



## Soil Application of Silicon: Effects on Economic Yield and Nutrition of Phosphorus, Zinc and Iron in Rice (*Oryza sativa* L.)

Sajal Pati, Susmit Saha<sup>1</sup>, Sushanta Saha\*, Biplab Pal,  
Bholanath Saha<sup>2</sup> and G.C. Hazra

Department of Agricultural Chemistry and Soil Science,  
Bidhan Chandra Krishi Viswavidyalaya, Mohanpur, Nadia, 741252, West Bengal

A field experiment was conducted for the two consecutive seasons to evaluate the effect of diatomaceous earth as a silicon (Si) source along with recommended doses of fertilizer nitrogen (N), phosphorus (P), potassium (K) and zinc (Zn) as well as farmyard manure (FYM) in nine different treatment combinations on the yield and P, Zn and iron (Fe) nutrition of rice. The results showed a significant increase in grain yield of rice upon Si application with a concomitant improvement of P metabolism. Increased phosphatase activities in soil by the application of Si showed synergism between Si and P in grain ( $r = 0.91^{**}$ ) and straw ( $r = 0.90^{**}$ ). Zinc and Fe nutrition was affected by Si application through 600 kg diatomaceous earth  $ha^{-1}$  with a decline in their concentrations in the grains by 39.6 and 25.7 per cent and in straw by 21.1 and 27.1 per cent, respectively over standard fertilizer practice. Better P metabolism as a results of Si fertilization may increase the production of phytic acid in rice which may retard translocation of micronutrients.

**Key words:** Diatomaceous earth, iron, phosphorus, rice, silicon, zinc

Rice (*Oryza sativa* L.) is an important staple food crop for more than two third of the population of South East Asia and plays a vital role in national food security and a means of livelihood for millions of people in India. Adequate nutrient management is essential to enhance its productivity to satisfy the rising global food demand without adverse impact on environment. Besides the essential nutrients, silicon (Si) imparts some role in improving the biomass yield of rice (Elmer and Datnoff 2014). In modern agriculture, Si has already been recognized as a 'functional nutrient' for a number of crops particularly rice, sugarcane, *etc.*, which plays an important role in the growth and development of the crops, especially gramineae crops (Epstein 1999). Although Si is abundant in the earth crust (~27%), its availability in soil is poor due to its lower solubility from insoluble silicates. Moreover, the available Si status in the

Inceptisols of India is decreasing with intensive cultivation of hybrid and other high yielding cultivars of rice without proper supplement of this element in soil. For this reason, a response of Si fertilization in rice in the Inceptisols of India may be expected.

Plant can absorb Si in the form of soluble monosilicic acid ( $H_4SiO_4$ ) from soil (Jones and Handreck 1967). Such absorbed Si, ranged from 0.1 to 10% in plant tissue (Epstein 1999; Elmer and Datnoff 2014), plays a significant role in combating biotic and abiotic stress. Silicon uptake of rice and sugarcane are sometimes higher than that of nitrogen (N) and potassium (K) uptake (Savant *et al.* 1997). Due to synergistic effect, Si application may improve N use efficiency in rice leading to enhanced productivity. Nitrogen fertilization tends to make rice leaves droopy, whereas Si keep them erect which enhances photosynthetic efficiency resulting increase in yield (Detmann *et al.* 2012). Similarly, phosphorus (P) use efficiency in rice increased from 24 to 34 per cent when applied with Si due to reduction in P retention capacity of soil that increases the level of available P (Singh *et al.* 2005). Silicon also modifies the translocation of nutrients within the plant and water use efficiency by reducing transpiration (Saud

\*Corresponding author (Email: sushanta.hau@gmail.com)

Present address

<sup>1</sup>College of Agriculture, Bidhan Chandra Krishi Viswavidyalaya, Burdwan, 713101, West Bengal

<sup>2</sup>Department of Soil Science and Agricultural Chemistry, Dr. Kalam Agricultural College, Bihar Agricultural University, Dist. Kishanganj, 855107, Bihar

*et al.* 2014). Moreover, it is also well documented that Si fertilization may be effective to improve phosphatase enzyme activities in soil with a propensity to enrich P nutrition in plant (Meena *et al.* 2014). Translocation of micronutrients, particularly zinc (Zn) and iron (Fe), may also be affected by Si fertilization in rice by the probable mechanisms: i) binding sites for Zn and Fe may be occupied by Si (You-Qiang *et al.* 2012), ii) chelation of Fe by Si induced biosynthetic chelators (Pavlovic *et al.* 2013), and iii) silicon improves citrate concentration controlling long distance transport along with utilization of Fe in leaves (Bitvutskii *et al.* 2014).

