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Silicon in mitigating biotic stresses in rice (*Oryza sativa* L.) – a review

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Abstract

Silicon (Si), the second most abundant element in the earth's crust (28% of the total soil weight) is assimilated solely as monosilicic acid. Absorption and accumulation of Si in different plants vary from 0.1-10% on dry weight basis. It is beneficial or quasi-essential to graminaceous plants, such as rice, wheat, barley, maize, sorghum, sugarcane, etc. Rice is a high Si accumulator plant and absorbs on an average 150-300 kg of Si ha^{-1}. It is probably the only element which is able to enhance the resistance to multiple stresses. Providing appropriate amounts of Si to the plants cultivated in Si deficient soils could considerably improve the rate of plant growth and its resistance against biotic-and-abiotic stresses. It has been found that, no lodging occurred in rice fields fertilised with calcium silicate and more than 66% lodging was observed in untreated control fields. Application of calcium silicate slag increased grain yield of rice by 10-17%. Silicon fertilizer shortens the leaf lesion caused by bacterial leaf blight by 5-22% and leaf and neck blast was reduced by 50.5 and 26.8%, respectively. Histosol soils in Florida amended with 5 t ha^{-1} of silicate slag resulted in 73-86% and 58-75% reduction in blast and brown spot diseases, respectively, in rice with concurrent yield increases between 56-88%. Silicon is as effective as conventional fungicides in controlling diseases of rice, such as leaf scald *(Monographella albescens)*, blast *(Magnaporthe grisea)*, brown spot *(Cochliobolus miyabeanus)* and grain discoloration. Silicon also suppresses diseases caused by bacteria and viruses. Silicon has been found effective against insect-pests, such as stem borer, brown plant hopper, rice green-leaf hopper and white backed plant hopper. Studies reported that use of silicate fertilizer reduced stem borer incidence by 10-20% through enhanced effect of Si deposition in the plant tissues which acts as a mechanical barrier against chewing by insects.

Key words: Biotic stresses, brown plant hopper, calcium silicate, rice, silicon

Rice (*Oryza sativa* L.) is the staple food for more than 50% of world population and its yearly production governs the world food security (Dass *et al.*, 2015). Rice provides 60-70% of energy requirement of more than two billion peoples in Asia alone. In India, rice is cultivated round the year in diverse ecologies spreading over 44.6 million hectare (m ha) with a production of 106 million tonne (mt) of rice with an average productivity of 2.96 t ha^{-1} (Yogendra *et al.*, 2014). The country has to enhance rice production by 3 mt every year to ensure its food and nutritional security (Dass *et al.*, 2017a) which is to be achieved by substantial enhancement in productivity, but with limited land and water resources (Dass *et al.*, 2017b). Currently, India's rice productivity level is about half of the world average and one-third of average productivity of neighbouring

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country, China (Dass *et al.*, 2012). Infact, rice yields are either decelerating or stagnating in post green revolution era mainly due to imbalance in fertilizer use, soil degradation, mono-cropping and lack of suitable rice genotypes for low moisture adaptability, insect-pest and disease resistance (Prakash, 2010).

