



Ameliorative Effect of Silicate in Soil and Plant. A Review

Hanan S. Siam¹, Abd El-Moez M.R., Safaa A. Mahmoud¹ A.S. Taalab¹, G.W. Ageeb²,
and Mona G. Abd El Kader³

¹Plant Nutrition Dept., and ²Soil and Water Use Dept. Agriculture and Biological Research Institute, National Research Centre, 33 El Buhouth St., 12622, Dokki, Giza, Egypt.

³Soils, Water and Environ. Res. Institute, Agric. Rec. Center, Giza, Egypt

Received: 20 Dec. 2021

Accepted: 10 Jan. 2022

Published: 20 Jan. 2022

ABSTRACT

Silica is the scientific name for a group of minerals made of silicon and oxygen. Silica is found in most mineral deposits in the world in both crystalline and non-crystalline (amorphous) forms. Silicon concentrations vary greatly in plant aboveground parts, ranging from 0.1 to 10.0% of dry weight. Silicates soil amendments provide effective and efficient means to correct a number of soil chemical imbalances, nutrient deficiencies and toxicity issues. Soil treatment with biogeochemically active Si substances optimizes soil fertility through improved water, physical and chemical soil properties and maintenance of nutrients in plant-available forms. The amount of Si in soil may vary considerably from 1 % to 45 %. Most Si is present in the soil as insoluble oxides or silicates, but plants can easily absorb silicic acid $\text{Si}(\text{OH})_4$ from soil. Silicic acid is generally found in the range of 0.1-0.6 mM in soils. Unfortunately, soluble Si polymerizes rapidly if the concentration of Si increases above 2 mmol L^{-1} . Uptake of Si from external solution and its transport through roots might be an active or a passive (diffusion) process. Once silicon is absorbed by the plant, it actively contributes to a balanced state of nutrient availability through uptake processes and micro-distribution of mineral ions. As a result of increasing silicon concentrations in plant tissues the mechanical strength may be improved. The Si content in plant tissue varies greatly among the species and can range from 0.1 to 10% on a dry weight basis. Rice is a typical Si accumulator and its uptake is about twice that of nitrogen. Application of silicon as a soil amendment has been reported to result in elevated concentrations of chlorophyll per unit area of leaf tissue, resulting in improved photosynthetic efficiency. Si is effective in mitigating salinity in different plant species, (barley, cucumber, tomato). Some possible mechanisms through which silicon may increase salinity tolerance in plants include immobilization of toxic sodium ion and enhanced potassium uptake. In plants growing under salt-stress conditions, added silicon helps in maintaining an adequate supply of essential nutrients and reduces sodium uptake and its transport to shoots. Important aspects of silicon fertilization that have gained interest are increased drought resistance. Reduction of transpiration rate (or increase of leaf resistance) has been attributed to silicon. An alleviative function of Si on Mn toxicity has been observed in rice, barley, and pumpkin. Silicon may be responsible for the alleviation of Zn and Fe excess toxicity in rice roots. Si-enhanced tolerance to Cd and this was attributed that not only to Cd immobilization caused by silicate-induced pH rise in the soils but also to Si-mediated detoxification of Cd in the plants. Several studies have shown that Si is effective in enhancing the resistance to diseases and pests. Silicon reduces the epidemics of both leaf and panicle blast at different growth stages. Silicon has been reported to prevent the incidence of powdery mildew disease, brown spot, and stem rot, sheath brown rot on rice, fusarium wilt, and corynespora leaf spot on cucumber. Silicon suppresses insect pests such as stem borer, brown plant hopper, rice green leaf hopper, and white backed plant hopper, and no insect pests such as leaf spider and mites. It prevents physical penetration and/ or makes the plant cells less susceptible to enzymatic degradation by fungal pathogens.

Keywords: Silica, soil, plant, silicates, silicic acid

Corresponding Author: Hanan S. Siam, Plant Nutrition Dept., National Research Centre, 33 El Buhouth St., 12622, Dokki, Giza, Egypt. E-mail: drhanansiam@yahoo.com

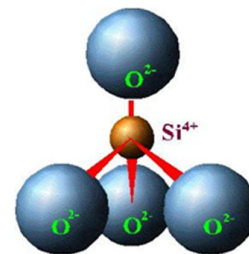
1. Introduction

In spite of the high Si accumulation in plants (its amount may equal concentration of macronutrients), until now it has not been considered as an essential element for higher plants. Many reports have shown that silicon may play a very important role in increasing plants' resistance to noxious environmental factors. Hence, Si is recognized as a beneficial element for plants growing under biotic and abiotic stresses, for example heavy metals, drought, salinity, pathogens Savvas *et al.*, (2009). Silicon (Si) is the second most abundant element in soil. Si occurs mainly as monosilicic acid (H_4SiO_4) at concentrations ranging from 0.1 to 0.6 mM in the soil solution (Balakhnina and Borkowska, 2013) and is taken up by plants in this form. After the uptake, Si accumulates on the epidermis of various tissues mainly as a polymer of hydrated amorphous silica (Epstein 1994; Ma and Takahashi 2002).

All terrestrial plants contain Si in their tissues although the content of Si varies considerably with the species, ranging from 0.1 to 10% Si on a dry weight basis (Ma and Takahashi 2002). However, Si has not been recognized as an essential element for plant growth. The major reason is that there is no evidence to show that Si is involved in the metabolism of plant, which is one of the three criteria required for essentiality. However, (Epstein and Bloom 2003) reconsidered this definition of essentiality and proposed a new definition of elements that are essential for plant growth: An element is essential if it fulfills either one or both of two criteria, viz. (1) the element is part of a molecule which is an intrinsic component of the structure or metabolism of the plant, and (2) the plant can be so severely deficient in the element that it exhibits abnormalities in growth, development, or reproduction, i.e. "performance," compared to plants with a lower deficiency. According to this new definition, Si is an essential element for higher plants because Si deficiency causes various abnormalities in the plant. Despite these arguments on the essentiality of Si, it has been known for almost one century that Si exerts beneficial effects on the growth of plants. Several beneficial effects of Si have been reported, including increased photosynthetic activity (Parveen and Ashraf 2010), increased insect and disease resistance, reduced mineral toxicity, improvement of nutrient imbalance, and enhanced drought and frost tolerance. Overall, the beneficial effects of Si show two characteristics. One is that the beneficial effects vary with the plant species. Beneficial effects are usually obvious in plants that accumulate high levels of Si in their shoots (Ma *et al.*, 2001a and Oliveira 2009). One typical example is rice, which accumulates Si up to 10% Si on a dry weight basis in the shoot. High accumulation of Si in rice has been demonstrated to be necessary for healthy growth and high and stable production (Ahmad *et al.*, 2013). For this reason, Si has been recognized as an "agronomically essential element" in Japan and silicate fertilizers have been applied to paddy soils. The other characteristic is that the beneficial effects of Si are usually expressed more clearly when plants are subjected to various abiotic and biotic stresses. Silicon is probably the only element which is able to enhance the resistance to multiple stresses.