Rice growing soils of India, however, are Si deficient due to intensive cultivation without proper application of Si fertilizers (Meena *et al.* 2014). We, therefore, hypothesized that rice plant requires Si to boost up economic yield with simultaneous modification in the nutrition of macro (mainly P) as well as micronutrients particularly Zn and Fe. It is well known that diatomaceous earth, fossilized remaining of salt and freshwater organisms mainly unicellular algae-like plants, is a naturally occurring source of Si. Amorphous diatomaceous earth (DE) is considered to be a good source of plant available Si as amorphous silica is more soluble than crystalline silica having high cation exchange and retention capacity. Considering these facts, this study aims to evaluate the effect of Si fertilization on the i) above ground biomass yield, ii) modification of P nutrition and iii) translocation of micronutrients (Zn and Fe) in rice.

## Materials and Methods

### Experimental site

Field trials were conducted in the new alluvial zone of Nadia (Madandanga) district of West Bengal, India, for two consecutive years *viz.* 2012 and 2013 in the *kharif* season. The field is situated at 22°58'162" N latitude, 88°30'651" E longitude, experiencing hot and humid climate with mean annual rainfall of 1310 mm, the minimum and maximum temperature of 21±1 and 32±2 °C, respectively. The soil was Typic Endoaquepts with silty clay loam texture, slightly alkaline in reaction, having rice-rice cropping sequence throughout the year.

### Management practices

Field was puddled during the onset of rainy season in the 1<sup>st</sup> week of July with a standing water of 4-5 cm. Seven days after puddling, three plants of 21-

day-old seedlings per hill were transplanted with 20 cm row to row and 20 cm hill to hill spacing. Water level up to 5.0 cm (700 litre water/m<sup>2</sup>/growing season) was maintained in the rice plots throughout from transplanting to grain filling stage. The plot size of the experiment was 20 m<sup>2</sup> (5 m × 4 m). The randomized block design (RBD) with three replications was used to study the response of each treatment on the tested cultivar. Other management practices including weed control measures were followed as recommended by the University. Tested rice cultivar was given nine treatment combinations of Si and recommended doses of fertilizer N, P and K (Table 1). Fertilizers (N:P:K::100:50:50) were applied during final land preparation. Half of the dose of N was given at the time of transplanting and the other half was given into two split doses, one at maximum tillering stage *i.e.* 22 days after transplanting (DAT) and another at panicle initiation stage (35 DAT) through urea. The entire quantity of P and K in the form of single superphosphate (SSP) and muriate of potash (MOP), respectively were applied at the time of transplanting. The different treatment combinations are presented in table 1.

**Table 1.** Treatment combinations used in the experiment

SI No.	Treatment details
T <sub>1</sub>	Control
T <sub>2</sub>	100% RDF
T <sub>3</sub>	50% RDF
T <sub>4</sub>	T <sub>2</sub> + 150 kg DE ha <sup>-1</sup>
T <sub>5</sub>	T <sub>2</sub> + 300 kg DE ha <sup>-1</sup>
T <sub>6</sub>	T <sub>2</sub> + 600 kg DE ha <sup>-1</sup>
T <sub>7</sub>	T <sub>3</sub> + 150 kg DE ha <sup>-1</sup>
T <sub>8</sub>	T <sub>3</sub> + 300 kg DE ha <sup>-1</sup>
T <sub>9</sub>	T <sub>3</sub> + 600 kg DE ha <sup>-1</sup>

100% RDF = standard fertilizer practice (SFP) (which content 100 kg N ha<sup>-1</sup>, 50 kg P ha<sup>-1</sup>, 50 kg K ha<sup>-1</sup> and 5.25 kg Zn ha<sup>-1</sup> (25 kg ZnSO<sub>4</sub>.7H<sub>2</sub>O ha<sup>-1</sup>) in combination with FYM @ 5 t ha<sup>-1</sup>); DE= Diatomaceous earth

### Composition of diatomaceous earth (DE)

Diatomaceous earth is commercially manufactured by Agripower Australia Ltd. It contains total SiO<sub>2</sub> (63.7%), P<sub>2</sub>O<sub>5</sub> (0.02%), K<sub>2</sub>O (0.40%), CaO (2.70%), MgO (3.25%), Fe<sub>2</sub>O<sub>3</sub> (2.0%), MnO<sub>2</sub> (0.02%), Al<sub>2</sub>O<sub>3</sub> (15.3%) and Na<sub>2</sub>O (0.55%) on dry weight basis.

### Collection and analysis of soil samples

Soil samples were collected from 0-0.2 m layer of the experimental field after primary land preparation for the crops and analyzed for pH in soil

**Table 2.** Physicochemical properties of the experimental soil

Properties	Values
Taxonomic classification	Typic Endoaquepts
pH (1:2.5 soil water suspension)	7.41
EC (dS m <sup>-1</sup> )	0.24
Organic carbon (%)	1.02
Available N (kg ha <sup>-1</sup> )	139
Available P (kg ha <sup>-1</sup> )	31
Available K (kg ha <sup>-1</sup> )	301
DTPA-extractable Zn (mg kg <sup>-1</sup> )	0.95
DTPA-extractable Cu (mg kg <sup>-1</sup> )	6.25
DTPA-extractable Fe (mg kg <sup>-1</sup> )	136
DTPA-extractable Mn (mg kg <sup>-1</sup> )	23.0
Available B (mg kg <sup>-1</sup> )	0.25
Available Si- CaCl <sub>2</sub> (mg kg <sup>-1</sup> )	43.0
Textural Class	
Sand (%)	17.5
Silt (%)	55.0
Clay (%)	27.5
Textural class	Silty clay loam