Application of silicon (Si) imparts resistance to the rice plant against biotic and abiotic stresses and, thereby, improves rice yields. Silicon is the second most abundant element in the earth's crust (28% of the total soil weight) (Pereira *et al.*, 2003; Rodrigues and Datnoff, 2005; Singer and Munns, 2005) next to oxygen (47%). It ranges from 200-300 g Si kg^{-1} in clay soil and 450 g Si kg^{-1} in sandy soils (Matichenkov and Calvert, 2002) and its content in soil varies from 1-45 % by dry weight (Sommer *et al.*, 2006). Most of the Si minerals are largely insoluble, though low levels of mono-and polysilicic acid are invariably found dissolved in the soil solution. Plants assimilate Si solely as monosilicic acid or orthosilicic acid [H_4SiO_4] which are highly unstable and convert to unavailable form (polymeric silicic acid) or forms complex with other compounds to form meta-silicates (Matichenkov and Calvert, 2002; Rodrigues and Datnoff, 2005). Concentrations of mono-silicic acid in the soil ranges from 0.1-0.6 mM and is taken up by plants in this form (Ma and Takahashi 2002). The ability of soils to meet plant requirements for Si depends upon the Si solubility. Once absorbed, Si is deposited as amorphous silica (SiO_2-nH_2O) throughout the plant, mainly in the cell walls, where it interacts with pectin and polyphenols and enhances cell wall rigidity and strength (Currie and Perry, 2007). It is not considered as an essential or functional plant nutrient, but it is considered as an absolutely useful element for a large variety of plants (Hayasaka *et al.*, 2008; Nakata *et al.*, 2008). It has been proved that Si is beneficial or quasi-essential to plants, especially graminaceous plants, such as rice, wheat, barley, maize, sorghum, sugarcane, etc. (Liang and Ding, 2002; Hamayun *et al.*, 2010; Chen *et al.*, 2011; Kim et al., 2011). Although, it did not come under essential elements, it is concentrated at levels equivalent to those of macro-nutrients (Kamenidou *et al.*, 2009). The beneficial effects of Si are particularly distinct on plants exposed to various forms of biotic stresses (plant disease and insect-pest damage) and abiotic stresses (aluminium and heavy metals toxicity, salinity stress, drought and high temperature stress, chilling stress, mineral nutrient deficiency stress and UV radiation *etc.*).

In plants, Si is assimilated mainly by roots, but accumulation is greater in aerial parts, capacity to accumulate in tissues is variable. Its content in plants ranges from 0.1-10% on dry weight basis, an amount equivalent to or even exceeding several macro-nutrients (Ma and Takahashi, 2002; Kamenidou *et al.*, 2009). Silicon concentrations are higher in monocotyledons than in dicotyledons (Rodrigues *et al.*, 2001; Rodrigues and Datnoff, 2005). Some plants absorb more silica than they require and this gets deposited on tissues as it cannot be excreted (Esan, 1953). Its content increased from legumes < fruit crops < vegetables < grasses < grain crops (Thiagalingam *et al.*, 1977). Based on the Si levels in tissues, three groups of plants were recognized *viz.* (i) dicotyledons with less than 0.1% on dry weight basis, (ii) dry land grasses like oats and rye with 1.5% and (iii) wet land grasses and paddy grown rice with Si content 5% or higher (Jones and Handreck, 1967). Rice is a high Si accumulator plant and absorbs 150-300 kg Si ha^{-1} (Yoshida, 1975; Bazilevich, 1993). The Si accumulation in rice plants can go upto 10% of plant dry weight. Ma *et al.* (2006) and Nakata *et al.* (2008) reported that rate of accumulation of other essential macro-nutrients such as nitrogen (N), phosphorus (P) and potassium (K) which makes Si the agronomically essential element. Silicon is deposited mostly in cell walls, but sometimes as silica bodies in the lumen of cells (Lanning *et al.*, 1958). Silica content in rice has been shown to increase with the age of the crop from transplanting to harvest (Nayar *et al.*, 1982). In rice, oat, rye and wheat, seed coat accumulates most of the silica and grain the least (Gallo *et al.*, 1974). Silicon is involved in several major roles in rice: carbohydrate synthesis, grain yield, phenolic synthesis and plant cell wall protection (Van, 2006).

Silicon confers rigidity and strength, resistance against pests and diseases (Yoshida, 1981; Takahashi *et al.*, 1990). Using appropriate amount of Si has been found to reduce the probability of plants being grazed by herbivores