2. Occurrence of silica in soil

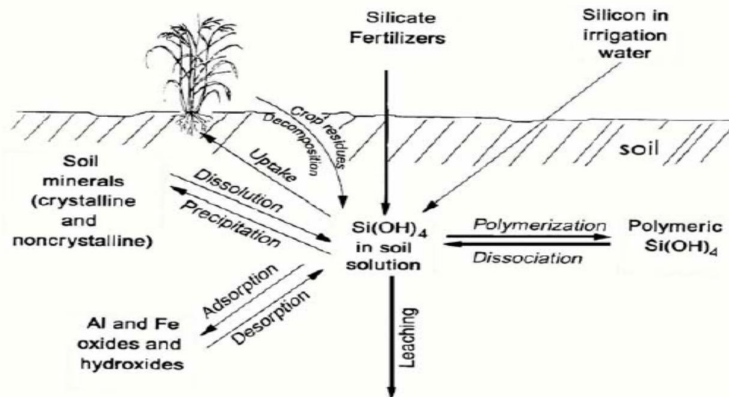
Silica is the scientific name for a group of minerals made of silicon and oxygen. Silica is found in most mineral deposits in the world in both crystalline and non-crystalline (amorphous) forms. Crystalline silica has its oxygen and silicon atoms arranged in a three-dimensional repeating pattern. Amorphous forms of silica have a random pattern. Crystalline silica occurs in several forms, including quartz, cristobalite and tridymite. Quartz is the most common form of crystalline silica (Sauer *et al.*, 2006).



Silicon belongs to group 14 of the periodic table, which also includes C, Ge, Sn and Pb. The element has an atomic number of 14, an atomic mass of 28, three main oxidation states (-4, +2 and +4), of which +4 is the most common in nature, and three naturally occurring isotopes (^{28}Si , ^{29}Si and ^{30}Si), of which ^{28}Si is the most abundant at 92% of the total mass. Silicon, at about 28%, is the second most abundant element in the Earth's crust after oxygen, and is mainly found in the silica or silicate forms, SiO_2 and SiO_4 respectively.

The median SiO_2 content in subsoil is 68.0% and in topsoil 67.7%, and the range of values varies from 0.61 to 98.1% in subsoil and 1.47 to 96.7% in topsoil. There is a good correlation between

grain size and silica content in soil samples, and this should be expected in such a large survey. When the proportion of quartz grains in a soil sample is higher, its proportion of fine-grained clay and silt is lower. This phenomenon influences the variation of most elements to some degree, as quartz (the major carrier of SiO_2) tends to dilute the other constituents in the sample. Calcareous areas contain a smaller amount of SiO_2 . Amorphous silicates apparently contribute to anion adsorption processes, and it has been suggested that silicate and phosphate ions compete for sites on mineral soil particles (Kabata-Pendias 2001). Quartz, because of its very low aqueous solubility, may be considered unreactive, and it is one of the residual minerals remaining in soil after other minerals have altered or dissolved (Hinman and Lindstrom 1996). Kabata-Pendias (2001) reported the existence of several interferences between Si and other ions such as P, Al, Ca and Fe occurring in soil that modify its behaviour. For example, in acid soil, silicate and phosphate ions form insoluble precipitates that may fix several cations, i.e., Fe and Al oxides having a marked capacity to sorb dissolved Si as H_4SiO_4 . Interference is organic matter, which, in high amounts in flooded soil, may induce a higher Si mobility apparently due to the reduction of Fe hydrous oxides that release adsorbed monosilicic acid.



The main processes influencing Si concentration in the soil (extracted from Savant *et al.*, (1997).

2.1. Functions of silica in soil

According to Matichenkov and Bocharnikova (2001) silicates soil amendments provide effective and efficient means to correct a number of soil chemical imbalances, nutrient deficiencies and toxicity issues. Their geochemical activity has been found to:

- Increase the number of exchange sites on soil and soil organic matter particles
- Supply calcium to exchange sites.
- Improve the soil's nutrient balance.
- Establish multiple silicate anion processes that reduce phosphorous fixation in the soil profile,
- Increase plant-available phosphorus and help in preventing phosphorus leaching.
- Form stable silicon-based complexes with potentially plant toxic forms of iron, manganese, and aluminum ions thereby reducing their bioavailability and phytotoxicity -- in the soil as well as in plant.

2.2. Plant-available silicate

Sauer *et al.*, (2006) reviewed the methodologies used to extract different Si fractions from soils and sediments. Methods were classified in those to assess plant-available Si and those to extract Si from amorphous silica and allophane. Plant-available Si is supposed to comprise silicic acid in soil solution and adsorbed to soil particles. Extraction techniques for plant-available Si include extractions with water, CaCl_2 , acetate, acetic acid, phosphate, H_2SO_3 , H_2SO_4 , and citrate. The extractants show different capabilities to desorb silicic acid, with H_2SO_3 , H_2SO_4 and citrate having the greater extraction potential. The most common extractants to dissolve amorphous silica from soils and aquatic sediments are NaOH and Na_2CO_3 , but both also dissolve crystalline silicates to varying degrees. In soils moreover Tiron is used to dissolve amorphous silica, while oxalate is used to dissolve allophanes and imogolite-type materials. Most techniques analyzing for biogenic silica in aquatic environments use a correction method to identify mineral derived Si. By contrast, in the soil

sciences no correction methods are used although pedologists are well aware of the overestimation of amorphous silica by the NaOH extraction, which is most commonly used to extract silica from soils. It is recommended that soil scientists begin to use the techniques developed in the aquatic sciences, since it seems impossible to extract amorphous Si from soils completely without dissolving some of the crystalline silicates.

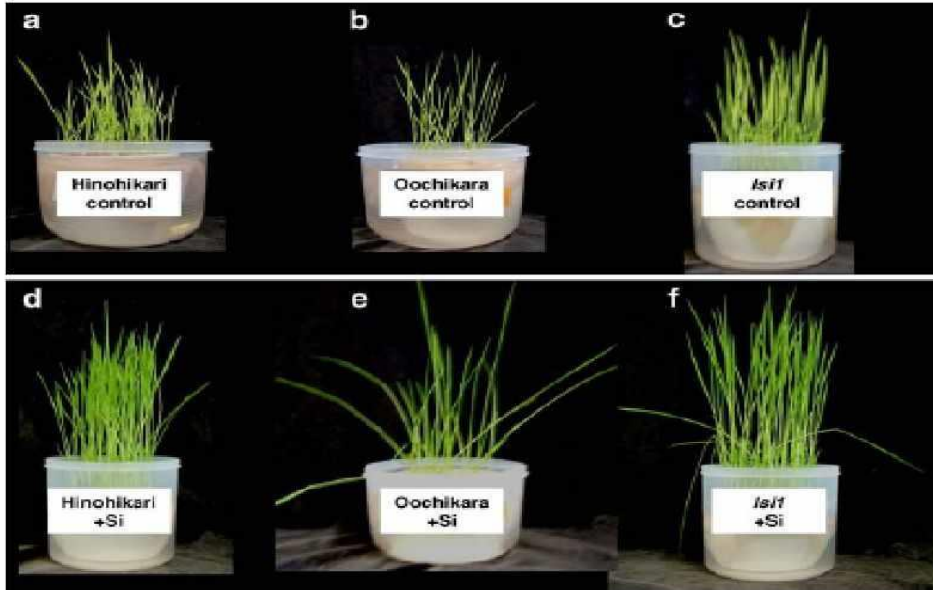
Silicon fertilization has a double effect on the soil-plant system. Soil treatment with biogeochemically active Si substances optimizes soil fertility through improved water, physical and chemical soil properties and maintenance of nutrients in plant-available forms. The optimization of Si plant nutrition increases the plant resistance to both biotic and abiotic stresses, (Liang, 1999; Matichenkov and Bocharnikova 2001; Ma 2004). Si can be applied as soil amendment or foliar spray, depending on the form of the Si fertilizer. Potassium silicate, Magnesium and Sodium silicate are often applied as foliar spray as it is a liquid silicate. Dramatic results have been found: highest basic branch, pods numbers, biological yield, Stover yield and plant high were obtained from Potassium silicate application to bean plants (Abou-Baker *et al.*, 2012). Silicate solubilizes insoluble phosphoric acid in the soil and substitutes a part of phosphoric acid's effects to reduce the amount of phosphoric fertilizer. Phosphorus is the most important element that is related to plant's vital phenomenon, which promotes the initial growth of plant, out-rooting and differentiation of growing points, and has deep relationship with the blooming and fruit ripening in the latter period. Silicate substitutes such functions of phosphoric acid and makes the growth of roots flourishing.

