Impact of Silicon in Managing Important Rice Diseases: Yield and Quality of Rice (ORYZA SATIVA L)

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Abstract: In the Asia regions, the most important staple food consumed by nearly one-half of the world’s population is the rice. However, important diseases of rice namely blast, brown spot, sheath blight and grain discoloration are major limitations on rice production and are becoming more severe on rice grown in silicon (Si) depleted soils, with blast being the most devastating disease. In order to evaluate the effect of silicon and phosphorus rate on disease severity of rice blast, a field experiment was carried out in factorial experiment as the complete randomized blocks design with four replications at Tonekabon, Mazandaran, Iran in 2015-16. Disease that occurs to plant may reduce the ability for the plant to survive and in more severe cases could eventually lead to plant death. Lucas et al. (1997) define plant disease as a disturbance that averts normal development and brings down the economic or aesthetic value of a plant. Although silicon (Si) has not been recognized as an essential element for plant growth, the beneficial effects of Si have been observed in a wide variety of plant species. Silicon also exerts alleviative effects on various abiotic stresses including salt stress, metal toxicity, drought stress, radiation damage, nutrient imbalance, high temperature, freezing and so on. These beneficial effects are mainly attributed to the high accumulation of silica on the tissue surface although other mechanisms have also been proposed. To obtain plants resistant to multiple stresses, genetic modification of the root ability to take up Si has been proposed. In this review, the role of Si in conferring resistance to multiple stresses is described.

Key words: Silicon resource, Phosphorus, Rice, Abiotic stress, Biotic stress, Resistance

Introduction

Rice is one of the world’s most important crops after wheat was awarded second place in terms of annual production, silicon is the second most abundant element in soil and is quite useful as an element to be considered for higher plants (Nakata et al., 2008 ). Many plants are able to absorb Si. Depending upon the species, the content of Si accumulated in the biomass can range from 10 to greater than 100 g/kg. Plant species are considered Si accumulators when the concentration of Si (in dry weight basis) is greater than 1 g/kg. Relative to monocots, dicots such as tomato, cucumber, and soybean are considered to be poor accumulators of Si with values less that 1 g/kg in their biomass. Dryland grasses such as wheat, oat, rye, barley, sorghum, corn, and sugarcane contain about 10 g/kg in their biomass, while aquatic grasses have Si content up to 50 g/kg. Silicon is accumulated at levels equal to or greater than essential nutrients in plant species belonging to the families Poaceae, Equisetaceae, and Cyperaceae. In rice, for example, Si accumulation is about 108% greater than that of nitrogen. It is estimated that a rice crop producing a total grain yield of 5000 kg/ha will remove Si at 230 to 470 kg/ha from the soil (57). Therefore, applications of calcium silicate at 5000 kg/ha (Si at 1000 kg/ha) appear to be sufficient for supplying enough Si to the plant so that the tissue content will be 3% or greater. Concentrations between 3 and 5% may be the minimum tissue levels needed for disease control. Diseases are caused by microorganisms which are usually regarded as pathogens, which include bacteria, fungi and viruses. A plant challenged by pathogenic microorganisms typically responds to changes of physical properties and composition of the cell walls and also, biosynthesis of secondary metabolites that function to restrain disperse of invading pathogens and necrotic lesions at the invasion region. These responses which are known as hypersensitive reaction are very complex and vary based on the nature of the causal agent (Hopkins and Hüner, 2004). Disease affects all parts of plants by reducing the growth and quality of plant, minimizing the absorption, distribution and use of nutrients by the plant, thus may lead to economic loss. Strategies to control diseases are limited and mainly centered on the usage of chemical treatments such as application of fungicides which are environmental concern. Thus, the potential role of mineral nutrition may provide a feasible and significant alternative for disease management. The article’s purpose is to review the research findings of beneficial role of silicon (Si) in protecting plants against diseases, mainly emphasizing on rice. The possible mechanisms involved in Si-mediated plant resistance towards disease are also being discussed in this paper.
Silicon and Rice Diseases: A Brief History

Probably, the first researcher who suggested that Si was involved in rice resistance to blast (Magnaporthe grisea (T. T. Hebert) Yaegashi & Udagawa) Barr (anamorph Pyricularia grisea (Cooke) Sacc.) was a Japanese plant nutrient chemist named Isenosuke Onodera. Onodera (46) published a milestone paper entitled ‘Chemical studies on rice blast disease’. This is the first report on Si research published in a scientific journal of agronomy. For this study, he collected rice plants from 13 different regions in western Japan. Onodera compared the chemical composition of the rice plants infected with blast with that of healthy ones grown in the same paddy field. He observed that diseased plants always contained less Si in comparison to healthy ones obtained from the same field, and that the natural Si content found in rice tissue depended on the paddy field in which the plants had been grown. His finding did not necessarily mean that blast infection was reduced by the Si content of the rice plants or that plants with less Si content were more susceptible. His results did show that there was a relationship between Si content and blast susceptibility. Although he did not intend to study the role of Si in rice resistance to blast, his discovery certainly stimulated further Si research in Japan.

Effect of Si in Suppressing other Diseases of Rice

Sheath blight is a fungal disease caused by Rhizoctonia solani Kühn and occurs mainly in the temperate and tropical rice-production areas (Zuo et al., 2006). The symptoms of this disease include lesions on sheaths of lower leaves near the water line. These lesions are usually oval to elliptical-shaped and greenish-gray with yellow margins (Gangopadhyay and Chakrabarti, 1982). Control management of sheath blight is limited since there are no strong genetic sources of resistance known yet. Currently, the cultivable varieties in the Southern US range from very susceptible to moderately resistant (Kumar et al., 2009). Therefore, biological and cultural management are being practiced to reduce the severity of sheath blight (Willocquet et al., 2000; Rodrigues et al., 2003). The rice cultivars were inoculated with R. solani using the colonized match-stick procedure and treated with two levels of Si, 0 (-Si) and 1.5 mM (+Si), respectively.