(Belanger *et al.*, 1995; Datnoff *et al.*, 1997; Rodrigues and Datnoff, 2005). Silicon is probably the only element which is able to enhance the resistance to multiple stresses (Ma *et al.*, 2004). Moreover, its presence in plant tissue at high concentrations does not cause any toxicity or damage to the plant (Ma *et al.*, 2006). Some soils contain little plant available Si in their native state and repeated cropping can reduce the levels of plant-available Si to the point that supple-mental silicon fertilization is required for maximum production (Hattori *et al.*, 2005). Long period of intensive crop cultivation depletes the available soil Si. Depletion of available Si in the soil could be one of the possible limiting factors amongst others contributing to declining rice yields. The lower values for Si in the soil can be justified due to (i) severe and frequent soil erosion and sediment transportation, (ii) usually plants absorb Si almost equal to the concentration of most of macronutrients, (iii) due to the desilica-tion process, Si in the soil is continuously lost as the result of leaching process. Sub-tropical and tropical soils are generally low in available Si and would benefit from Si fertilization (Juo and Sanchez, 1986; Rodrigues and Datnoff, 2005). Silicon deficiency has also been observed in highly organic soils, as these soil types contain low amounts of minerals; (Rodrigues and Datnoff, 2005). Rice productivity has been reported to be higher in temperate regions as compared to the tropics (Savant *et al.*, 1997; Rodrigues and Datnoff, 2005) because the amount of Si in the tropical soils is about 5 to 10 times lower than its amount in the temperate region soils (Foy, 1992; Rodrigues and Datnoff, 2005). Hence, improved Si management appears to be necessary to increase yield and sustain crop productivity in temperate and tropical regions (Meena *et al.*, 2014).

Silicon fertilizer has a double effect on the soil-plant system as under; (i) improved plant-Si nutrition reinforces plant-protective properties against diseases, insect-pest attack, and unfavourable climatic conditions, (ii) soil treatment with bio geochemically active silicon substances optimizes soil fertility through improved water, physical and chemical soil properties, and maintenance of nutrients in plant-available forms (Meena *et al.*, 2014). Providing appropriate amounts of Si to the plants cultivated in Si deficient soils could considerably improve the rate of plant growth as well as its resistance against biotic and abiotic stresses (Menzies *et al.*, 1991; Savvas *et al.*, 2002; Kamenidou *et al.*, 2009). Increased application rate of silica fertilizer (0, 250, 500 kg ha^{-1}) increased silica concentration in shoot, leaves and panicle of rice (Fallah *et al.*, 2011). Rice crop producing a grain yield of 5 t ha^{-1} normally removes 234-470 kg Si ha^{-1} (500-1000 kg SiO_2 ha^{-1}) (Amarsari and Perera, 1975). Because of its high requirement, rice responds well to Si application.

Sources of silicon

The first attempt to assess the possible uses of industrial by-products containing Si as fertilizers was conducted in China during late 1950's. Subsequently, Si application as fertilizers has increased steadily since 1970, and Si fertilizers have been applied repeatedly to improve rice production by enhancing resistance to diseases (Wang *et al.*, 2001) and increasing yields (Zhu and Chen, 1963). As a fertilizer, it must provide sufficient water-soluble Si with relatively high Si content to meet the plant needs, should be cost effective, have a physical nature that facilitates storage and application, and does not contain substances that will contaminate the soil (Gascho, 2001). Many potential sources meet the first requirement (Table 1); however, only a few meet all of these requirements. Crop residues, especially of Si accumulating plants, such as rice, are used as Si sources. However, the crop demand for Si generally exceeds that supplied by crop residues. Inorganic materials, such as quartz, clays, micas, and feldspars, although rich in Si, are poor silicon-fertilizer sources because of the low solubility of the Si. Calcium silicate, obtained

Table 1. Different sources of silicon (Si)

Si source	Chemical formula	Si content (%)
Salicic acid	H_4SiO_4	29
Calcium silicate slag	-	18-21
Calcium silicate	$CaSiO_3$	24
Potassium silicate	K_2SiO_3	18
Sodium silicate	Na_2SiO_3	23
Quartz sand (fine grind)	SiO_2	46

Source: Meena *et al.* (2014)

as a by-product of steel and phosphorus production, is one of the most widely used Si fertilizer. Potassium silicate, though expensive, is highly soluble and can be used in hydroponic culture. Other sources that have been used commercially are calcium silicate hydrate, silica gel and thermo-phosphate (Gascho, 2001). International Rice Research Institute (IRRI) research indicates that Si deficiency can be rectified by the application of calcium silicate slag at the rate of 120-200 kg ha^{-1}.