2.3. Mechanisms of silicon uptake

Silicon (Si) is the second, after oxygen, most abundant element in earth crust and its percentage value reaches 26%. In nature, Si does not occur as an elemental form but it is a compound of many minerals which form rocks. Silicon occurs mainly in the form of silicon dioxide (silica) and silicates that contain Si, oxygen and metals (Rezanka and Sigler 2008). Minerals containing Si are resistant to weathering processes and decomposition, hence the amount of silicon in soil solution is low (Brogowski 2000). Monosilicic acid ($H_4SiO_4 = Si(OH)_4$) is amobile and soluble form of Si which is available to plants. Concentration of Si in soil solution ranges from 0.0004 to 2.0 mmol dm⁻³ but most values lie between 0.1 and 0.6 mmol dm⁻³ (Sommer *et al.*, 2006). Uptake of Si from external solution and its transport through roots might be an active or a passive (diffusion) process. Ma and Yamaji (2008) described Si transport process in three species that evidently differ in the ability of Si accumulation: rice (high accumulation), cucumber (medium) and tomato (low Si level).

Results of investigations conducted on four different species of mono- and dicotyledonous plants (*Oryza sativa*, *Zea mays*, *Helianthus annuus*, *Benincasa hispida*) showed that both active and passive components of Si uptake system co-exist in plants (Liang *et al.*, 2006a). Relative contribution of these components depends on plant species and external Si concentrations. In the case of rice and maize (both gramineous species), the active component is the major mechanism responsible for Si uptake (Liang *et al.*, 2006a). A very important step in Si translocation is its transport from cortical cells to the xylem (xylem loading). In rice, a typical silicon accumulator, its concentration in xylem sap is high (2 mM) and process of xylem loading of Si is mediated by specific transporters (Mitani and Ma 2005). Whereas in cucumber and tomato, xylem loading is a passive process, hence transport efficiency is very limited. The determined Si concentration of xylem sap in rice was 20- and 100-fold higher than that in cucumber and tomato respectively. Moreover, Si concentration in xylem of both plants was lower than in the external solution. Some dicotyledonous plants such as legumes do not accumulate Si in tissues and tend to exclude this element — rejective uptake (Liang *et al.*, 2005a). These plants take up Si more slowly than water and they contain less silicon than would be expected from nonselective passive up-take of silicic acid during plant growth.

Silicon distribution in aerial parts of plants is dependent on intensity of transpiration. In the transpiration stream in xylem, silicic acid is transported to leaves and it is accumulated in older tissues (it is not mobile within the plant). In the shoot, owing to the loss of water (transpiration), silicic acid is concentrated and polymerised (Ma and Yamaji 2008). In consequence, Si forms colloidal silicic acid and finally silica gel. Silicon in the form of silica gel may amount to 90% of total Si concentration in shoots.

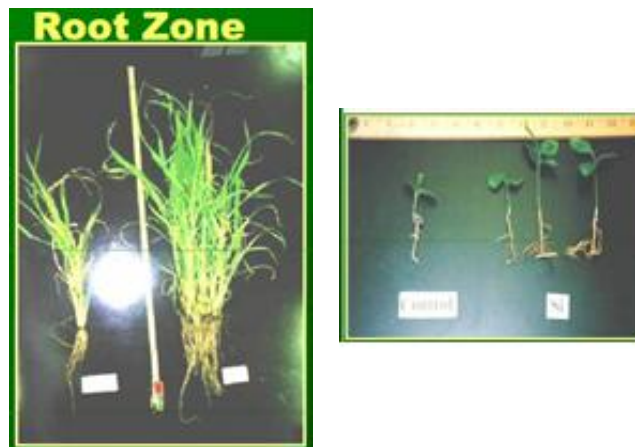


Effects of Si-treatment on growth of cvs. Hinohikari, Oochikara and Is11 mutant. Aspects of wild type rice cvs. Hinohikari (a, d), Oochikara (b, e) and Is11 mutant (c, f) were observed after control nutrient treatment of rice seedlings (a, b, c) and 14-day silicic acid treatment of rice seedlings (Ma and Yamaji 2008).

2.4. Silicate promotes balanced nutrient availability and transport

Nutrients are required in any successful fertilizer program. Nitrogen, while valuable in the growth and photosynthetic processes of plants, must be managed carefully to avoid excessive top growth that will deplete or minimize carbohydrate reserves and encourage disease formation. However, the availability of nitrogen, phosphorus, potassium and other nutrients required for a balanced nutrient fertilizer program, even when supplemented with fertilizers, can fail to reach the plant as they move through the soil profile. Other elements, such as toxic heavy metals can also be released and accumulate around the roots where they damage root systems and plant health. Sufficient supplies of water soluble silicon provide the soil profile with a comprehensive, multifunctional menu of beneficial geochemical reactions that enhance the management and correction of nutrient deficiencies, metal toxicity (Aluminum and other metals), phosphorus fixation and soil deflocculation (Matichenkov and Bocharnikova 2001; Ma and Yamaji, 2006; Liang *et al.*, 2007).

Once silicon is absorbed by the plant, it actively contributes to a balanced state of nutrient availability through uptake processes and micro-distribution of mineral ions as well as compartmentalization of metal ions.

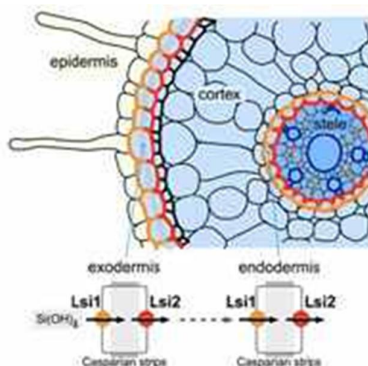


3. Function of silicon in plants

Silicon (Si) is a beneficial nutrient in plant biology. Although the element is classified as essential for only a few plant species, many crops respond positively to supplemental silicon. Si is never found in a free form and is always combined with other elements, usually forming oxides and it is absorbed by plants in the form of uncharged silicic acid, $\text{Si}(\text{OH})_4$ (Ranganathan *et al.*, 2006; Balakhnina and Borkowsak, 2013). The Si content in plant tissue varies greatly among the species and can range from 0.1 to 10% on a dry weight basis (Epstein 1999). Rice is a typical Si accumulator with absorption active by root system, and it present leaf levels normally higher than 10.0 g kg Si and its uptake is about twice that of nitrogen (Savant *et al.*, 1997 and Oliveira 2009). There is a thick layer of silica beneath the cuticle of rice leaves and sheaths. This cuticle–Si double layer may be responsible for impeding pathogen penetration and, consequently, decreasing the number of lesions (NL) on leaf blades as reported for the rice–*Pyricularia grisea* patho-system (Seebold *et al.*, 2001). However, the soluble Si in plant tissue may somehow be associated with an increase in rice resistance to blast through the production of phenolic-like compounds, diterpenoid phytoalexins and the activation of some PR-genes (Rodrigues *et al.*, 2005).