The results revealed that Si treatment decreased the disease ratings (rated from 0 to 9) of sheath blight by 2.96 and 0.65, for Ningjing 1 and Teqing. For +Si Ningjing 1, there was a significant reduced in disease ratings compared with –Si treatment and this showed that Si engaged actively in improving the basal resistance towards sheath blight. However for +Si Teqing, the disease rating was slightly lower than –Si Teqing, but it was not statistically different due to the intrinsic resistance of this cultivar to sheath blight. A study by Rodrigues et al. (2003) investigated the influence of Si amendment on R. solani in six Brazilian rice cultivars. The rice was grown in pots containing soil that was Si-deficient and Si treatment was applied at several different rates. At occurrence of maximum tillering level, plants were inoculated with R. solani. This result showed that the Si content in straw was directly related to the quantity of Si applied to the soil. The sheath blight potency was largely decreased for the rice cultivars given the highest rate of Si compared to the rice grown without Si. Meanwhile, the application of Si has also been reported to enhance resistant of rice towards sheath blight although there was no significant difference between high and low levels of Si (Mathai et al., 1977).
Role Of Silicon In Rice Blast Resistance

Rice is the second most important food crop after wheat in Pakistan. In last few years rice yield has been found diminishing and nutritional imbalance has been reported as one of major reasons. In a more specific study of nutrients; the micronutrients have now have been found equally important as macronutrients although they are required in a minute quantity. Balancing the micronutrients for rice cultivation enhances the quality and yield. Micronutrients such as silicon are the most important for sustainable production of Basmati rice. Among all the micronutrients assimilated by plants, silicon alone is consistently present at concentrations similar to those of the macronutrients. Its concentration in different plants ranges from 0.1 per cent (similar to phosphorus and Sulfur) to more than 10 per cent of whole plant dry matter. Silicon is an important micronutrient for healthy and competitive growth of all cereals including rice. Role of silicon in plant health and growth has been investigated in silicon accumulating crops and it seemed significantly affecting. Research evidences proved that adequate uptake of silicon can increase the tolerance of agronomic crops especially rice to both abiotic and biotic stress, which ultimately improves crop yield and quality. Low silicon uptake has been proved to increase the susceptibility of rice to diseases such as rice blast, leaf blight of rice, brown spot, stem rot and grain discoloration. Among all rice diseases, the rice blast is most devastating. It is found in 85 rice growing countries of World and may cause up to 75 per cent yield reduction. An integrated control strategy for implementation in environments with high epidemic potential to blast includes the use of partially resistant cultivars, early sowing or seedlings transplanting, water and nitrogen management, seed treatment with fungicides as well as foliar and soil application of silicon. Applying fungicide to control the disease is neither economical nor environment friendly.

Furthermore, rice blast spreads very fast and the use of resistant varieties is considered as a short term remedy. Silicon can decrease the intensity of blast as effectively as some fungicides, mainly because it has the potential to increase the partial resistance of cultivars to the same level observed in cultivars with complete resistance. It has also been reported that rice blast severity is directly related with silicon deficiency in soils. In this context, soil amendment with Si can be considered an effective strategy to decrease blast intensity, especially when rice is cultivated in Si-deficient soils. There are different hypotheses on how silicon confers and induces resistance to some plants specially rice against diseases such as blast. Effects of silicon on yield are related to the deposition of the element under the leaf epidermis which results a physical mechanism of defense, reduces lodging, increases photosynthesis capacity and decreases transpiration losses. Silicon can be deposited by the plants at the infection site thus inhibiting the penetration of cell walls by the attacking fungus. The ability of silicon solution to reduce the impact of plant diseases has been clearly described in the case of rice blast. Many scientists working on role of silicon in plant growth have concluded that reduced amount of silicon in plant develops necrosis, disturbance in leaf photosynthetic efficiency, growth retardation which aggravates attack of rice blast. Although silicon has not been considered important for vegetative growth but it aids the plant in healthy development under stresses in different grasses especially in rice. Plant tissue analysis has revealed the optimum amount of silicon is necessary for cell development and differentiation. So following the recent research it is needed to enter micronutrients like silicon in rice nutrient management for efficient control of rice blast.
Silicon and Plant Disease

Reportedly, Si is able to decrease the susceptibility of rice against sheath blight diseases. Plant opal or glass and hard coating of SiO2 polymerisation in the plant cuticle layer is the possible mechanism for reducing disease susceptibility by Si. The physical hindrance created by SiO2 enhances the incubation period in the leaf sheath of rice and results in impeding R. solani penetration to decrease the number and extension of sheath wounds. In comparison to the physical hindrance to early penetration, the lesion extension is a more important factor in terms of resistance to sheath blight disease, particularly in susceptible cultivars. Silicon leads to increase the sheath blight resistance through creating a physical hindrance by SiO2 and reduce the intensity of disease. Reduction of the leaf lesions of rice after 96 hrs of inoculation with M. grisea between Si-treated and untreated plants has been examined by Rodrigues et al. However, separate and tiny lesions that seemed to be restricted at the expansion step were observed in Si-treated rice. Moreover, leaves of the control plants presented strong chlorosis compared to the Si-treated plants. The intensity of neck and leaf blasts in both sensitive and partially resistant rice cultivars can be decreased via Si treatment depending on the rate of Si application and the disease severity. Superior inherent disease severity at specific sites needs a lot of Si fertiliser to decrease the neck and leaf blast disease as effectively as in resistant rice cultivars. Additionally, it has been reported that the occurrence of powdery mildew disease decreased after increasing the concentration of Si in the culture solution.
The Element Silicon

Since the last decade, Si has become a major subject of interest due to its relevancy to various branches of fields including global change biogeochemistry, agronomy and biotechnology (Guntzer et al., 2010; Neethirajan et al., 2009; Laruelle et al., 2009). After oxygen, Si is the next most plentiful element on the surface of the earth (Matichenkov and Calvert, 2002). Silicon infrequently exists as an integral part of biological matter although it is 146 times more ample than carbon. Silicon shares many properties with carbon which forms the backbone of many organic molecules. In the shoot, concentration of Si may exhibit a scale from 0.1-10% Si on dry weight basis and the presence of Si in plants is equivalent to or even exceeding certain amount of other macronutrients such as P, Mg and Ca (Vasanthi et al., 2012; Epstein, 1994). Up to now, essentiality of Si has not been verified thus, Si is considered as a beneficial element. Silicon is not considered as an essential element because it does not play role as a fundamental constituent of the plant structure or metabolism, hence its absence does not affect the completion of plant’s life cycle (Epstein and Bloom, 2003).