suspension (Page *et al.* 1982), oxidizable organic carbon (Walkley and Black 1934) and available N, P and K (Jackson 1973), available micronutrients *viz.*, Zn and Fe by extracting with 0.005 M DTPA, 0.01 M CaCl<sub>2</sub> and 0.1 M triethanol amine (Lindsay and Norvell 1978), available B (hot-CaCl<sub>2</sub> extractable; Parker and Gardner 1981) and available Si (0.01M CaCl<sub>2</sub> extractable; Haysom and Chapman 1975) following standard protocols (Table 2).

#### Collection and analysis of plant samples

The rice cultivar (Swarna Masuri) was harvested plot-wise upon maturity. The plant samples were threshed followed by sun drying and finally their weight was taken for estimating the grain and straw yield. The representative samples for plant tissue analysis were collected from this large pool of harvested plant samples. Immediately after collection (*i.e.* on the same day), the plant samples were first washed with running tap water to remove all visible soil particles followed by washing with 0.1 M HCl and finally with double distilled water. After that, plant samples were dried in a hot air oven at 70 °C for 48 h till the constant weight. After drying, the samples were ground to make it fine powder by using stainless steel grinder.

Finely ground plant samples (0.5 g) were taken in porcelain crucibles for dry ashing in a muffle furnace at 550 °C for 5 h. After cooling, next day, the ash was dissolved in 5 mL of 6N HCl solution and simultaneously washed with double distilled water up to 50 mL and filtered through Whatman no. 42 filter

paper. Concentrations of cationic micronutrients (Zn and Fe) in the filtrate were measured directly in an atomic absorption spectrophotometer (Perkin Elmer PinAAcle™ 900F, USA), while total P content of the plant samples were analyzed in aqueous extracts after dry ashing using UV-Visible spectrophotometer (Perkin Elmer, Lambda 65) (Tandon 1995).

For analysis of Si in plant tissues, 0.1 g powdered sample was mixed with the digestion mixture containing 7 mL of 62% HNO<sub>3</sub>, 2 mL of H<sub>2</sub>O<sub>2</sub> (30%) and 1 mL of HF (46%) and kept for 10–15 min for pre-digestion and the samples were then digested in a hot plate at 100 °C for 1 h. The digested samples were diluted to 50 mL with 4% boric acid. The Si concentration in the digested solution was estimated by molybdenum blue colorimetric procedure (Hallmark *et al.* 1982) by transferring 0.1 mL of digested aliquot to a plastic centrifuge tube with consecutive addition of 3.75 mL of 0.2 N HCl, 0.5 mL of 10% ammonium molybdate, 0.5 mL of 20% tartaric acid and 0.5 mL of reducing agent (ANSA) with subsequent volume make up to 12.5 mL with distilled water and kept for one hour. After one hour, the absorbance of Si was measured at 600 nm with a UV-visible spectrophotometer (Perkin Elmer, Lambda 65).

#### Statistical analysis

The data on biomass yield (straw and grain), P, Fe, Zn and Si concentration in plant and economical part of the crop were statistically analyzed and the mean effects of 3 replicates were further subjected to Post-Hoc test to identify the homogenous means at 5% level using the window-based SPSS software (version 17.0, SPSS Inc., Chicago, USA).

## Results and Discussion

#### Effect of Si on yield

Results showed that application of silicon along with standard fertilizer practice (both full and half doses) significantly increased grain and straw yield of rice (Table 3). Highest increase both in grain and straw yield of 89.7 and 58.7 per cent, respectively over control, was observed on application of Si through 600 kg DE ha<sup>-1</sup> with full standard fertilizer practice (T<sub>6</sub>). Treatment-wise increases in grain yield over control (T<sub>1</sub>) were 70.4, 41.0, 76.8, 78.4, 89.7, 51.0, 53.6 and 51.6 per cent with 100% RDF (T<sub>2</sub>), 50% RDF (T<sub>3</sub>), T<sub>2</sub> + DE @ 150 kg ha<sup>-1</sup> (T<sub>4</sub>), T<sub>2</sub> + DE @ 300 kg ha<sup>-1</sup> (T<sub>5</sub>), T<sub>2</sub> + DE @ 600 kg ha<sup>-1</sup> (T<sub>6</sub>), T<sub>3</sub> + DE 150 kg ha<sup>-1</sup> (T<sub>7</sub>), T<sub>3</sub> + DE 300 kg ha<sup>-1</sup> (T<sub>8</sub>) and T<sub>3</sub>

**Table 3.** Effect of diatomaceous earth on economical yield, available nutrient status, nutrient concentration and enzymatic activity at the time of post-harvest