3.1. Silicate adds structural strength and rigidity to plants.

As a result of increasing silicon concentrations in plant tissues the mechanical strength may be improved. Grain crops lacking adequate silicon may be more susceptible to lodging. The amount of insect attack on plant tissues may be inversely related to the silicon concentration. Ma (2004); Ma and Yamajai (2006) reported that plants supplied with Si resist lodging (drooping, leaning, or becoming prostrate). It can increase mechanical strength of plants, which enables them to achieve and maintain an upright growth habit and allows maximum light interception, comes from the structural components of the plants cell walls. Likewise, these treatments (50 and 100 ppm Si) could increase flower number per plant. Hwang *et al.*, (2008) reported similar results on roses. Higher chlorophyll contents in Si treatments resulted in photosynthetic activity improvement and higher productivity.



(Ma and Yamajai 2008)

Plants, especially grasses, can take up large amounts of silicon and this contributes to their mechanical strength. Besides a structural role, silicon helps to protect plants from insect attack, disease, and environmental stress. For some crops, silicon fertilization of soils increases crop yield even under favourable growing conditions and in the absence of disease. Benefits due to silicon nutrition are;

- Direct stimulation of growth and yield.
- Counteracts negative effects of excess N nutrition
- Suppression of plant diseases caused by bacteria and fungi (Powdery mildew on cucumber, pumpkin, wheat, barley, Gray leaf spot on perennial ryegrass, leaf spot on Bermuda grass)
- Suppression of stem borers, leaf spider mites, and various hoppers (Ma *et al.*, 2006).
- Alleviates various abiotic stresses including lodging, drought, temperature extremes, freezing, UV irradiation and chemical stresses including salt, heavy metals, and nutrient imbalances.

Results on the beneficial effects of Si in enhancing the tolerance of plants to biotic and abiotic stresses in several crops, and their relevance to the world of agriculture have been widely described (Epstein 1999; Ma 2004). Si benefits to drought tolerance in wheat (Gong *et al.*, 2006). maize (Li *et*

al., 2007; Yong *et al.*, 2007), sorghum (Hattori *et al.*, 2003, 2005) and salt tolerance of barley, tomato and cucumber (Liang *et al.*, 2003; Al-Aghabary *et al.*, 2004; Zhu *et al.*, 2004) have been related to its effect on the antioxidant enzyme activity.

Gong *et al.*, (2005) reported that application of Si increased the activities of SOD, CAT and GR, the fatty acid unsaturation of lipids, and the contents of photosynthetic pigments and soluble proteins as well as total thiols under drought stress on wheat, whereas the content of H₂O₂, activity of acid phospholipase (AP) and oxidative stress of proteins were decreased by applying Si compared with those of non-Si treatments under drought stress. In sorghum, Si ameliorated the decrease in dry weight under drought stress conditions, and Si-applied sorghum had a lower shoot to root (S/R) ratio, indicating the facilitation of root growth and the maintenance of the photosynthetic rate and stomatal conductance at a higher level compared with plants grown without Si application (Hattori *et al.*, 2005). Optimization of Si nutrition results in increased weight and volume of roots by 20% to 200% and enhanced drought and salt resistance of plants (Matichenkov *et al.*, 2001).

Essential or not, silicon does provide substantial benefits to many crops, particularly greenhouse crops. supplemental silicon improves yield and reduce the plant biotic and abiotic stresses (Epstein, 1999). Additionally, Si can play a role of physical barrier, especially in case of leaves and stems, or it is also able to activate some defense mechanisms of plants. Silicon is reported to increase yields in rice, spring wheat (Hashemi *et al.*, 2010; Rafi and Epstein, 1999), sugarcane (Savant *et al.*, 1999), and barley. Silicon can directly or indirectly affect other elements absorption in plants (Datnoff *et al.*, 2001). Matoh *et al.*, (1986) reported that shoot and root growth was severely inhibited in rice grown at 100 mM NaCl but was significantly ameliorated by addition of Si at 0.89 mM. The bean is highly sensitive to salinity and the soil salinity and yield losses can be tolerated in less than 2 ds/m.

3.2. Silicon improves photosynthetic activity.

Application of silicon as a soil amendment has been reported to result in elevated concentrations of chlorophyll per unit area of leaf tissue, resulting in improved photosynthetic efficiency (Saeed *et al.*, 2009). By far, silicon's greatest contribution to a successful fall fertilization program is that it improves photosynthetic activity and contributes to the build-up of carbohydrate reserves. The use of silicon as an integrated component of fall fertilizer programs can take carbohydrate production to a new level.

The effect of silicon (Si) was investigated on the major antioxidant enzyme activities including superoxide dismutase (SOD), catalase (CAT), ascorbate peroxidase (APX), peroxidase (POD), relative water content (RWC), chlorophyll and soluble protein contents, proline (Pro) and glycine betaine (GB) accumulation in three different growth stages (2nd, 4th leaf and tillering stages) of wheat (*Triticum aestivum* L.) plants under drought stress, (Desingh and Kanagaraj 2007, Li *et al.*, 2007). The results indicated that Si partially offset the negative impacts of drought stress increasing the tolerance of wheat by rising Pro and GB accumulation and soluble protein content. This Si effect was time-dependent and became stronger in the tillering stage. The results of the present experiment coincided with the conclusion that Si alleviates water deficit of wheat by preventing the oxidative membrane damage and may be associated with plant osmotic adjustment (Sara and Raheem 2011).

3.3. The influences of exogenous silicon

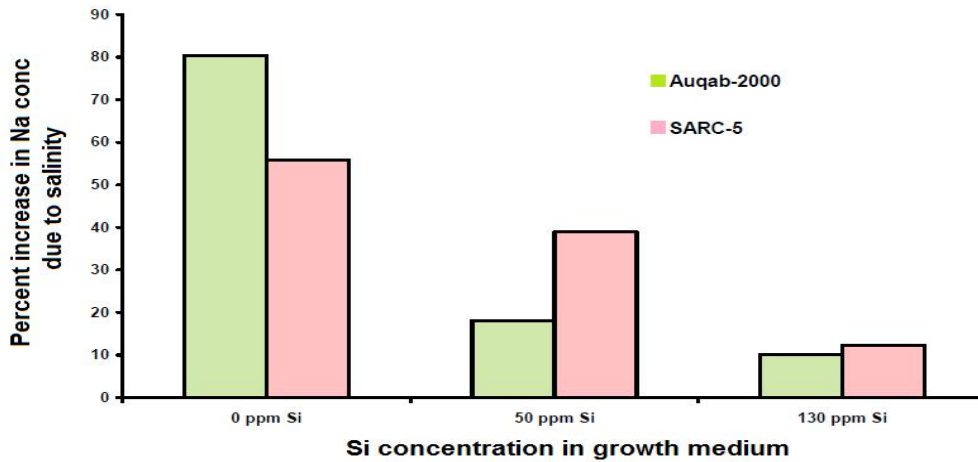
Added silicon to salt treated barley significantly increased superoxide dismutase, catalase activity and decreased malondialdehyde (MDA) concentration in plant leaves (Liang, 1999). Wang *et al.*, (2011); Arab *et al.*, (2013) concluded that the changes of antioxidative enzymes activity varied in different organs of alfalfa plant after salt stress, while silicon could alter the activity of antioxidative enzyme of one or several organs of plants to improve the salt tolerance.