Silicon and Chemical Stress

There has been a considerable amount of work on the effects of Si under chemical stresses including nutrient imbalance, metal toxicity, salinity and so on. Silicon and deficiency in or excess of P. Deficiency in P in soil is a worldwide problem. The beneficial effects of Si under P-deficiency stress have been observed in many plants including rice and barley. Early observations from a long-term field experiment conducted at Rothamsted Experimental Station, showed that barley yield was higher in a field amended with Si than in a field without Si application when P fertilizers were not applied. In an experiment using a nutrient solution, Si supply resulted in a larger increase of the dry weight of rice shoot at a low P level (14 f.LM P) than at a medium level (210 f.LM) (Ma and Takahashi 1990a). Such beneficial effects of Si were previously attributed to a partial substitution of Si for P or to the enhancement of P availability in soil. However, subsequent experiments showed that Si was unable to affect P availability in soil. Silicon is present in the form of silicic acid in the soil solution, which does not undergo dissociation at a pH below 9. Therefore, it is unlikely that interaction between silicic acid and phosphate (anionic form) occurs in soil. The uptake of P was also not affected by the Si supply at a low P level in both soil and solution culture (Ma and Takahashi 1990a, b, 1991). Therefore, the larger beneficial effect of Si on plant growth under deficiency stress may be attributed to the enhanced availability of internal P through the decrease of excess Fe and Mn uptake. Excess P stress hardly occurs in natural soils, but was observed in some green house soils where P fertilizers had been heavily applied or in nutrient solution culture where a high P concentration is supplied. Excess P causes chlorosis or necrosis in leaves, probably due to the decreased availability of essential metals such as Fe and Zn. Silicon can alleviate the damage caused by P excess by decreasing the excessive uptake of P, resulting in a decrease in the internal inorganic P concentration. Silicon deposited on the roots and / or Si-induced decrease of transpiration may be responsible for the decreased uptake of P when the P concentration in the medium is high. Si has been found to be deposited in the endodermal cells of roots in many plant species (e.g. Lux et al. 1999, 2003), which may form apoplastic barriers against the radial movement of P across the root.

Material and Methodology

The experiment was carried out in the field of Tonekabon (36°32’N 53°0’E), Mazandaran, Iran in 2009. The soil texture was clay with a pH of 7.43. Characteristics of soil exist in Table 1.

| Table 1. Characteristics of Soil in experimental site, Tonekabon, 2015 |
|---------------------------|-----------------|-----------------|
| Soil Properties | Value | Criteria* |
| pH(H2O) | 5.57 | Slightly acid |
| EC (Dsm-1) | 3.41 | |
| Total C (gkg-1) | 21.63 | Moderate |
| Total N (gkg-1) | 2.09 | Moderate |
| Exchangeable cations (cmol kg-1) Ca | 9.01 | Moderate |
| K | 0.21 | low |
| Mg | 1.36 | Moderate |
| Na | 0.17 | low |
| Available (mg SiO2kg-1) | 426.54 | High** |

Note. *: Referred to Iranian Soil Research Institute (2014) **
sulfate were applied before transplanting by hand broadcasting and second 70 kg ha⁻¹ of nitrogen was applied when rice was at the tillering stage and the third 60 kg ha⁻¹ in prior to heading stage. We randomly selected 6 hills per plot, 5 plants per hill, 4 leaf per plant (the leaves under flag leaf) with movement of the length, width and diameter of each plot and evaluate the number of lesion diameter (10 lesion of per leaf) by ruler then obtained the percentage of leaf blast by the following formula at 33 days after transplanting (Seebold et al., 2001).

**Results**

The main chemical components of slag fertilizers were measured by SEM. Scanning electron microscopy was performed in a JSM-6510 SEM at accelerating voltage of 20 kV attached with an X-ray energy-dispersive spectrometer, EDS (Genesis XM2). Before the scanning process, all samples were dried and coated with gold to enhance the electron conductivity.

The available Si content in slag was determined following extraction with 0.5 M HCl [slag/(HCl) ratio of 1:50, shaking at 300 rpm for 1 h] and analyzed by the colorimetric silicon molybdenum blue method [39]. Slag pH and EC were measured at a water/soil ratio of 2.5.

Plant-available Si content in soil was extracted by 0.25 M citric acid [soil/(citric acid) ratio of 1:5] for 5 hrs, and analyzed by the colorimetric silicon molybdenum blue method [40]. The soil pH was measured at a water/soil ratio of 2.5.

The silicon content in rice plants was determined by the colorimetric silicon molybdenum blue method [41–42]. Briefly, 100 mg of plant tissue was mixed with 3 mL of 50% (w/v) NaOH in a polyethylene tube. These tubes were covered with loose-fitting plastic caps and autoclaved at 125°C for 1 h and analyzed by the colorimetric silicon molybdenum blue method.

**Statistical analysis**

All data in figures and tables are shown as means ± SD of three replicates. Two-way ANOVA was used for statistical analysis and Fisher's L.S.D. test was adopted to detect the significant difference (p≤0.05) between the means of different treatments. All statistical analyses were done using the Excel 2007 and SPSS (PASW Statistics 18.0).