Treatments	Grain yield (t ha <sup>-1</sup> )	Straw yield (t ha <sup>-1</sup> )	Available P (kg ha <sup>-1</sup> )	Si in soil (mg kg <sup>-1</sup> )	Si in grain (% dry wt)	Si in straw (% dry wt)	Acid Phosphatase (µg PNP g <sup>-1</sup> of soil)	Alkaline Phosphatase
T <sub>1</sub> : Control	2.75 <sup>e</sup>	4.89 <sup>e</sup>	23.3 <sup>h</sup>	37.5 <sup>d</sup>	0.40 <sup>d</sup>	2.46 <sup>e</sup>	37.5 <sup>d</sup>	452 <sup>g</sup>
T <sub>2</sub> : 100% RDF	4.69 <sup>b</sup>	7.01 <sup>bcd</sup>	28.6 <sup>ef</sup>	36.1 <sup>d</sup>	0.50 <sup>bc</sup>	2.66 <sup>d</sup>	36.1 <sup>d</sup>	546 <sup>cd</sup>
T <sub>3</sub> : 50% RDF	3.88 <sup>d</sup>	6.64 <sup>d</sup>	25.4 <sup>g</sup>	37.0 <sup>d</sup>	0.47 <sup>c</sup>	2.55 <sup>de</sup>	37.0 <sup>d</sup>	478 <sup>fg</sup>
T <sub>4</sub> : T <sub>2</sub> + DE @ 150 kg ha <sup>-1</sup>	4.86 <sup>b</sup>	7.50 <sup>ab</sup>	33.4 <sup>c</sup>	50.6 <sup>c</sup>	0.53 <sup>b</sup>	2.93 <sup>c</sup>	50.6 <sup>c</sup>	581 <sup>bc</sup>
T <sub>5</sub> : T <sub>2</sub> + DE @ 300 kg ha <sup>-1</sup>	4.91 <sup>b</sup>	7.33 <sup>abc</sup>	35.1 <sup>b</sup>	62.2 <sup>b</sup>	0.57 <sup>a</sup>	3.36 <sup>b</sup>	62.2 <sup>b</sup>	592 <sup>b</sup>
T <sub>6</sub> : T <sub>2</sub> + DE @ 600 kg ha <sup>-1</sup>	5.22 <sup>a</sup>	7.77 <sup>a</sup>	37.9 <sup>a</sup>	69.9 <sup>a</sup>	0.60 <sup>a</sup>	3.76 <sup>a</sup>	69.9 <sup>a</sup>	640 <sup>a</sup>
T <sub>7</sub> : T <sub>3</sub> + DE @ 150 kg ha <sup>-1</sup>	4.15 <sup>cd</sup>	7.02 <sup>bc</sup>	26.6 <sup>deg</sup>	52.9 <sup>c</sup>	0.48 <sup>c</sup>	3.02 <sup>c</sup>	52.9 <sup>c</sup>	485 <sup>ef</sup>
T <sub>8</sub> : T <sub>3</sub> + DE @ 300 kg ha <sup>-1</sup>	4.22 <sup>c</sup>	7.13 <sup>bc</sup>	28.1 <sup>ef</sup>	64.5 <sup>b</sup>	0.50 <sup>bc</sup>	3.08 <sup>c</sup>	64.5 <sup>b</sup>	510 <sup>de</sup>
T <sub>9</sub> : T <sub>3</sub> + DE @ 600 kg ha <sup>-1</sup>	4.17 <sup>cd</sup>	7.02 <sup>bcd</sup>	30.2 <sup>d</sup>	70.2 <sup>a</sup>	0.52 <sup>b</sup>	3.11 <sup>c</sup>	70.2 <sup>a</sup>	533 <sup>cd</sup>

PNP: *p*-nitrophenol; Value in the same column within same treatment and parameter followed by different lower case letters (a-f) are significantly difference at  $P < 0.05$  accordingly Duncan multiple range test for separation

+ DE 600 kg ha<sup>-1</sup> (T<sub>9</sub>), respectively. The corresponding increase in straw yield was 43.2, 35.5, 53.2, 49.8, 58.7, 43.4, 45.7 and 43.3 per cent, respectively.

Application of Si through DE had positive effect on grain and straw yield of rice (Table 3). There was a significant increase in grain and straw yield of rice in treatment with 100% RDF + DE @ 600 kg ha<sup>-1</sup> (T<sub>6</sub>) over 100% RDF (T<sub>2</sub>). This may be due to combined effects of various factors providing strength to fight against biotic and abiotic stresses in rice plant (Meena *et al.* 2014), stimulating the number of tillers in vegetative growth stages (Prakash *et al.* 2011), increasing photosynthetic efficiency (Ma *et al.* 2004) as well as imparting a homeostatic effect for micronutrient nutrition (Xu *et al.* 2015) to resist their deficiency and or toxicity in rice plant. It was obvious that the application of Si through 600 kg DE ha<sup>-1</sup> along with full standard fertilizer practice had an edge over other treatments.