Silicon on growth and development of rice

Silicon is an essential component of rice plants and its accumulation is helpful in maintaining sustainable production (Yamaji and Ma, 2011). It improves the leaf angle, making leaves more erect, thus reducing self-shading, especially under high N-rates (Yoshida *et al.*, 1969). The effect of Si on leaf erectness is mainly due to Si depositions in the epidermal layers of the leaf panicle (Takahashi and Miyake, 1982). This Si induced erectness of leaves results in increased photosynthesis, improves water usage, and decreases toxicity of heavy metals and cuticular transpiration (Epstein, 1994; Nakata *et al.*, 2008). Silicon nutrition improves the light receiving posture of the plants, thereby stimulating photosynthate production in plants (Savant *et al.*, 1997). Gerami *et al.* (2012) reported that with the increase of Si levels, the dry weight of the plant will increase together with its height and number of tillers, increased leaf area led to enhanced photosynthetic rate and prevents the destruction of chlorophyll. Liang *et al.* (1994) found practically no lodging in rice fields fertilised with calcium silicate, but more than 66% lodging occurred in untreated control fields.

Lee *et al.* (1965) also discovered that Si fertilization reduced lodging in lowland rice that was caused by an excessive N application. The photosynthesis rate, transpiration rate and stomatal conductance were increased by the addition of slag at the flowering stage, but the intercellular CO_2 concentration fell. Application of slag based silicate fertilizers not only enhanced plant height, tiller number and shoot dry weight biomass, but also improved yield components including the panicle weight and 1000 grain weight (Li *et al.*, 2011). Positive effects and importance of Si as a nutrient element in rice plants have been reported in several studies (Deren *et al.*, 1992; Ando *et al.*, 2002; Ma and Takahashi, 2002; Gao *et al.*, 2004; Ma *et al.*, 2006; Hayasaka *et al.*, 2008; Kamenidou *et al.*, 2009). Si content in different organs of a rice plant generally ranged from high to low, in descending rank in the hull, leaf, leaf sheath, culm, and root (Zhu, 1985). The distribution of Si in rice plant is presented in Table 2.

Table 2. Distribution of Si in rice plant

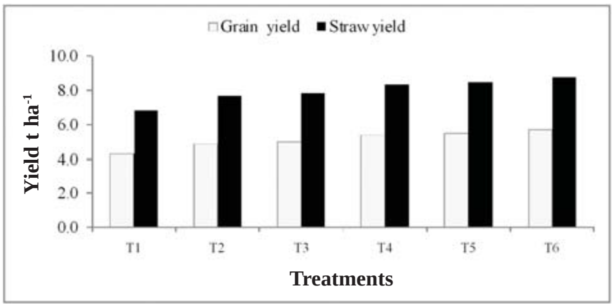
Plant parts	Si content (g kg^{-1})
Polished rice	0.5
Rice bran	50
Rice straw	130
Rice hull	230
Rice joints (base of the grain)	350

Source: Van (2006)

Silicon on yield and yield attributes

Silicon is essential, from an agronomic standpoint, to increase and/or provide sustainable yields of rice crop (Barbosa *et al.*, 2000). Silicon increases the number of spikelets $panicle^{-1}$ (Ma *et al.*, 1989; Deren *et al.*, 1994; Takahashi, 1978), spikelet fertility (Barbosa, 1987; Takahashi, 1978), and the mass of grains (Balastra *et al.*, 1989; Carvalho, 2000). Application of 600 mg SiO_2 kg^{-1} soil results in significantly lower blank spikelet number in comparison to no Si (Dastan and Ghanbari, 2011).

Savant *et al.* (1997) also reported that an adequate supply of Si increases the number of panicles, the number of grains $panicle^{-1}$, and the percentage ripening. Silicon addition to soils increased rice yields by up to 10% and these increased yields could exceed 30% where leaf blast was severe (Yoshida, 1981; Korndorfer and Lepsch, 2001). Again, Fleck and Schenk (2011) reported that Si application increased straw and grain yield by 21 and 17%, respectively. The likely explanation for the increase in grain mass would be the greater deposition of Si on the palea and lemmas (Balastra *et al.*, 1989). Research findings from China revealed that rice yield of 7.5 t ha^{-1} require 750-1,500 kg ha^{-1} of silica. On an average, 1,125 kg ha^{-1} of silica is required to achieve that yield. This far exceeds the absorption of the three major plant nutrients, namely, N, P, and K.