**Table 2** - Mean values of some traits of rice as affected by different silicon levels

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Plant height (cm)</th>
<th>Number of tiller plant</th>
<th>Number of productive tiller</th>
<th>Straw yield (t/ha)</th>
<th>Branches panicel-1</th>
<th>Spike panicle-1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Si0</td>
<td>5.77 A</td>
<td>268.96</td>
<td>248.01A</td>
<td>10.49 c</td>
<td>10.41 b</td>
<td>113.22d</td>
</tr>
<tr>
<td>Si1</td>
<td>103.60</td>
<td>244.28</td>
<td>225.76 d</td>
<td>10.96 b</td>
<td>10.74 a</td>
<td>115.37</td>
</tr>
<tr>
<td>Si2</td>
<td>104.69</td>
<td>259.58</td>
<td>240.33 b</td>
<td>11.93 a</td>
<td>10.74 a</td>
<td>116.73 b</td>
</tr>
<tr>
<td>Si3</td>
<td>101.85</td>
<td>248.77</td>
<td>233.10c</td>
<td>11.93 a</td>
<td>10.41 a</td>
<td>121.46 a</td>
</tr>
<tr>
<td>LSD (0.05)</td>
<td>NS</td>
<td>0.538</td>
<td>6.32</td>
<td>0.016</td>
<td>0.184</td>
<td>1.32</td>
</tr>
</tbody>
</table>

Si0= 0.0%        Si1= 0.25 %       Si2=0.50%       Si3=1.01.0%

Means not sharing a letter differ significantly using LSD at 5% probability level.

**Table 3** - Mean values of some traits of rice as affected by different silicon levels

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Panicle length (cm)</th>
<th>1000 grain weight (g)</th>
<th>Paddy yield (t/ha)</th>
<th>Abortive kernels (%)</th>
<th>Grain Diameter (mm)</th>
<th>Grain length (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Si0</td>
<td>25.13</td>
<td>15.74 d</td>
<td>4.16b</td>
<td>5.77a</td>
<td>1.90c</td>
<td>9.24</td>
</tr>
<tr>
<td>Si1</td>
<td>25.87</td>
<td>17.66 c</td>
<td>4.71a</td>
<td>5.28b</td>
<td>1.92b</td>
<td>9.29</td>
</tr>
<tr>
<td>Si2</td>
<td>26.57</td>
<td>17.35 b</td>
<td>4.78a</td>
<td>5.32b</td>
<td>1.93a</td>
<td>9.31</td>
</tr>
<tr>
<td>Si3</td>
<td>26.88</td>
<td>17.98 a</td>
<td>4.88a</td>
<td>5.20b</td>
<td>1.85d</td>
<td>9.52</td>
</tr>
<tr>
<td>LSD (0.05)</td>
<td>NS</td>
<td>0.33</td>
<td>0.214</td>
<td>0.29</td>
<td>1.15</td>
<td>NS</td>
</tr>
</tbody>
</table>

Si0= 0.0%        Si1= 0.25 %       Si2=0.50%       Si3=1.0%

Means not sharing a letter differ significantly using LSD at 5% probability level.
Means not sharing a letter differ significantly using LSD at 5% probability level.

Maximum number to productive tillers (248.01) was found in control which is followed by 0.05% silicon application (240.03) while minimum in 0.025% silicon solution application as shown in Table 2. These findings are in line to Li et al. (2002), Rodrigues et al. (2003) and Mobasser et al. (2008) while contradicted to Pereira et al. (2004). They reported that increase in applied silicon amount enhanced the number of productive tillers and total number of tillers/m2. Number of branches presenting in Table 2 showed that all three applications of silicon are statistically similar but significantly higher than control. These results are similar to that of Ahmad et al. (2007) and Shahidhar et al. (2008). Data regarding spikes/panicle showed significant effect. The maximum number of spike/panicle present in (Si3) at the rate 1.00% have 121.48 number of spike/panicle followed by Si2 having (116.73). Silicon application significantly affects the 1000 kernel weight. Silicon at the rate 1.00% (Si3) produced maximum kernel weight (17.98 g) followed by 0.50% silicon solution and 0.25% silicon while control (Si0) resulted minimum as 15.74 g (Table 3). These findings are similar to Malidareh (2011) but against the results of Mobasser et al. (2008) who reported that silicon application does not affect 1000 kernel weight in rice. Foliar application of 1.00% silicon solution produced highest paddy yield (4.88 t ha-1) but all three silicon applications are statistically similar while differing from control (Si0) (Table 3). These results resembled to the findings reported by Mobasser et al. (2008) and Malidareh et al. (2011) but against to the finding of Mauad et al. (2003), who reported that silicon application does not affect 1000 kernel weight in rice. Similar were reported by Ahmad et al. (2007), Surapornpiboom et al. (2008) and Elzieta (2009). They reported that silicon is responsible to control stomatal activity, photosynthesis and water use efficiency which ultimately results in better vegetative growth and straw yield. Sterile kernels percentage was found maximum (10.95%) in control (Si0) where as this percentage is significantly reduced by silicon application as shown in Table 4. This reduction in kernel sterility is might be due to balanced nutrition, optimum metabolic activities or nullification of stresses by silicon application. These findings are near to the Mauad et al. (2003) and Wang et al. (2010), who reported that silicon is not directly evolved in quality enhancement but it control diseases and stresses to maximize the quality. Abortive kernels percentage presented in Table 3 proved that silicon application to rice was found significant regarding this parameter as all three silicon applications although statistically similar but differing from control (Si0). Similar findings had also reported by Li et al. (2002), Buck et al. (2008) and Elzieta (2009). Maximum grain protein (6.30%) was found in 0.50% silicon (Si2), followed by 0.25% silicon (Si1) solutions application with 6.20% grain protein contents significantly higher than control. Grain starch regarding silicon application found maximum (77.57%) in with 1.00% silicon (Si3) application while control (Si0) produce minimum starch percentage (77.31%).

### 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). My 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; Kashwagi 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.