Percent increase in shoot Na concentration under salinity in two wheat genotypes grown at different levels of Si (Tahir *et al.*, 2006).

Salinity exerts oxidative stress due to the production of variety of active oxygen species (AOS) such as superoxide anion (O₂⁻), hydrogen peroxide (H₂O₂) and hydroxyl (OH[•]) radicals (McCord, 2000). To scavenge these toxic species, plants develop antioxidant enzymes. Their activities and transcripts are altered when plants are subjected to different stressors including salinity (Hasegawa *et al.*, 2000).

Si may act to alleviate salt stress in plant by decreasing the permeability of plasma membranes and maintenance of cell form and structure due to the increase of anti-oxidative enzymes SOD and

CAT (Moussa, 2006). Si partially offset the negative impacts of NaCl stress and increase the tolerance of maize leaves to NaCl salinity by enhancement of chlorophyll content and photosynthetic activity. The level of proline accumulated in salt-stressed with Si treatment was not as high as it was in salt-stressed without Si treatment.



4. Silicon increases the resistance to abiotic stresses

4.1. Role of silicon in alleviating salt stress

Studies have shown that Si is effective in mitigating salinity in different plant species, such as barley (Liang *et al.*, 1996; Liang *et al.*, 2003), cucumber (Zhu *et al.*, 2004), maize (Moussa, 2006), tomato (Romero-Aranda *et al.*, 2006), and wheat (Tuna *et al.*, 2008). Some possible mechanisms through which silicon may increase salinity tolerance in plants (Liang *et al.*, 2003) include: immobilization of toxic sodium ion, reduced sodium uptake in plants and enhanced potassium uptake (Liang *et al.*, 2005) and higher potassium, sodium selectivity (Hasegawa *et al.*, 2000). Si alleviates water deficit of wheat by preventing the oxidative membrane damage and may be associated with plant osmotic adjustment (Ahmad and Haddad 2011).

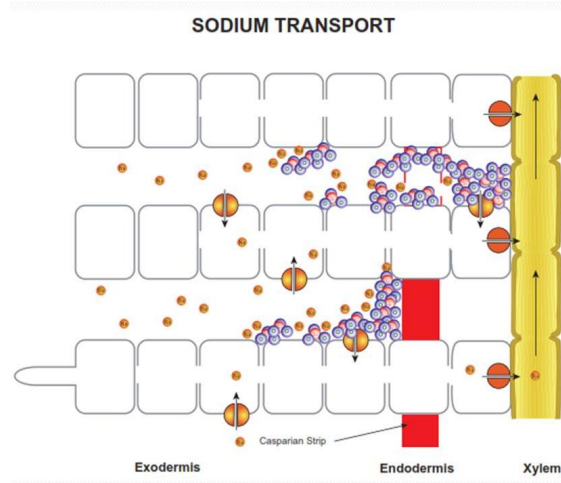


In plants growing under salt-stress conditions, added silicon helps in maintaining an adequate supply of essential nutrients and reduces sodium uptake and its transport to shoots (Liang 1999, Tuna *et al.*, 2008). In experiments with salt-stressed barley, Liang (1999) indicated that Si (1 mmol dm⁻³ K₂SiO₃) decreases sodium but increases potassium concentrations both in roots and shoots. Selective uptake of mineral ions is associated with the activity of H⁺-ATP-ase. It is interesting to note that salt stress caused substantial fall in potassium and calcium concentrations and added silicon led to a nearly 2-fold increase in K⁺ level but had little effect on calcium content in shoots.

Liang (1999) and several other authors re-ported that addition of silicon considerably lowers concentration of potentially toxic ions in aerial parts of plants (Yeo *et al.*, 1999, Gunes *et al.*, 2007a,b, Tuna *et al.*, 2008, Zuccarini 2008). It is possible that silicon present in plant cells limits uptake of toxic ions and prevents their translocation to shoots. The beneficial effect of silicon may be related to the depression of water loss by transpiration and

consequently reduced rate of passive uptake and transport of minerals (Yeo *et al.*, 1999, Gao *et al.*, 2006, Romero-Aranda *et al.*, 2006). Silicon nutrition ameliorated the deleterious effects of salinity on the growth of canola plants through lower tissue Na^+ contents, maintaining the membrane integrity of root cells as evidenced by reduced lipid peroxidation, increased reactive oxygen species scavenging capacity and reduced lignification (Hashemi *et al.*, 2010).

On the other hand, silicon deposited in the form of polymerised SiO_2 in the apoplast of roots considerably restricts ionic trans-location from roots to shoots (Epstein 1999; Wang *et al.*, 2004). However, some reports indicate that added silicon does not lower concentration of Na^+ and Cl^- (Romero-Aranda *et al.*, 2006). Maintenance of low concentration of saline ions in plant tissues is a very important mechanism of salt stress tolerance, although more crucial is the capability of plants to take up and retain water in tissues despite its low potential in external medium.



The beneficial effect of Si under salt stress has been observed in rice (Match *et al.* 1986; Yeo *et al.*, 1999). Shoot and root growth of rice was inhibited by 60% in the presence of 100 mM NaCl for three weeks, but Si addition significantly alleviated salt-induced injury. The Na concentration in the shoot decreased to about half by Si addition. This function of Si may be ascribed to the Si-induced decrease of transpiration and to the partial blockage of the transpirational bypass flow, the pathway by which a large proportion of the uptake of Na in rice occurs (Yeo *et al.*, 1999; Wang *et al.*, 2010). Silicon has been shown to alleviate salt stress by enhancing sodium exclusion and transport into shoots from roots. Silicon increases soluble substances in the xylem that results in reduced sodium absorption by plants. Silicon also reduces further sodium uptake by blocking sodium movement into the xylem.