[100% RDF(T1), T1 + Calcium silicate @ 2 t ha^{-1} (T2), T1 + 120 Si ha^{-1} through Fly Ash (T3), T1+ Silixol Granules @12.5 kg ha^{-1} (T4), T1 + Silixol Granules @ 25.0 kg ha^{-1} (T5), T1 + Silixol Granules @ 37.5 kg ha^{-1} (T6)] Source: (Jawahar *et al.*, 2015)

Fig. 1 Effect of silixol granules on grain and straw yields of rice

Application of Si in rice increased the grain yield under both upland and water logged conditions (De and Shinde, 1985). The application of silicate augmented the absorption by rice plant of other nutrients as well. Application of potassium,-magnesium-and calcium-silicate increases the rice yield. On an average 10-30% increments in yields were recorded with silicate amendments (Gascho, 2001). Application of silixol granules at the rate of 37.5 kg ha^{-1} along with 100% recommended dose of fertilizers (RDF) registered its superiority over others for panicles m^{-2}, filled grains panicle^{-1}, test weight and grain and straw yields of rice (Jawahar *et al.*, 2015) (Figure 1).

Magnesium silicate consumption rate of 100 to 200 kg ha^{-1} increased rice yield from 21-33% (Bernal, 2008). Nolla *et al.* (2012) found that use of Si reduced lodging and increased number of filled spikelet panicle^{-1} and 1000-grain weight resulting in increase in grain yield. Potassium silicate application resulted in increase grain yield by 34.2% compared to control treatment (Wang and Du, 2011). Several studies have suggested positive growth effects of silicon nutrition on biomass, yield and pollination (Korndorfer and Lepsch, 2001). Park (1975); Mengel and Kirkby (2001) reported that a high correlation exists between straw silica content and yield of grain upto about 12% silica in the straw.

Silicon in alleviating biotic stress

The beneficial effect of Si is more evident under stress conditions (Ma and Takahashi, 2002). This is because Si is able to protect plants from multiple biotic and abiotic stresses (Ma, 2004). Silicon depleted soils have been associated with lower resistance to insect-pests and fungal diseases as well as crop lodging (Flinn and De, 1984; Savant *et al.*, 1997). Recent evidence suggests that Si may re-inforce plant pest and disease resistance by stimulating the expression of natural defence reactions through the production of low molecular weight metabolites, which include flavonoid, phytoalexins (Meyer and Keeping, 2000). Numerous studies have shown that Si is effective in controlling diseases caused by both fungi and bacteria in different plant species.

Silicon and diseases

Insect-pests and diseases cause significant losses to rice yield (Ou, 1985; Nakata *et al.*, 2008). Under Si deficient conditions, some diseases, such as blast, brown spot and sheath blight can be extremely threatening to rice cultivation (Rodrigues and Datnoff, 2005). Development of efficient and cost-effective methods to manage the diseases is one of the priority issues in rice production (Hayasaka *et al.*, 2008). The suppressive effect of Si on rice blast was reported as early as 1917 by Onodera. By then, a number of investigators have demonstrated the influence of Si in suppressing foliar and root diseases in both dicots and monocots. Rice blast disease, caused by the fungus *Pyricularia oryzae* (Couch and Kohn, 2002), is particularly prevalent and causes heavy yield losses in all rice growing areas. A 3-5% SiO_2 content in rice seedlings would be effective in controlling blast disease under a range of conditions (Datnoff *et al.*, 1997; Hayasaka *et al.*, 2005). Foliar applications of Si have been found to increase the resistance against pathogens in plant species that do not absorb Si efficiently (Bowen *et al.*, 1992; Epstein, 1994). Silicon increases the thickness of cell wall below the cuticle, which imparts mechanical resistance to the penetration of pathogenic fungi and it also decrease transpiration (Yoshida *et al.*, 1962). It has also been reported that rice blast severity is directly related with Si deficiency in soils (Kim *et al.*, 2002; Rodrigues *et al.*, 2004; Ranganathan *et al.*, 2006). The amount of Si applied to soil and the concentration of Si in rice husks and straw had a linear relationship and both were inversely proportional with blast severity.