**Silicon enhances rice resistance to diseases**

Kozaka (1965) made a comprehensive review in English of the research done in Japan on the effects of Si on rice resistance to diseases. The author cited the research of several Japanese scientists dating from 1917 to 1959. General observations indicated that rice plants treated with Si had fewer blast lesions, a large number of silicated epidermal cells and an increased resistance to blast.

A positive correlation between Si content in rice tissues and blast resistance within a given rice cultivar occurred; however, this correlation was not observed between different rice cultivars. Winslow (1992) and Deren et al. (1994) have made similar observations for blast and several other diseases. Nevertheless, Kozaka (1965) showed that the susceptible cultivar Kurusmochi amended with Si had lower number of blast lesions at a level comparable to the resistant cultivar Ishikirishiroke which was not amended with this element.

Kim & Lee (1982) investigated the effects of Si soil amendments on the susceptibility of several rice cultivars (Tongil or Japonica types) to neck blast development in Korea. Their study revealed that Tongil types were the most susceptible to neck blast with incidence ranging from 37 to 79% in the controls vs. 4.6 to 6.3% for the Japonicas. Disease control of Tongil types in response to Si amendments was 56 to 60% as compared with 6 to 46% in the Japonica types. Yield increases among all the cultivars due to Si amendments ranged from 9 to 22%. Interestingly, the cultivar Akibare, which might be considered the most resistant to rice blast in their study, had yield increases of 10% over the non-amended control even though its resistance was little improved with the addition of Si. These findings suggest that cultivars that have complete genetic resistance to blast or any other disease might still have their yields augmented without further genetic improvements by using Si.

Rice cultivars that have lost resistance to a disease such as blast, but show some good agronomic traits, might be re-employed simply by using Si fertilization for disease management. Winslow (1992) reported that African japonica upland rice genotypes had 50 to 100% higher Si concentration in mature flag leaves, and were more resistant to neck blast than Asian indica upland genotypes.

Seebold et al. (2000) conducted an extensive study on the interaction of Si rates with rice cultivars with different levels of resistance to blast. Blast resistant, Oryzica Llanos 5, partially resistant, Linea 2, and susceptible Oryzica 1 cultivars were planted in soil amended with Si at 0, 500 or 1000 kg.ha⁻¹. Although blast disease intensity was low (> 1 to 6%), leaf blast was reduced by Si at the highest rate by 50 and 73% on Linea 2 and Oryzica 1, respectively, as compared to the control. The level of resistance to leaf blast in Linea 2 amended with 500 or 1000 kg.ha⁻¹ of Si was augmented to the same level of Oryzica Llanos 5 without Si. Similar results were obtained by Osuna-Canizalez et al. (1991). The authors conducted experiments with nutrient solutions of Si and three IR cultivars varying in levels of blast resistance. The IR36 and IR50 were lowland cultivars, and IR36 contained a higher level of partial resistance to blast than IR50. The IAC165 was an upland cultivar with almost complete resistance to M. grisea used in this study. They demonstrated significant reductions in number of lesions per cm² of leaf tissue (30 to 35 lesions for IR50 and IR36 cultivars non-amended with Si versus 2 to 4 lesions on amended Si plants). The resistance of these two cultivars was greatly improved with the addition of Si. In addition, the level of resistance of these two cultivars amended with Si was equivalent to that of IAC165 without Si fertilization.

Seebold et al. (2000) also investigated neck blast incidence in blast resistant Oryzica Llanos 5, partially resistant, Linea 2, and susceptible Oryzica 1 cultivars of rice. Neck blast incidence was significantly different among the cultivars and varied according to the rate of Si applied. Silicon reduced the incidence of neck blast for Linea 2 and Oryzica 1. No detectable changes were recorded for Oryzica Llanos 5. For Linea 2 and Oryzica 1, neck blast incidence decreased by 37 and 28%, respectively, as the rate of Si increased from 0 to 1000 kg.ha⁻¹. Cultivars Linea 2 and Oryzica 1 had higher blast incidence at 500 or 1000 kg of Si ha⁻¹ as compared to the non amended blast resistant cultivar Oryzica 5. However, the addition of 1000 kg of Si ha⁻¹ reduced the incidence of neck blast on Oryzica 1 as effectively as partially resistant Linea 2 without Si. Rough rice yields of Oryzica 1 amended with 500 and 1000 kg.ha⁻¹ Si did not differ from either the non amended Oryzica Llanos 5 or Linea 2. The increase of Si rates from 0 to 1000 kg.ha⁻¹ increased yields by 20% for both Oryzica Llanos 5 and Linea 2.
Effective disease control strategies for agronomic crops include the incorporation of genetically controlled resistance into cultivars. Since genotypes vary in disease resistance, the relationship between Si content among genotypes and disease resistance needs to be investigated. In a test of 18 rice cultivars grown at three locations representing high (116 mg Si l⁻¹ soil), typical (40 mg Si l⁻¹ soil), and low (6 mg Si l⁻¹ soil) Si status, cultivars varied significantly for tissue concentration (Deren et al., 1992). Certain genotypes consistently ranked high or low in Si concentration across locations. This suggests that the acquisition of Si may be an inherited trait. Selected genotypes were further evaluated for Si accumulation and brown spot development on a low-Si soil (Histosols) amended with 0 and 10 ton.ha⁻¹ of calcium silicate slag (Deren et al., 1994). Results indicated that genotypes differed for Si concentration and brown spot severity at each location and for each Si treatment, but the ranking remained fairly consistent. Most genotypes had a 30 to 40% relative decrease in brown spot severity when Si was added. Rico 1, which is known to be brown spot susceptible, was severely diseased at two locations, whereas Katy and Experimental Line 1 were consistently the least diseased. Genotypes with intermediate ranks shifted ranking with location and treatment, which was reflected in the significant genotype x Si treatment interaction in the analysis of variance. This variation in cultivar susceptibility with either high or low Si content simply may reflect variability within the pathogen population. However, resistance may be controlled by other factors inherent within a genotype as well as by plant accumulation of Si. Among genotypes, brown spot severity was negatively correlated (mean r = -0.58) with Si concentration in plant tissue. The correlation obtained in this experiment is based upon a small number of genotypes; a larger population would merit further investigation. Furthermore, Rico 1 and Della X2 had the greatest Si concentrations, yet were also consistently the most severely diseased genotypes. This also has been observed with blast; some cultivars with low Si were more resistant whereas others with high Si concentration were more susceptible (Ou, 1985). Rice genotypes accumulating higher levels of Si are not necessarily more resistant to diseases in comparison to genotypes accumulating low levels of Si when grown under the same Si fertility level (Kozaka, 1965). Hence, although Si concentration varied among genotypes and is negatively correlated with brown spot severity, the strength of this association may be mitigated by other genotypic factors which also affect disease to disease.