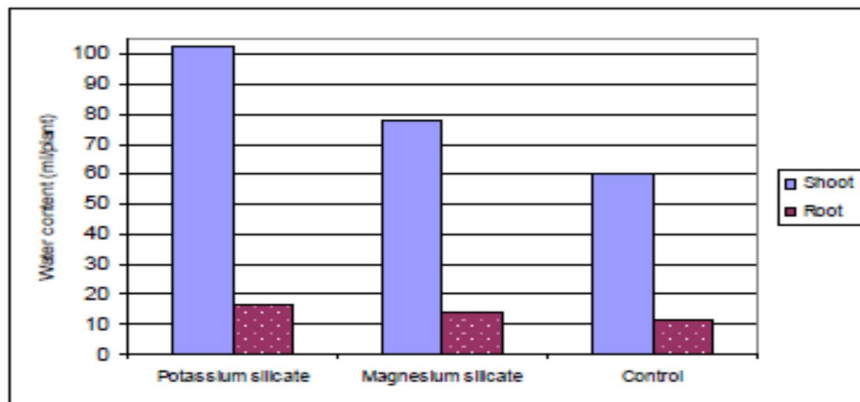
The mechanism for silicon inhibition of sodium uptake has been its activation of an H^+ -ase enzyme that selectively favors potassium absorption over sodium. In barley, Si increased the leaf superoxide dismutase activity and suppressed the lipid peroxidation caused by salt stress and stimulated root H^+ -ATPase in the membranes, suggesting that Si may affect the structure, integrity and functions of plasma membranes by influencing the stress-dependent peroxidation of membrane lipids, although these effects may be indirect (Liang *et al.*, 2002). Increased potassium uptake and decreased sodium uptake by silicon additions are considered to be major mechanisms responsible for better growth of plants under salinity. Silicon's involvement improves the K: Na ratio that not only mitigates the toxic effects of sodium but also frees more potassium to participate in fall stress relief processes.

4.2. Silicon and water stress

Important aspects of silicon fertilization that have gained interest are increased drought resistance and increased flower diameter. A potential cause for both of these benefits is the reduction in water lost by plants through evapotranspiration. Reduction of transpiration rate (or increase of leaf resistance) has been attributed to silicon. Most silicon studies have used agricultural crops and the effects were accelerated with increased environmental stresses like drought and metal toxicity. Reduction of the transpiration rate could further benefit floriculture crop production.

Plants growing under natural conditions are subjected to a multitude of different stress factors through their life cycle. Cellular water deficiency may result not only from drought, salinity and low temperature but can be a secondary effect caused for example by heavy metals or high radiation.

The beneficial function of silicon does not reveal itself under optimal circumstances but mainly under stress conditions (Henriet *et al.*, 2006; Kaya *et al.*, 2006). Silicon exerts positive effects when its concentration in plant tissues is high.



Shoot and root water content (ml/plant) of faba bean plants at 75 days of sowing. (Abou-Baker *et al.*, 2012)

Mechanisms which are important in plant resistance to water stress and a possible role of Si in these processes may be considered at different levels (molecular, cellular, whole-plant). Essential features of plants' response to water stress are following: i) maintenance of homeostasis, including ionic balance and osmotic adjustment, ii) counteraction to damages and their prompt repair, e.g. elimination of ROS and prevention of oxidative stress, iii) detoxification of excess salts under salinity, iv) regulation and recovery of growth (Elzbieta Sacala, 2009).

Results of experiments conducted by Kaya *et al.*, (2006) on maize growing under water stress indicated that silicon (1 and 2 mmol dm⁻³ Na₂SiO₃) significantly improve shoot growth although it did not affect root growth. It is worthy of note that higher Si dose was more efficient than lower one, although in the case of leaf relative water content (RWC) both Si concentrations caused similar increase of this parameter in comparison to plants growing without Si. Improved plant water status (higher RWC index) may result from reduced water loss by transpiration due to deposition of Si (forming silica gel layer) on epidermal cell walls. It was surprising that both Si treatments lowered proline concentration in maize plants grown under water stress (Kaya *et al.*, 2006). Similar response was observed in wheat growing under salinity (Tuna *et al.*, 2008). Amino acid proline occurs widely in proteins but it may also accumulate in the cytosol in response to environmental stresses, especially under osmotic stress. Accumulated free proline contributes substantially to osmotic adjustment and may protect and stabilise sub-cellular structures (e.g. proteins and membranes).

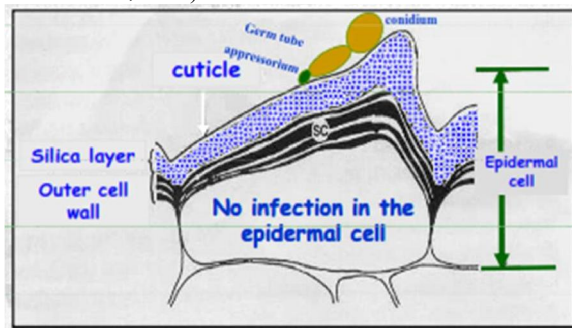
Addition of Si may increase concentrations of Ca in plant tissues and hence restore membrane integrity in water-stressed plants. Disruption of ion homeostasis may result from reduced K⁺ concentrations in water-stressed plants. Potassium plays an important role in processes involving osmotic adjustment and its adequate level in plants may improve water stress tolerance. Under water-stress conditions, the presence of Si may result in better supply of K (Kaya *et al.*, 2006). This beneficial effect may be attributed to the stimulating action of Si on H⁺-ATP-ase (Liang 1999).

Kaya *et al.*, (2006) reported that under drought stress maize leaves contained approx. 50% less calcium than control plants while in roots its amount was higher comparing to the control. Decrease in Ca concentration in plant cells is harmful because this element plays an essential role in maintaining the structural and functional integrity of plant membranes and regulation of their permeability and selectivity.

The effect of supplemental silicon on stomatal conductance, which is the mechanism plants use to open and close "water vapor" valves was investigated by (Cavins *et al.*, 2010) under normal greenhouse conditions, they indicated that leaf resistance (reduction of transpiration) increased with a high rate of sodium silicate foliar sprays. They concluded that sodium silicate foliar spray applications can act as a film-forming anti-transpirant that increases leaf resistance.

The mechanical barrier hypothesis

Cuticle-silica double layer (Yoshida *et al.*, 1962)



Water deficiency (drought stress) leads to the closure of stomata and subsequent decrease in the photosynthetic rate. Silicon can alleviate water stress by decreasing transpiration. Transpiration from the leaves occurs mainly through the stomata and partly through the cuticle. As Si is deposited beneath the cuticle of the leaves forming a Si-cuticle double layer, the transpiration through the cuticle may decrease by Si deposition. Silicon can reduce the transpiration rate by 30% in rice, which has a thin cuticle (Ma *et al.*, 2001a; Elzbieta Sacala, 2009). Under water-stressed conditions (low humidity), the effect of Si on rice growth was more pronounced than on rice that cultivated under non-stressed conditions (high humidity) (Ma *et al.*, 2001a).

When rice leaves were exposed to a solution containing polyethylene glycol (PEG), electrolyte leakage (EI) (an indicator of membrane lesion) from the leaf tissues decreased with the increase in the level of Si in the leaves (Agarie *et al.*, 1998). The level of polysaccharides in the cell wall was higher in the leaves containing Si than in those lacking Si. These results suggest that Si in rice leaves is involved in the water relations of cells, such as mechanical properties and water permeability. Among the yield components, the percentage of ripened grains is most affected by Si in both rice and barley (Ma and Takahashi 2002). This function of Si may be attributed to the alleviative effect of Si on water stress. One important factor for the normal development of the spikelets is to keep a high moisture condition within the hull (Elzbieta Sacala, 2009). The Si content in the hull of the rice grain becomes as high as 7% Si and that of the barley grain is 1.5%. Silicon in the hull is also deposited between the epidermal cell wall and the cuticle, forming a cuticle-Si double layer as in the leaf blades. However, in contrast to the leaves, transpiration occurs only through the cuticle because the hull does not have a stoma. Silicon is effective in decreasing the transpiration from the hull. The rate of water loss from Sifree spikelets was about 20% higher than that from spikelets containing Si (7% Si) at both the milky and maturity stages (Ma *et al.*, 2001a). Therefore, Si plays an important role in keeping a high moisture condition within the hull by decreasing the transpiration rate from the hull. This is especially important under water deficiency stress and stress associated with climatic conditions.

