. Leng, A.G. Parker, H.J. Sloane and J.F. Ma. 2009. Effects of active silicon uptake by rice on ^{29}Si fractionation in various plant parts. *Rapid Commun. Mass Spectrum.,* 23: 2398-2402.

Li, Y., Q. Qian, Y. Zhou, M. Yan, L. Sun, M. Zhang, Z. Fu, Y. Wang, B. Han, X. Pang, M. Chen and J. Li. 2003. Brittle culm1, which encodes a COBRA-like protein, affects the mechanical properties of rice plants. *Plant Cell,* 15: 2020-2031.

Liang, Y.C. and R.X. Ding. 2002. Influence of silicon on microdistribution of mineral ions in roots of salt-stressed barley as associated with salt tolerance in plants. *Sci China* (Series C), 45: 298-308

Liang, Y.C., Q.R. Shen, Z.G. Shen and T.S. Ma. 1996. Effects of silicon on salinity tolerance of two barley cultivars. *J. Plant Nutr*., 19: 173-183.

Liang, Y.C., R.X. Ding and Q. Liu. 1999. Effects of silicon on salt tolerance of barley and its mechanism. *Sci Agricult Sinica*, 32(6): 75-83.

Ma, J.F., Y. Miyak and E. Takahashi. 2001. Silicon as a beneficial element for crop plants. In: *Silicon in agriculture*. (Eds.): L.F. Datonoff, G.H. Snyder and G.H. Korndorfer. Elsevier Science Publishers, Amsterdam, pp. 17-39.

Ma, Q.H., Y. Xu, Z.B. Lin and P. He. 2002. Cloning of cDNA encoding COTM from wheat which is differentially expressed in lodging sensitive and resistant cultivars. *J. Exp. Bot.,* 53: 2281-2282.

Matoh, T., S. Murata and E. Takahashi. 1991. Effect of silicate application on photosynthesis of rice plants. *Japanese J. Soil Sci. and Plant Nutr.,* 62: 248-251 (in Japanese).

Mauad, M., C.A.C. Crusciol, H. G. Filho and J. C. Corrêa. 2003. Nitrogen and siliconfertilization of upland rice. *Scientia Agricola,* 60(4): 761-765.

Mitani, N. and J. Ma. 2005. Uptake system of silicon in different plant species. *J. Experimental Botany,* 414: 1255-1261.

Mitani, N., N. Yamaji and J.F. Ma. 2008. Characterization of substrate specificity of a rice silicon transporter, Lsi1. *Pflugers Arch. - Eur. J. Physiol.,* 456: 679-686.

Mobasser, H.R., R. Yadi, M. Azizi, A.M. Ghanbari and M. Samdaliri. 2009. Effect of density on morphological characteristics related-lodging on yield and yield components in varieties rice (*Oryza sativa* L.) in Iran. *American-Eurasian J. Agric. Environ. Sci.,* 5(6): 745-754.

Nwugo, C.C. and A.J. Huerta. 2008. Effects of silicon nutrition on cadmium-uptake, growth and photosynthesis of rice (*Oryza sativa* L.) seedlings exposed to long-term low level cadmium. *Plant Soil*, 311: 73-86.

Parveen, A. and F. Hussain. 2008. Salinity tolerance of three range grasses at germination and early growth stages. *Pak. J. Bot.,* 40(6): 2437-2441.

Savant, N.K., G.H. Snyder and L.E. Datnoff. 1997. Silicon management and sustainable rice production. *Adv. Agron.*, 58: 151-199.

Seebold, K.W., L.E. Datnoff, F.J. Correa-Victoria, T.A. Kucharek and G.H. Snyder. 2000. Effect of silicon rate and host resistance on blast, scald, and yield of upland rice. *Plant Dis.,* 84: 871-876.

Takahashi, E., J.F. Ma and Y. Miyake. 1990. The possibility of silicon as an essential element for higher plants. *Comm. Agric. Food Chem.,* 2: 99-122.

Tanaka, K., K. Murata, M. Yamazaki, K. Onosato, A. Miyao and H. Hirochika. 2003. Three distinct rice cellulose synthase catalytic subunit genes required for cellulose synthesis in the secondary wall. *Plant Physiol.,* 133: 73-83.

Terashima, K., T. Ogata and S. Akita. 1994. Eco-physiological characteristics related with lodging tolerance of rice in direct sowing cultivation. II. Root growth characteristics of tolerant cultivars to root lodging. *Jpn. J. Crop Sci.,* 63: 34-41.

Won, J.G., Y. Hirahara, T. Yoshida and S. Imabayashi. 1998. Selection of rice lines using SPGP seedling method for direct seeding. *Plant Prod. Sci.,* 1: 280-285.

Yang, J., J. Zhang, Z. Wang and Q. Zhu. 2001. Activities of starch hydrolytic enzymes and sucrose-phosphate synthase in the stems of rice subjected to water stress during grain filling. *J. Exp. Bot.,* 52: 2169-2179.

Yoshida, S., Y. Ohnishi and K. Kitagishi. 1962. Histochemistry of silicon in rice plant. III. The presence of cuticle-silica double layer in the epidermal tissue. *Soil Sci. Plant Nutr.,* 8: 1-5.

Zuccarini, P. 2008. Effects of silicon on photosynthesis, water relations and nutrient uptake of *Phaseolus vulgaris* under NaCl stress. *Biologia Plantarum,* 52(1): 157-160.

(Received for publication 17 August 2011)