Winslow (1992) reported that indica upland rice genotypes had a great reduction in the severity of sheath blight in response to Si application in comparison to African japonica and intermediate genotypes. Rodrigues et al. (2001a) showed that high Si content in rice tissues of tropical japonicas (LSBR-5, Drew, Kaybonnet, Lemont, and Labelle) and an indica type (Jasmine) rice cultivar contributed to a reduction in sheath blight severity. This clearly indicates that enhanced resistance to sheath blight conferred by Si was not limited to indica types as previously reported by Winslow (1992). To determine whether the application of Si to moderately susceptible and susceptible cultivars could suppress the severity of sheath blight to those cultivars with high levels of partial resistance, which had not been treated with Si, Rodrigues and collaborators (2001a) selected cultivar-Si combinations and compared them by single degree of freedom contrasts. The statistical analysis showed that the combination of Drew and Kaybonnet (moderately susceptible) and Lemont and Labelle (susceptible) grown with Si reduced the severity of sheath blight to the same statistical level as the cultivars (Jasmine and LSBR-5) containing high levels of partial resistance. The level of sheath blight resistance for Jasmine and LSBR-5 was also further enhanced when these cultivars were supplemented with Si.

**Effects of Silicon on Components of Host Resistance**

Seebold et al. (2001) evaluated the effect of Si on several components of resistance in four rice cultivars with different levels of resistance to race IB-49 of M. grisea grown in Si-deficient soil amended with 0, 2, 5, and 10 ton calcium silicate ha⁻¹. The cultivar M201 has no known major or minor genes for resistance to race IB-49 of M. grisea and is highly susceptible. The cultivars Rosemont and Lemont are partially resistant and Katy is highly resistant. For each cultivar tested, the incubation period was extended by increased rates of Si while lesion length, rate of lesion expansion and disease leaf area were dramatically decreased.

The relative infection efficiency of M. grisea, determined as the number of sporulating lesions per square millimeter of leaf area, was highest on M201 and Rosemont and lowest on Katy. The relationship between the number of sporulating lesions per leaf area and the rate of calcium silicate was linear for all cultivars. The cultivar Lemont had 92% fewer sporulating lesions per leaf area than M201. Relative infection efficiency was 97% lower on Katy compared with M201 and was significantly lower when compared with Rosemont or Lemont, except at the highest rate of Si. The number of sporulating lesions counted on Lemont treated with 10 ton.ha⁻¹ was not significantly different from Katy, but there was no significant change in the number of sporulating lesions on Katy at any rate of calcium silicate. When the rate of calcium silicate was increased from 0 to 10 ton.ha⁻¹, the number of sporulating lesions per leaf area decreased by 71% on M201, Rosemont, and Lemont. By reducing relative infection efficiency, the number of sporulating lesions that can produce inoculum for secondary cycles is curtailed, and reductions in size of lesions further limit production of inoculum. The effect of Si on this component of resistance was more apparent on partially resistant or susceptible cultivars and was rate responsive. In the case of blast-resistant Katy, the number of sporulating lesions found on plants that did not receive calcium silicate was near zero. Osuna-Canizales et al. (1991) also found no differences in the number of sporulating lesions between resistant cultivars grown in a solution containing Si and those that had not received Si. The number of spores per square millimeter of lesion was different among all four cultivars. Sporulation per
The relationship between rate of calcium silicate and the number of spores per square millimeter of lesion was linear for all cultivars, but significant only at \( P = 0.10 \). Sporulation per square millimeter of lesion on all cultivars was reduced by 47% as the rate of calcium silicate increased from 0 to 10 ton.ha\(^{-1}\). Only M201 showed a decrease in spores per square millimeter of lesion as the rate of Si increased. The effect of Si on the number of conidia per lesion was not clear. Although a general decline in number of conidia was observed across all cultivars, an examination of means by cultivar shows that, in reality, sporulation per lesion area was reduced by Si on M201 only. Despite having nearly the same content of Si in leaf tissue as M201, no change in sporulation occurred on Rosemont or Lemont at 0, 5, and 10 ton of calcium silicate per hectare, and no conidia were recovered from lesions on Katy. It is important to note that the total number of lesions available for estimation of number of conidia was smaller on the partially resistant and resistant cultivars than on the susceptible cultivar, and the number of lesions decreased as the rate of Si increased. Thus, the small sample sizes and inherent resistance in some cultivars contributed to erratic estimates of the number of conidia per square millimeter of lesion. In the case of Katy, sporulating lesions were rare at any rate of Si. Sporulation per lesion is probably of less epidemiological importance than the reduction in lesion number. Regardless of the rate of Si, the daily rate of lesion expansion was significantly higher on M201 than on Rosemont, Lemont, or Katy.