#### *Influence of Si fertilizer on its concentration*

Results showed that Si application through DE caused a significant increase in its concentration in both of the rice grain and straw over control (Table 3). Such increase was the maximum in the grain (0.60%) as well as straw (3.76%) when Si was applied through 600 kg DE ha<sup>-1</sup> along with 100% RDF (T<sub>6</sub>) (Table 3) followed by DE @ 300 kg ha<sup>-1</sup> with 100% RDF (T<sub>5</sub>). It has been found that application of Si through 600 kg DE ha<sup>-1</sup> along with 100% RDF (T<sub>6</sub>) increased its concentration in grain and straw by 20.0 and 41.4 per cent, respectively over 100% RDF (T<sub>2</sub>). A comparison between the results of Si+NPK fertilizer application (T<sub>4</sub>, T<sub>5</sub>, T<sub>6</sub>, T<sub>7</sub>, T<sub>8</sub> and T<sub>9</sub>) with only NPK fertilizer application (T<sub>2</sub> and T<sub>3</sub>), therefore, indicated

that Si nutrition in rice was improved by the Si application in soil along with the standard doses of NPK fertilizers.

It appeared that applied Si, took part in the nutrition of rice and the maximum enrichment in grains (0.60%) and straw (3.76%) occurred on application of 600 kg DE ha<sup>-1</sup> with 100% RDF (T<sub>6</sub>). Enrichment of grain with an element depends upon its re-translocation and redistribution pattern from leaves *via* phloem (Sperotto 2013). Results clearly indicated that application of 600 kg DE over 300 kg ha<sup>-1</sup> along with 100% RDF (T<sub>6</sub> over T<sub>5</sub>) did not significantly increase grain loading of Si (0.60% over 0.57%, Table 3). Thus, application of 300 kg DE ha<sup>-1</sup>, as a source of Si, may be considered as threshold level to enrich rice grains with Si. We expect that phloem mobility of Si in tested rice cultivar controlled its enrichment in the grain. Some phloem barrier may be responsible to resist further re-distribution of Si as mono or di-silicic acid from leaf to grain above the mentioned dose of DE (300 kg ha<sup>-1</sup>). For this, only straw rather than grain could be enriched with Si by its precipitation as amorphous silica (Ding *et al.* 2008) when 600 kg DE ha<sup>-1</sup> was applied along with 100% RDF. Such finding may be useful to standardize the dose of applied Si in rice plant in future.

#### *Silicon fertilizer and P nutrition*

Results showed that Si fertilization had a synergistic effect on P-nutrition in rice grain ( $r = 0.91^{**}$ ,  $P < 0.01$ ) and straw ( $r = 0.89^{**}$ ,  $P < 0.01$ ) (Fig 1a and 1b). We also noticed a maximum of 16.0 and 33.3 per cent increase in P concentration in rice grain and straw, respectively by Si application through 600 kg DE ha<sup>-1</sup> along with 100% RDF (T<sub>6</sub>) over no Si

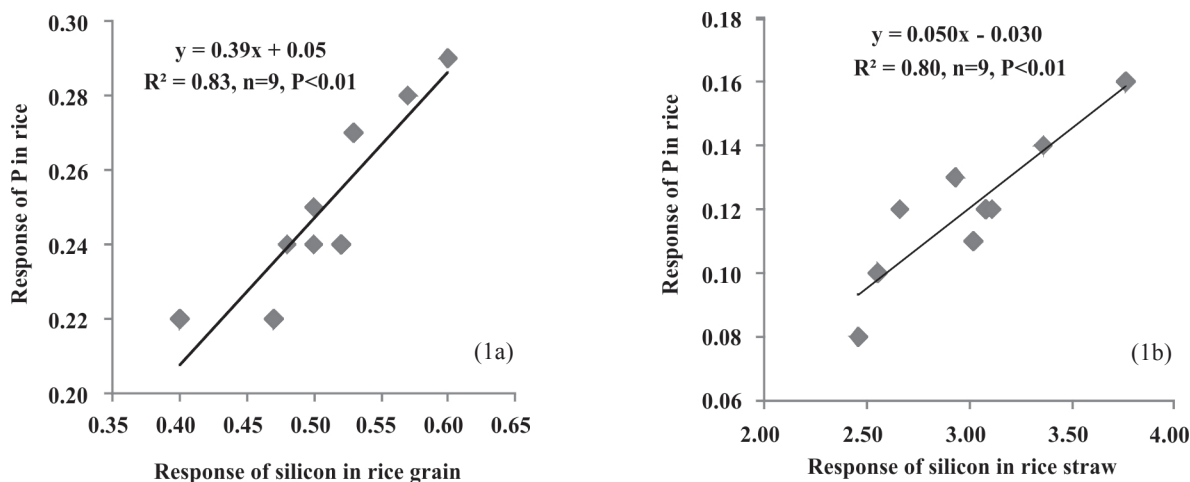


Fig. 1. Relationship between Si and P in rice grain (1a) and rice straw (1b)

but 100% RDF ( $T_2$ ). The increased P concentration in rice grains and straws with Si application might be due to the enhanced soil P availability owing to displacement of colloid bound phosphate in presence of silicate ions. Our finding are in good agreement with the previous study of Pati *et al.* (2017) where they reported positive significant correlation of available Si with available P concentration in soil.