4.3. Silicon and stress associated with climatic conditions

A number of studies have showed that Si alleviates physical stresses, including radiation, low and high temperature, wind, drought and water logging, low and high light and so on.

Silicon application in rice is effective in alleviating the damage caused by climatic stress such as typhoons, low temperature and insufficient sunshine during the summer season (Ma *et al.*, 2001a; Ma 2004). A typhoon attack usually causes lodging and sterility in rice, resulting in a considerable reduction of the rice yield. Deposition of Si in rice enhances the strength of the stem by increasing the thickness of the culm wall and the size of the vascular bundles (Savant *et al.*, 1997), thereby preventing lodging. Strongwinds also cause excess water loss from the spikelets, resulting in sterility. Silicon deposited on the hull is effective in preventing excess water loss. In addition, the effect of Si on the rice yield is also obvious under stress due to low temperatures and insufficient sunshine.

4.4. Silicon and heat stress.

Silicon also increases the tolerance to heat stress in rice plants. Agarie *et al.*, (1998) observed that electrolyte leakage caused by high temperature (42, S°C) was less pronounced in the leaves

grown with Si than in those grown without Si. These results suggest that Si may be involved in the thermal stability of lipids in cell membranes although the mechanism has not been elucidated.

Protection against temperature extremes



Photograph of creeping bentgrass exposed to high temperature.

Plants had been grown for 55 days at 20 °C, and then exposed to a temperature of 35-40 C under constant light and humidity for 20 days.

The growth of creeping bentgrass applied silicon sources was similar. However, most of the control plants grown 35 °C above had died day 20

5. 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, and salinity.

5.1. Silicon and Al toxicity

Al toxicity is a major factor limiting crop production in acid soils. Ionic Al inhibits root growth and nutrient uptake (Ma *et al.*, 2001b). Alleviative effect of Si on Al toxicity has been observed in sorghum, barley, teosinte, maize, rice, and soybean. In an experiment with maize, Si addition as silicic acid significantly alleviated Al-induced inhibition of root elongation (Ma *et al.*, 1997). The alleviative effect was more apparent with increasing Si concentration. Concentration of toxic AP⁺ was found to decrease by the addition of silicic acid. These results suggest that interaction between Si and Al occurs in the solution, presumably by the formation of Al-Si complexes, a non-toxic form. However, other mechanisms for the alleviative effect of Si have also been proposed, including codeposition of Al with Si within the plant, action in the cytoplasm, effect on enzyme activity and indirect effects (Cocker *et al.*, 1998). The alleviative effect of Si on Al toxicity varies with plant species, probably due to difference in Al tolerance and / or differences in the mechanisms involved.

5.2. Silicon and N excess.

Application of N fertilizers is an important practice for increasing yield. However, excess N causes lodging, mutual shading, susceptibility to diseases and so on. Silicon deposited on the stems and leaf blades prevents lodging and mutual shading, as stated above. The occurrence of blast disease is significantly inhibited by Si application in the field, especially when N application is heavy (Ohyama 1985). These functions of Si are especially important in the cultivation systems with dense planting and high N application. Excessive application of nitrogen fertilizers also causes high protein content in brown rice, which affects its quality. Sufficient supply of Si to rice is effective in producing low protein rice and reduced activity of micro – organisms (such as the critical nitrification of Ammonium – N to nitrate). (Mason *et al.*, 1994).

5.3. Silicon and phosphorus deficiency or excess

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 (Ma and Takahashi, 1990a). In a solution culture experiment, there was no significant effect of Si on the dry weight of shoot, root and grain of rice when P was supplied at an adequate level (200 mM) (Nagaoka, 1998). However, when the P level was decreased to 12.5 mM, the effects of Si were obvious. P uptake was not enhanced by Si when the P level was low, but the rate of P translocation to panicle is enhanced by Si in rice. This

implies that Si improves internal P utilization. In a P-deficient soil, previous addition of silicic acid at various concentrations did not affect the P fixation capacity of soil (Ma and Takahashi 1990b). Fixed phosphorus was not desorbed by various concentrations of silicic acid (Ma and Takahashi 1991). 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 1991). However, the uptake of Fe and Mn significantly decreased in the Si-treated plants. Phosphorus is translocated and redistributed in plants in an inorganic form. Since P shows a high affinity with metals such as Fe and Mn, internal availability of P could be controlled by the level of Mn, Fe, and other metals when the P concentration is low.

Therefore, the larger beneficial effect of Si on plant growth under P deficiency stress may be attributed to the enhanced availability of internal P through the decrease of excess Fe and Mn uptake. This is supported by the fact that Si supply increased the rate of P translocation to the panicles in rice (Nagaoka 1998). 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 (Lux *et al.*, 2003), which may form apoplastic barriers against the radial movement of P across the root. The Si-induced decrease of P uptake has also been observed in some Si non-accumulating plants, including tomato, soybean, strawberry and cucumber (for a review, see Ma *et al.*, 2001a), in which roots Si is also deposited.

5.4. Silicon and heavy metal toxicity.

An alleviative function of Si on Mn toxicity has been observed in rice, barley, and pumpkin (Iwasaki and Matsumura, 1999). Three different mechanisms seem to be involved depending on the plant species. In rice, Si reduced Mn uptake by promoting the Mn oxidizing power of the roots which led to a homogeneous distribution of Mn in the leaf blade. Although the mechanism for this homogeneous distribution has not been elucidated, (Horst *et al.*, 1999) found that Si led to a lower apoplastic Mn concentration in cowpea and suggested that Si modifies the cation binding properties of the cell wall. However, further studies have indicated that the maintenance of a reduced state of the apoplast by soluble Si was also involved in the Si-enhanced Mn tolerance in cowpea (Iwasaki *et al.*, 2002a, b). This is supported by the evidence that there was no correlation between the apoplastic Mn concentration and the expression of Mn toxicity, but that there was a negative correlation between the apoplastic Si concentration and the expression of Mn toxicity.

A negative correlation was observed between the apoplastic guaiacol peroxidase (POD) activity and the Si concentrations in apoplastic washing fluid (AWF). Silicon seems to affect the oxidation process of excess Mn mediated by POD through the interaction with phenolic substances in the solution phase of the apoplast (Iwasaki *et al.*, 2002a). By contrast, Si caused a localized accumulation of Mn around the base of trichomes in pumpkin (Iwasaki and Matsumura 1999). The uptake of Mn was also not affected by Si in this plant. Silicon was also effective in alleviating Fe excess toxicity in rice through enhancing the oxidative power of rice roots, resulting in enhanced oxidation of Fe from ferrous iron to insoluble ferric iron. Therefore, excess Fe uptake was indirectly prevented by Si application. For upland plants, excess Fe stress is not a problem. In heavy metal-tolerant *Cardaminopsis halleri*, grown on Zn- and Cd-polluted soil, Zn coexisted with Si in the cytoplasm (Neumann and zur Nieden 2001).