Silicon fertilization was reported to have significantly reduced the occurrence of blast in rice plants (Qin, 1979; Zang, 1989). Application of calcinated serpentinite as a Si source prior to rice planting has also been reported to be effective in reducing leaf blast severity and this reduction has a linear relationship with tissue sugar content (Prabhu *et al.*, 2007). The degree of resistance increased in proportion to the amount of Si accumulated in the plants (Chen *et al.*, 1985). Shui *et al*. (1995) determined the efficacy of Si fertilization on rice disease resistance to leaf-and neck-blast in Si deficient soil. The results revealed that the resistance of rice to blast was enhanced by Si application and disease index for leaf-and neck-blast was reduced by 50.5 and 26.8%, respectively. Datnoff *et al*. (1992) reported decrease in blast severity ranging from 17-30% in the rice under Histosols, where Si was applied. Silicon reduces the epidemics of both leaf and panicle blast of rice at different growth stages. Rice seedling blast is significantly suppressed by the application of Si fertilizers in the nursery (Maekawa *et al.*, 2001). Application of silicate Si at 1,000 kg ha^{-1} reduced neck blast by 38.8% over the control (Datnoff *et al.*, 2007).

Datnoff *et al.* (2008) in studies on the effects of nano-Si stated that in all treatments with Si application caused decrease in blast extension compared to control treatment. Chen *et al.* (2011) stated that Si can increase enzyme activity that has important role for defence reaction to gene expression and blast disease. Ghanbari (2009), Fallah (2011) and Yazdpour *et al.* (2014) stated that N-application for enhanced rice yield caused increase in blast disease, but silicon application decreased disease extension. Seebold *et al.* (2001) found that, regardless of the cultivar resistance, incubation period was lengthened and the number of sporulating lesions, lesion size, rate of lesion expansion and the number of spores per lesion were significantly reduced by Si application. In a well-studied rice-*Magnaporthe grisea* pathosystem, the incubation period was lengthened by Si accumulation, whereas lesion length, rate of lesion expansion and disease leaf area dramatically decreased (Seebold *et al.*, 2001). In rice, Si has been as effective as a fungicide in controlling rice blast *(Magnaporthae grisea, Pyricularia grisea)* and has even reduced the rate or number of necessary fungicide applications (Datnoff *et al.*, 2001). In addition, amending partially blast-resistant rice cultivars with silicon, resistance increased to the same level as completely resistant cultivars (Seebold *et al.*, 2000).

Increasing the Si supply, increases rice resistance to leaf and neck blast, sheath blight, brown spot, leaf scald and stem rot (Rodrigues and Datnoff, 2005). Chang *et al.* (2002) reported that in the cultivar TN-1 which is susceptible to blast disease, the Si content in leaves was lower than that of the resistant breeding line, TSWY-7 under the nutrient cultural system adopted. Silicon induced decrease of soluble sugar content in the leaves seems to contribute to the field resistance of the disease. Also, Si fertilizer can shorten the leaf lesion caused by bacterial leaf blight by 5-22%. Reducing the size of lesions is directly proportional to the reduction of soluble sugar in the leaves due to the presence of silicon. Application of 200 kg silica ha^{-1} can reduce the infection of dirty panicle (grain discoloration) by as much as 18 % and increased rice yield by 20%. When the available SiO_2 in soil increased from 60 to 220 ppm, the Si content in flag-leaf increased correspondingly from 7.4 to 18.7% besides reducing neck-rot infection from 8.6 to1.5% (Salim and Saxena, 1992). Exogenous application of salicylic acid (SA) and / or Si significantly reduced the blast disease index of rice, effects of disease control was better with Si and SA treatment together than they did it alone (Chen *et al.*, 2011). Furthermore, this suppression has been effective against not only fungal diseases, but those caused by bacteria and viruses. Silicon appears to affect a number of components of host plant resistance, *i.e.* delays the incubation and latent period, reduces lesion expansion rates, lesion size, lesion number, the number of sporulating lesions and the number of conidia produced per lesion. As a consequence, disease progress and / or final disease severity is dramatically reduced. Disease severity of blast increased with increasing N in the treatment not receiving silicate fertilizer, but significantly reduced in the treatment receiving silicate fertilizer. The average sheath blight spots decreased in plants treated with silicate fertilizer in this experiment (Fallah *et al.*, 2011). Histosol soils amended with 5 t ha^{-1} of silicate slag resulted in a 73-86% and 58-75% reduction in