#### Silicon fertilizer on acid and alkaline phosphatase

We found that Si-fertilization along with RDF (both 50% and 100%) increased the amounts of acid and alkaline phosphatase over control (Table 3). The maximum concentration of these enzymes (acid and alkaline phosphatase) were observed (69.9 and 640  $\mu\text{g PNP g}^{-1}$  soil, respectively) when Si was applied through 600 kg diatomaceous earth  $\text{ha}^{-1}$  along with 100% RDF ( $T_6$ ) followed by  $T_5$  (62.2 and 592  $\mu\text{g PNP g}^{-1}$  soil, respectively) and  $T_4$  (50.6 and 581  $\mu\text{g PNP g}^{-1}$  soil, respectively) treatments. A strong positive relationship was recorded between the phosphatase enzyme and available P content ( $r = 0.99^{**}$  for acid phosphatase;  $r = 0.98^{**}$  for alkaline phosphatase) in the post-harvest rice soil. Therefore, application of Si along with full dose of standard fertilizer practice in rice field was very effective for improving extractable P status in soil for better P nutrition in rice. Nutrition of P was also improved by the application of Si in rice. Applied Si, however, accelerated the activity of acid and alkaline phosphatase enzyme in soil (Table 3) which in turn produced more plant available P through phosphorylation for better growth and development of rice plant (Fig. 1a and 1b). The reason behind such positive correlation between Si and phosphatase enzyme activities may be due to better production of

root exudates (Guo *et al.* 2006) with improved microbial activities in rhizosphere zone by external application of Si.

#### Effect of Si-fertilizer on Zn and Fe nutrition of rice

The results (Fig. 2) showed that Si application had an antagonistic effect on Zn and Fe nutrition of rice. Silicon had significant negative correlation with Zn ( $r = -0.67^*$ ) and Fe ( $r = -0.57^*$ ) in rice grain (Fig. 2a). Rice straw also showed significant negative correlations of Si with Zn ( $r = -0.75^{**}$ ) and Fe ( $r = -0.62^*$ ) (Fig. 2b). The results, therefore, revealed a possibility of an obstacle or barrier, created by the external application of Si through DE, for the assimilation of native Zn and Fe in the rice. Antagonistic effect of Si was more pronounced with Zn than Fe (Fig. 2a and 2b). It was found that application of 600 kg DE  $\text{ha}^{-1}$  along with 100% RDF ( $T_6$ ) reduced Zn and Fe concentration in rice grain by 39.6 and 25.7 per cent, respectively over 100% RDF ( $T_2$ ). Similar effect was also found in case of rice straw where corresponding reductions were 21.2 and 27.1 per cent, respectively.

Antagonistic relationship of Si with Zn and Fe may be due to better internal metabolism of P results in more phytic acid production which disrupts Zn and Fe bioavailability in rice (Bohn *et al.* 2008) and better internal homeostatic effect of Si fertilization on Zn and Fe metabolism affecting shoot to grain ratio (Xu *et al.* 2015). The relation between Zn and Fe in rice is obscure; seldom synergistic (Zeidan *et al.* 2010), sometimes indifferent (Qing *et al.* 2011) and very often antagonistic (Giordano and Mortvedt 1972). The shoot to grain transfer coefficients of Zn and Fe (Fig. 3) showed the maximum drop in Zn and Fe translocation on application of 600 kg DE  $\text{ha}^{-1}$  with

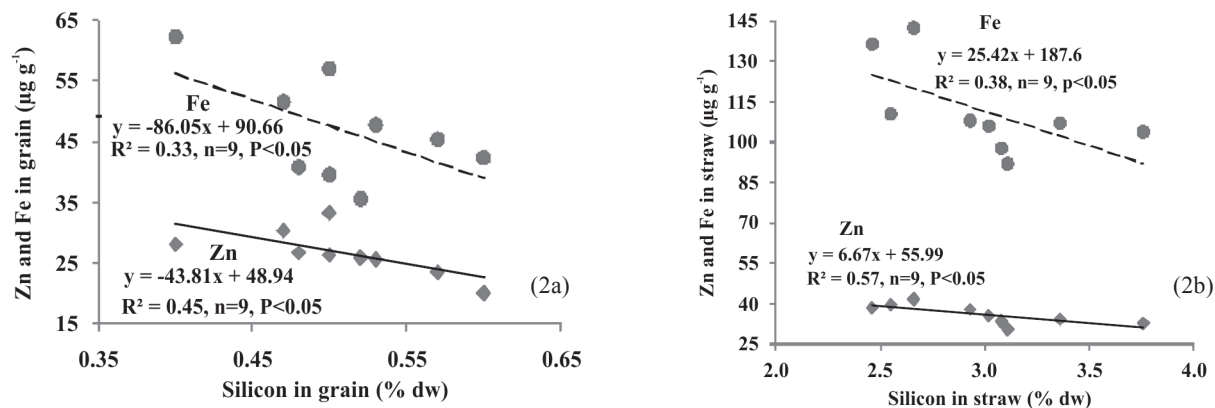


Fig. 2. Relationship between Si and Zn as well as Si and Fe in rice grain (2a) and rice straw (2b)