Rate of lesion expansion was 42 and 59% slower on Rosemont and Lemont, respectively, compared with M201 and did not differ significantly between these two cultivars. Rate of lesion expansion was slower on Katy than on Rosemont, Lemont, or M201. For all cultivars, rate of lesion expansion decreased from 0.8 to 0.43 mm per day (49%) as the rate of calcium silicate increased from 0 to 10 ton.ha\(^{-1}\) (\( P \leq 0.07 \)). The effect of rate of Si on lesion length was less significant than for relative infection efficiency. Unlike relative infection efficiency, lesion length was reduced on all cultivars by an average of 46% with increasing rates of Si. The reduced lesion size with Si application enhanced the blast resistance exhibited by the cultivars tested in this study. The rate of lesion expansion was closely associated with the length of lesions. Lesions caused by \( M. \) grisea are determinate in size and reached maximum size at roughly the same time for all cultivars and rates of Si, resulting in measurements similar to those for length of lesion. Of these two components, lesion length appears to be a more important component of resistance to leaf blast than rate of lesion expansion because sporulation was not observed on lesions from any treatment until maximum size was reached.

Rodrigues et al. (2003c) investigated the effect of Si on sheath blight development in Brazil. The predominant commercial rice cultivars BR-Irgra 409, Metica\(^1\), EPAGRI-109, Rio Formoso, Javaé, and CICA-8 were grown in pots containing soil from a Si-deficient typic acrustox red yellow latosol amended with 0, 0.48, 0.96, 1.44, and 1.92 g Si pot\(^{-1}\). Plants were inoculated at the maximum tillering stage by placing a \( R. \) solani colonized toothpick into the lowest inner sheath of the main tiller. For all cultivars, Si concentration in straw increased more than 60% as the rate of Si increased from 0 to 1.92 g.pot\(^{-1}\). Incubation period of \( R. \) solani was slightly prolonged with increasing Si rates and ranged from 53 to 64 h depending upon the cultivar. Total number of sheath blight lesions, total area under the relative lesion extension progress curve, severity of sheath blight, and the highest relative lesion height on the main tiller decreased by 37, 40, 52, and 24%, respectively, as the rate of Si increased in the soil. Overall, rice cultivars grown at highest Si rate had sheath blight intensities that were greatly reduced as compared with cultivars grown in pots not amended with Si (Figure 3).

### Possible Mechanisms for Silicon-Mediated Rice Resistance

In the rice-M. grisea pathosystem, increased resistance through Si treatment has been associated with the density of silicified bulbiform, long, and short cells in the leaf epidermis that act as a physical barrier to impede penetration by \( M. \) grisea (Ito & Hayashi, 1931; Suzuki, 1940; Hemmi et al., 1941). This physical barrier hypothesis is strengthened by the findings of Yoshida et al. (1962), who reported the existence of a layer of silica of approximately 2.5 µm thick beneath the cuticle of rice leaves and sheaths. This cuticle-Si double layer can impede penetration and, consequently, decrease the number of blast lesions on leaf blades. According to Volk et al. (1958), Si might form complexes with organic compounds in the cell walls of epidermal cells, therefore increasing their resistance to degradation by enzymes released by \( M. \) grisea. Indeed, Si can be associated with lignin-carbohydrate complexes in the cell wall of rice epidermal cells (Inanaga et al., 1995).

Kim et al. (2002) investigated some of the cellular features of Si-mediated resistance to blast. The authors observed that the epidermal cell wall thickness was not significantly affected by Si. However, the thickness ratios of silica layers to epidermal cell walls were much higher in the resistant cultivar than in the susceptible cultivar. Although the fortification of epidermal cell walls was considered the main cause for the reduced number of leaf blast lesions, no evidence in relation to the physical impedance offered by the fortified cell wall was given to the penetration peg of \( M. \) grisea. Interestingly, Ito & Sakamoto (1939) studied the puncture resistance of rice epidermal cells to a needle tip from beneath a torsion balance using leaves collected from rice plants grown under different Si rates. Their results showed that the puncture resistance was not explained solely by the leaf epidermis silification; rather, it was attributed mainly to the nature of the protoplasm of epidermal cells. In another study, it was reported that rice cultivars resistant to blast had lower lesion numbers and silicified epidermal cells than susceptible cultivars (Kawamura & Ono, 1948). As reported by Hashioka (1942), the density of silicified cells in rice leaf epidermis is not always proportional to the level of resistance of some rice cultivars to blast. Altogether, these observations suggest that resistance of Si-treated plants
to M. grisea is much more complex than a physical resistance against penetration due to the silicified cells or to the cuticle-Si double layer.

Seebold et al. (2001) made some inferences about the mechanisms by which Si acts to reduce blast. The authors noted that the reduced number of sporulating lesions (relative infection efficiency) on partially resistant and susceptible cultivars fertilized with calcium silicate indicated there were fewer successful infections established per unit of inoculum, lending support to the physical barrier hypothesis. The reductions in the total number of lesions as the rates of Si increased, clearly indicated that Si manifested its effect before the penetration peg of M. grisea actually entered the epidermis, or soon thereafter, indicative of blockage to ingress by the fungus.