Table 3. Diseases suppressed by Si nutrition

Rice Diseases	Pathogen	Reference(s)
Leaf and neck blast	*Pyricularia oryzae*	Winslow (1992)
Brown spot	*Bipolaris oryzae*	Datnoff *et al.* (1992)
Sheath blight	*Rhizoctonia solani*	Gangopadhyay and Chattopadhyay (1975)
Leaf scald	*Monographella albescens*	Datnoff *et al.* (1992)
Grain discoloration	*Bipolaris fusarium*	Winslow (1992)
Stem rot	*Magnaporthe salvinii*	Elawad and Green (1979)

blast and brown spot diseases in rice with concurrent yield increases between 56-88% (Datnoff *et al.*, 1991). Some of the diseases suppressed by Si nutrition in rice crop are given in table 3.

Silicon and insect-pests

It is evident from the literature that nutrients, such as N and Si play important roles in the susceptibility and resistance of a range of crops to insect-pest damage. Rice with low tissue Si is associated with increased susceptibility to insect pests and fungal diseases as well as increased problems with crop lodging (Sawant *et al.*, 1994). Some plants like rice, wheat and sugarcane accumulate high amounts of silica in their tissues that seem to interfere in the feeding of insect larvae (Epstein, 1999). Savant *et al.* (1999) reported that plants containing high Si content in their tissues showed better resistance against the infestation of pests. Further, Sujatha *et al.* (1987) explained the positive association among the deposition of silica substance and insect-pest resistance in rice plants. It has been reported that the mandibles of larvae of the rice stem borer are damaged when the Si content of rice plants is high (Jones and Handreck, 1967). Silicon suppresses insect-pests, such as stem borer, brown plant hopper, rice green-leaf hopper and white backed plant hopper, and non-insect-pests, such as leaf spider and mites (Savant *et al.* 1997; Ma and Takahashi, 2002). This Si enhanced effect is attributed to Si deposition in the plant tissues, which provides a mechanical barrier against probing and chewing by insects (Ma and Takahashi, 2002). Stems attacked by the rice stem borer were found to contain a lower amount of Si (Sasamoto, 1961). Fallah *et al.* (2011) reported that use of silicate fertilizer increased grain yield by 10% and reduced stem borer by about 10-20%.