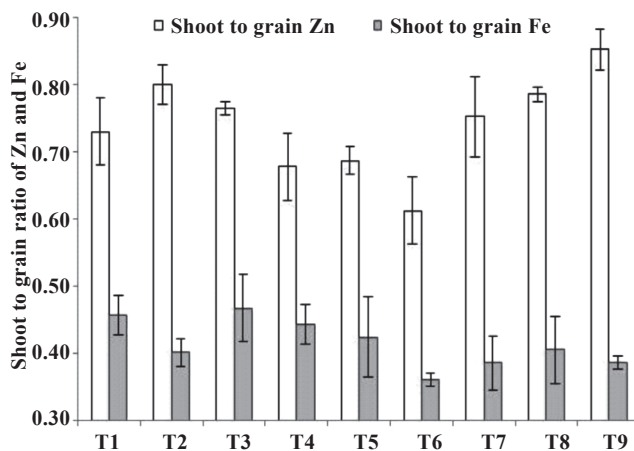


Fig. 3. Shoot to grain transfer coefficients of Zn and Fe in rice affected by Si fertilization

100% RDF( $T_6$ ). However, the maximum enrichment of Si was observed in the grains and straw of the rice by this treatment. It is, however, important to consider such antagonistic relationship of Si with these micronutrient cations in view of the significance of Zn and Fe in human nutrition.

### Conclusions

Our study showed that the external application of Si in rice may increase the crop yield by improving the use efficiency of Si and P. Such an application of Si may induce a synergism with P nutrition but an antagonism with Zn and Fe nutrition in rice. Application of Si through 300 kg diatomaceous earth  $ha^{-1}$  along with 100% RDF can nourish rice seeds with Si optimally. Further increase in its (Si through diatomaceous earth) dose may be useful to enrich the rice straw only. A detailed study, however, is needed in future to address the effect of external Si application on Zn and Fe nutrition in rice growing in the soils limiting these two micronutrients.

### Acknowledgement

The authors wish to acknowledge the financial assistance of the Agripower Australia Ltd. through a Network Project on 'Diatomaceous earth as a source of silicon for growing rice and potato in soils of India' for carrying out this research.

### References

- Bityutskii, N., Pavlovic, J., Yakkonen, K., Maksimovi, V. and Nikolic, M. (2014) Contrasting effect of silicon on iron, zinc and manganese status and accumulation of metal-mobilizing compounds in micronutrient-deficient cucumber. *Plant Physiology and Biochemistry* **74**, 205-211.
- Bohn, L., Meyer, A.S. and Rasmussen, S.K. (2008) Phytate: impact on environment and human nutrition. A challenge for molecular breeding. *Journal of the Zhejiang University Sciences B* **9**, 165-191.
- Detmann, K.C., Araujo, W.L., Martins, S.C., Sanglard, L.M., Reis, J.V., Detmann, E., Rodrigues, F.A., Nunes-Nesi, A., Fernie, A.R. and Da Matta, F.M. (2012) Silicon nutrition increases grain yield, which, in turn, exerts a feed-forward stimulation of photosynthetic rates via enhanced mesophyll conductance and alters primary metabolism in rice. *Scientific World Journal* **196**, 752-62.
- Ding, T.P., Tian, S.H., Sun, L., Wu, L.H., Zhou, J.X. and Chen, Z.Y. (2008) Silicon isotope fractionation between rice plants and nutrient solution and its significance to the study of the silicon cycle. *Geochimica et Cosmochimica Acta* **72**, 5600-5615.
- Elmer, W.H. and Datnoff, L.E. (2014) Mineral nutrition and suppression of plant disease. In *Encyclopedia of Agriculture and Food Systems* (Neal Van Alfen, Ed.). San Diego, Elsevier, pp. 231-244.
- Epstein, E. (1999) Silicon. *Annual Review of Plant Physiology and Plant Molecular Biology* **50**, 641-664.