In an attempt to gain further insight into the role of Si in rice blast resistance, Rodrigues et al. (2003a) investigated the ultrastructural outcome of the rice-M. grisea interaction upon Si application. The authors provided the first cytological evidence that Si-mediated resistance to M. grisea in rice correlated with specific leaf cell reaction that interfered with the development of M. grisea. Ultrastructural observations of samples collected from plants grown in soil unamended with Si revealed that some host cells were devoid of organelles and that some host cell walls were no longer discernible in the massively colonized mesophyll and vascular bundle (Figure 4A and B). A light deposition of osmiophilic material with a granular texture, occasionally interacting with fungal walls, was seen in some epidermal cells (Figure 4C, arrows). In plants amended with Si, empty fungal hyphae were evenly surrounded by a dense layer of granular osmiophilic material partially occluding the epidermal cells (Figure 4D, arrows), the vascular bundle (Figure 4E, arrowheads), and the mesophyll cells (Figure 4F, arrows). The possibility that this amorphous material constitutes phenolic compounds appears realistic, considering not only its staining with toluidine blue and its texture and osmiophilic properties, but also the occurrence of marked fungal hyphae alterations. Cytochemical labeling of chitin revealed no difference in the pattern of chitin localization over fungal cell walls of either samples from plants amended or not with Si at 96 h after inoculation with M. grisea, indicating limited production of chitinases as one mechanism of rice defense response to blast. On the other hand, the occurrence of empty fungal hyphae, surrounded or trapped in amorphous material, in samples from plants amended with Si suggested that phenolic-like compounds or phytoalexin(s) played a crucial role in rice defense response against infection by M. grisea. Therefore, Si could be acting as a modulator to positively amplify rice defense response(s), namely by influencing the synthesis of antifungal compounds after the penetration peg of M. grisea enters the epidermal cell.
In a further study, Rodrigues et al. (2004) tested the hypothesis that an alteration in the development of M. grisea in leaf tissues of rice plants amended with Si could be associated with an enhanced production of phytoalexin(s). Analysis of the ethyl ether fraction (FII) obtained from leaf extracts of plants amended with (+Si) or without (-Si) and inoculated with M. grisea revealed that of the five sub-fractions (SF) collected, only SF5, which corresponded to compounds eluting after 90 min in
the HPLC chromatograms, displayed antifungal activity against M. grisea. The SF5 from Si\(^+\) treatment showed higher fungitoxicity against M. grisea than SF5 from Si treatment. Sub-fractions 1, 2, 3, and 4 had no apparent antifungal activity against M. grisea regardless of Si treatment. Based on these observations, SF5 from FII was further analyzed by HPLC. This allowed separation of the two momilactones on the basis of their ultraviolet spectra and retention time (R\(_t\)) (momilactone A R\(_t\), 46 min and momilactone B R\(_t\), 47 min). These compounds were present in minute or small quantities in non-inoculated plants amended or not with Si. By contrast, both products showed a two to three-fold increase in leaf extract from plants grown in soil amended with Si and inoculated with M. grisea treatment compared to the lower levels observed in leaf extract from inoculated plants non-amended with Si. Rice plants not amended with Si and inoculated with M. grisea, in spite of releasing antifungal compounds including momilactones, were obviously not protected efficiently against fungal colonization. By contrast, rice plants amended with Si and inoculated with M. grisea, releasing higher amounts of momilactones probably earlier in the infection process, benefited from a lower level of rice blast severity (Figure 5).

![Si- vs Si+ leaves](image)

**FIG. 5** - Development of leaf blast symptoms at 96 h after inoculation with *Magnaporthe grisea* in rice plants nonamended (-Si) or amended (+Si) with silicon.

While little is known about the mechanism(s) of resistance of rice plants amended with Si in response to *M. grisea* infection, two mutually agreeable hypotheses must be considered. On the one hand, it is possible that in certain areas of heavy Si deposition, delayed fungal ingress and colonization provides the rice plant enough time for momilactones, synthesized in response to infection by M. grisea, to accumulate to considerable levels and express their fungitoxicity within the zone of the infection site. On the other hand, as proposed by Fawe et al. (2001), the soluble Si present in the plant cells may mediate some defense responses that are functionally similar to systemic acquired resistance. The results of this study, together with the ultrastructural observations, strongly suggest that Si plays an active role in the resistance of rice to blast rather than simply forming a physical barrier in leaf epidermis to avoid fungal penetration.

**Conclusion**

Applying Si fertilizer to Si-deficient paddy soil is necessary for both high rice yield and brown spot resistance. Both steel slag and iron slag are effective in this regard. In this experiment, silicon fertilizer H produced significantly higher grain weight than silicon fertilizer Q at the same plant-available Si application rate. Composition and cooling process of slags influence Si-dissolution from slags. Si availability of slag to plants cannot be precisely determined only by the extraction method using 0.5 M HCl. The immobile silicon deposited in host cell walls and papillae sites is the first physical barrier for fungal (Bipolaris oryzae) penetration and soluble Si in the cytoplasm enhances physiological or induced resistance to restrain fungal colonization.

As we know, application of mineral elements in adequate concentration could directly or indirectly reduce disease incidence and severity of crops. However, these results confirmed the similar conclusions, which are soil fertility management, could have several effects on plant quality, which in turn, can affect disease damage like rice blast and finally increased the grain...
yield. In where plant-available Si is known to be deficient, supplying an adequate level of Si, as shown in this study, could increase yield and control of rice blast to help rice growers meet the demand for greater production of rice. The beneficial effects of Si under stress conditions are summarized in Fig. 1 (Ma et al. 2001a; Ma and Takahashi 2002). It is obvious that most of the effects of Si were expressed through Si deposition on the leaves, stems, and hulls. The more Si accumulated in the shoots, the larger the effect. However, Si accumulation in the shoot varies considerably with the plant species and most plants are unable to accumulate high levels Si in the shoots. The difference in Si accumulation was attributed to the ability of the roots to take up Si. Therefore, although Si is abundant in soil, since most plants especially dicots are unable to take up a large amount of Si from soil, they do not benefit from Si. One approach to enhance the resistance of plants to multiple stresses is to genetically modify the Si uptake ability. Rice is a typical Si-accumulating plant and elucidation of the uptake system of Si in rice roots may provide valuable information for the genetic modification of root Si uptake ability. Recently, it has been reported that Si uptake by rice roots is mediated by a kind of transporter with a low affinity for silicic acid (Tamai and Ma 2003). The superior capacity of rice to take up Si compared to other plants is probably due to the fact that other plants do not harbor such kind of Si transporter. To analyze the Si uptake system in rice roots, a mutant of rice defective in Si uptake has also been isolated and characterized (Ma et al. 2002). This mutant could provide a tool for the identification of the transporter gene, which is being undertaken in our laboratory. The results of the present study are evidence that Si acts on several factors of resistance that seems to limit the production of conidia on rice leaves infected by M. grisea, so, it can be concluded that silicon was an important component in the mechanism of resistant to blast and it was effective regardless of the original level of resistance for the cultivar used. This could make Si a useful element for managing rice disease, possibly in conjunction with reduced rates of fungicides or specific times of application and may provide alternatives to rice growers.

References


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