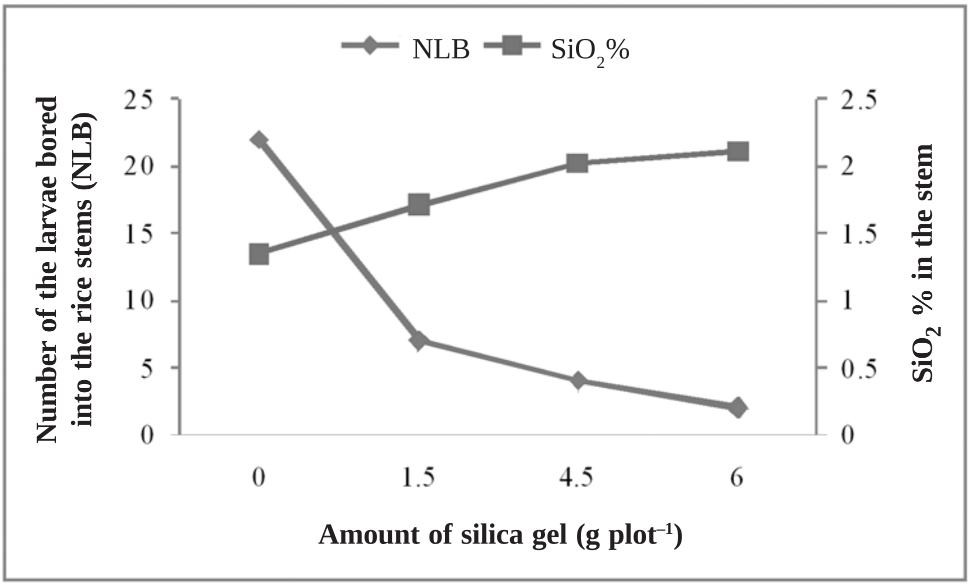


Fig. 2 Effect of silica supply on the resistance of rice to *Chilo suppressalis* (Ma and Takahashi, 2002).

Table 4. Insect-pests of rice suppressed by Si nutrition

Rice insect-pests	Scientific name	Reference(s)
Stem maggot	*Chlorops oryzae*	Sawant *et al.* (1994)
Green leaf hopper	*Nephotettix bipunctatus*	Maxwell *et al.* (1972)
Brown plant hopper	*Nilaparvata lugens*	Yoshihara *et al.* (1979); Sujatha *et al.* (1987)
White backed plant hopper	*Sogetella furcitera*	Salim and Saxena (1992)
Leaf spider	*Tetranychus spp.*	Yoshida (1975)
Stem borer	*Chilo suppressalis*	Sasamoto (1961); Sawant *et al.* (1994)
Grey garden slug	*Deroceras reticulatum*	Wadham and Parry (1981)
African striped borer	*Chilo zacconius*	Ukwungwu and Odebiyi (1985)
Yellow rice borer	*Scirpophaga incertulas*	Panda *et al.* (1975)

Silicon amendment may contribute to the suppression of *Chilo suppressalis* directly through impeding larval penetration and performance and indirectly by delaying penetration, resulting in prolonged exposure of larvae to other control measures.

Silicon supply impairs penetration more strongly in the third instars than in the first instars; and, susceptible rice cultivar benefits more from Si addition than resistant one in deterring boring by rice stem borer larvae (Han and Hou, 2011). Chinese scientists reported that when the available SiO_2 in soil is increased from 60 to 220 ppm, pink stem borer infection was reduced from 33.6 to 6.6%. Silicon nutrition reduces the number of nymphs becoming adults; reduce adult longevity and female fecundity of plant hoppers (Salim and Saxena, 1992). Ma and Takahashi (2002) opined that the number of larvae, which bored into the stems decreased as the Si content in the stems increased (Figure 2). In a field study, a positive relationship between the Si content of rice and resistance to the brown plant hopper has been observed (Sujatha *et al.*, 1987).

The deposition of silica on epidermal layers offers a physical barrier to insects. Sucking pests and leaf-eating caterpillars have a low preference for the silicified plant tissues. The incidences of stem maggots, green-leaf hopper, brown plant hopper and white backed plant hopper, leaf folder etc. in rice were reduced due to Si nutrition (Table 4).

Conclusion

Productivity of rice crop is limiting owing to various biotic and abiotic stresses. Among the biotic stresses, rice blast, sheath blight, brown spot, brown plant hopper, stem borer and green-leaf hopper have become problems in almost all rice cultivating areas of India. Application of Si could be an efficient and cost-effective alternative to cope up with these biotic stresses. Although Si is not considered as essential nutrient for plant growth, its absorption brings several benefits, especially for rice, such as improvement of the leaf angle, making leaves more erect, thus reducing self-shading, thereby, reducing incidence of insect-pest and diseases in rice. Application of Si as calcium silicate slag increased the rice grain yield by 10-17% besides reducing the incidence of blast diseases by 26-50% and brown spot by 58-75%. Among the insects, stem borer and pink stem borer incidence reduced by 10-20% and 20-27%, respectively by silicate application. Hence, for optimizing and sustaining the productivity of rice, Si application should be promoted, particularly in Si-deficient rice-growing areas. However, optimum dose of Si that provides adequate protection against biotic stresses and economically enhances rice yields should be found out for different rice ecologies through well designed field experiments.

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