- Giordano, P.M. and Mortvedt, J.J. (1972) Rice response to zinc in flooded and non-flooded soil. *Journal of Agronomy* **64**, 521-524.
- Guo, Z.G., Liu, H.X., Tian, F.P., Zhang, Z.H. and Wang, S.M. (2006) Effect of silicon on the morphology of shoots and roots of alfalfa (*Medicago sativa*). *Australian Journal of Experimental Agriculture* **46**, 1161-1166.
- Hallmark, C.T., Wilding, L.P., Smeck, N.E. (1982) Silicon. In *Methods of Soil Analysis. Part 2. Chemical and Microbiological Properties* (A.L. Page et al., Eds.), American Society of Agronomy and Soil Science Society of America, Madison, Wisconsin, pp. 263-273.
- Haysom, M.B.C. and Chapman, L.S. (1975) Some aspect of calcium silicate trial at Mackay. *Proceedings of the Queensland Society of Sugar Cane Technologists* **42**, 117-122.
- Jackson, M.L. (1973) *Soil Chemical Analysis*. Prentice Hall of India (Pvt.) Ltd., New Delhi.
- Jones, J.H. and Handreck, K.A. (1967) Silica in soils plants and animals. *Advances in Agronomy* **19**, 107-149.
- Lindsay, W.L. and Norvell, W.A. (1978) Development of a DTPA soil test for zinc, iron, manganese and copper. *Soil Science Society of America Journal* **42**, 421-428.
- Ma, J.F., Mitani, N., Nagao, S., Konishi, S., Tamai, K., Iwashita, T. and Yano, M. (2004) Characterization of the silicon uptake and molecular mapping of the silicon transporter gene in rice. *Plant Physiology* **136**, 3284-3289.
- Meena, D., Dotaniya, M.L., Coumar, V., Rajendiran, S.A., Kundu, S. and Subba Rao, A. (2014) Case for silicon fertilization to improve crop yields in tropical soils. *Proceedings of the National Academy Science India, Section B, Biological Sciences* **84**, 505-518.
- Page, A.L., Miller, R.H. and Keeney, D.R. (1982) *Methods of Soil Analysis. Part-2, 2<sup>nd</sup> Edition*, Soil Science Society of America Journal, Madison, Wisconsin, USA.
- Parker, D.R. and Gardner, E.H. (1981) The determination of hot water soluble boron in some acid Oregon soils using a modified azomethine-H procedure. *Communications in Soil Science and Plant Analysis* **12**, 1311-1322.
- Pati, S., Saha, S. Hazra, G.C., Saha, B.N., Pal, B. and Mandal, B. (2017) Distribution of silicon in rice growing soils of West Bengal in relation to some important soil chemical properties. *Journal of the Indian Society of Soil Science* **65**, 181-188.
- Pavlovic, J., Samardzic, J., Masimovic, V., Timotijevic, G., Stevic, N., Laursen, K.H., Hansen, T.H., Husted, S., Schjoerring, J.K., Liang, Y. and Nikolic, M. (2013) Silicon alleviates iron deficiency in cucumber by promoting mobilization of iron in the root apoplast. *New Phytologist* **198**, 1096-1107.
- Prakash, N.B., Chandrashekar, N., Mahendra, C., Patil, S.U., Thippeshappa, G.N. and Laane, H.M. (2011) Effect of foliar spray of soluble silicon acid on growth and yield parameters of wetland rice in hilly and coastal zone soils of Karnataka, South India. *Journal of Plant Nutrition* **34**, 1883-1893.
- Qing, Z.A., Li, B.Q., Hong, T.X., Chun, L.X. and Gale, W.J. (2011) Combined effect of iron and zinc on micronutrient levels in wheat (*Triticum aestivum* L.). *Journal of Environmental Biology* **32**, 235-239.
- Saud, S., Li, X., Chen, Y., Zhang, L., Fahad, S., Hussain, S., Sadiq, A. and Chen, Y. (2014) Silicon application increases drought tolerance of Kentucky bluegrass by improving plant water relations and morpho-physiological functions. *The Scientific World Journal* **2014**, 1-10.
- Savant, N.K., Datnoff, L.E. and Snyder G.H. (1997) Depletion of plant available silicon in soils: a possible cause of declining rice yields. *Communications in Soil Science and Plant Analysis* **28**, 1245-1252.
- Singh, A.K., Singh, R. and Singh, K. (2005) Growth, yield and economics of rice (*Oryza sativa*) as influenced by level and time of silicon application. *Indian Journal of Agronomy* **50**, 190-193.
- Sperotto, R.A. (2013) Zn/Fe remobilization from vegetative tissues to rice seeds: should I stay or should I go? Ask Zn/Fe supply. *Frontiers in Plant Science* **4**, 1-4.
- Tandon, H.L.S. (1995) Major nutritional constraints to crop production and the soil fertility management strategies in different agroclimatic regions of Asia. In *Proceedings of the International Potash Institute Colloquium on Potassium in Asia*. Balanced fertilization to increase and sustain agricultural production. Chiang Mai, Thailand, 21-24 February, 1995. International Potash Institute, Basel, pp. 43-72.
- Walkley, A. and Black, I.A. (1934) An examination of the Degtjareff method for determining soil organic matter, and a proposed modification of the chromic acid titration method. *Soil Science* **37**, 29-38.
- Xu, C.X., Ma, Y.P. and Liu, Y.L. (2015) Effects of silicon (Si) on growth, quality and ionic homeostasis of aloe under salt stress. *South African Journal of Botany* **98**, 26-36.
- You-Qiang, F.U., Hong, S., Dao-Ming, W.U. and Kun-Zheng, C.A.I. (2012) Silicon-mediated amelioration of Fe<sup>2+</sup> toxicity in rice (*Oryza sativa* L.) roots. *Pedosphere* **22**, 795-802.
- Zeidan, M.S., Mohamed, M.F. and Hamouda, H.A. (2010) Effect of foliar fertilization of Fe, Mn and Zn on wheat yield and quality in low sandy soils fertility. *World Journal of Agricultural Sciences* **6**, 696-699.