It was observed that Zn-silicate is a transient storage compound for the metal and undergoes a slow degree of degradation to SiO₂. Zn is then translocated into the vacuoles and accumulated in an unknown form. It was suggested that the formation of Zn-silicate is part of the mechanism of heavy metal tolerance and may be responsible for the alleviation of Zn toxicity in *Cardaminopsis*.

Silicon alleviated heavy metal toxicity

Effects of Cd and Si on fresh weight, dry weight and DW/FW quotient of the shoot of maize plants after 10 days of hydroponic cultivation in four different treatments.

Treatment	Fresh weight(g)	SD	Dry weight (g)	SD	DW/FW
C	1.044a	0.20	0.073a	0.014	0.070
Cd	0.979b	0.14	0.069b	0.018	0.070
Cd + Si	1.110a	0.32	0.086c	0.022	0.077
Si	1.121a	0.31	0.092c	0.016	0.082

C- control without Cd or Si, Cd - 5µM cadmium treatment, (Vaculik *et al.*, 2009)

Cd+ Si - 5µM cadmium with 35 mM silicon treatment.

Si- 35 mM silicon treatment.

Values are means ± SD (n=4), different letters mean significant differences between the treatments at 0.05 %levels.

Heavy metals enter the food chain through the soil and become hazardous contaminants of food, entering the human body as a cumulative poison (Benavides *et al.*, 2005). The rehabilitation of soil contaminated by heavy metals relies on methods such as managing the mobility of heavy metals in the soil so that they don't leach into waterways or get taken up by plants. This can be achieved by changing the pH (heavy metals are less mobile at high pH) or by adding soil amendments to increase the soil's adsorption capacity thereby reducing the plant's ability to access the heavy metal. However, these measures may not be sufficient or are costly and inefficient.

A recent report (Matichenkov and Bocharnikova, 2010) demonstrated that the leaching of heavy metals (Cu, Pb, Cr, Ni, and Co) was reduced significantly, by over 50%, with the addition of a Si fertilizer (diatomaceous earth). This reduction in leaching of heavy metals may be explained by the interaction between the heavy metals and Si-rich substances, such as diatomaceous earth.

Several mechanisms are proposed in this recent report as responsible for inactivating the heavy metals: a weak physical or strong chemical adsorption between the heavy metals and the diatomaceous earth and a reaction between PAS (monosilicic acid) and the heavy metals

Liang *et al.*, (2005), assessing the alleviative effects of exogenous silicon (Si) on cadmium (Cd) phytotoxicity in maize, reported that Cd treatment significantly decreased shoot and root dry weight, while addition of Si at both levels significantly enhanced biomass. Addition of Si at 400 mg kg⁻¹ Si significantly increased soil pH but decreased soil Cd availability, thus reducing Cd concentration in the shoots and roots and total Cd in the shoots. Moreover, more Cd was found to be in the form of specific adsorbed or Fe-Mn oxides-bound fraction in the Si-amended soil. In contrast, soil pH, available Cd and Cd forms were unaffected by addition of Si at 50 mg kg⁻¹ Si, but shoot Cd concentration in the Si-amended Cd treatments significantly decreased at both Cd levels used compared to the non-Si-amended Cd treatments. H concluded that Si-enhanced tolerance to Cd and attributed that not only to Cd immobilization caused by silicate-induced pH rise in the soils but also to Si-mediated detoxification of Cd in the plants (Yongchao *et al.*, 2005).

6. Silicon enhances the resistance to biotic stresses

Several studies have shown that Si is effective in enhancing the resistance to diseases and pests. Plant available silicon plays a key role in activating plant processes that enhance and improve the efficiency and effectiveness of defense response systems under environmental stress conditions and biological attack. Trials conducted on the silicon research plots at Rutgers University, New Jersey Agriculture Experiment Station show that calcium silicate slag is an effective liming material and silicon fertilizer. Plants grown on calcium silicate slag amended soil exhibited increased silicon uptake, (Heckman and Provance-Bowley 2011). Pumpkin fruit and wheat grain yields were increased in some years in association with suppression of powdery mildew disease on calcium silicate slag amended soil. Corn plants grown on soil previously amended with calcium silicate slag exhibited less injury to the stem tissue from European corn borer.

Provance-Bowley *et al.*, (2010) reported that, forage yields were improved by liming low pH soil with either calcium carbonate or calcium silicate slag, 3 and 4 years after the last application. Cabbage yields were improved by liming low pH soil but calcium silicate slag increased yield more than calcium carbonate. The residual benefits of calcium silicate slag applications were evident in crops produced 3 to 4 years after the last application.



Unnamed, control acid soil

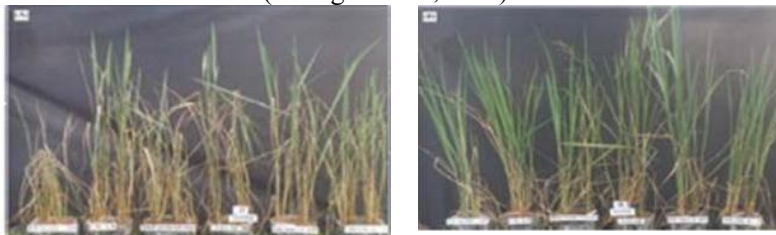


Calcium silicate slag, CSS, AgrowSil™

6.1. Silicon and rice blast disease

The suppressive effect of Si on rice blast was well established. Rice blast is the most destructive fungal disease of rice, particularly in temperate, irrigated rice and tropical upland rice. The pathogen can infect all the above-ground parts of the rice plant, but occurs most commonly on leaves causing leaf blast during the vegetative stage of growth or on neck nodes and panicle branches during the reproductive stage, causing neck blast (Bonman *et al.*, 1989; Rodrigues *et al.*, 2005). Silicon reduces the epidemics of both leaf and panicle blast at different growth stages. In Florida, where soil is deficient in Si, application of silicate fertilizer is as effective as fungicide application in controlling rice blast (Datnoff *et al.*, 1997).

Silicon induced disease resistance in rice (Rodrigues *et al.*, 2009)



Symptoms of sheath blight on six Brazilian of rice. (A) Control (0 g Si pot⁻¹) and (B) plants grown at the highest rate of Si (1.92g Si pot⁻¹)

Rice seedling blast is significantly suppressed by the application of Si fertilizers in the nursery (Maekawa *et al.*, 2001). Seebold *et al.*, (2001) tested the effects of Si on components of resistance to blast using susceptible, partially resistant, and completely resistant rice cultivars. They 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. Maekawa *et al.*, (2002) reported that Si accumulated near the blast appressorium on inoculated rice leaves. However, the soluble Si in plant tissues may somehow be associated with an increase in rice resistance to blast through the productivity of phenolic-like compounds, diterpenoidphtoalex and the activation of some PR-genes (Rodrigues *et al.*, 2005). Also, Si nutrition has been associated with improved resistance to Faungal diseases such as leaf or panicle blast and brown spot (Rezende *et al.*, 2009).

6.2. Silicon and powdery mildew disease

Kanto *et al.*, (2006) tested liquid potassium silicate for the control of powdery mildew of strawberry. They reported that soluble silicon suppressed the disease more effectively as a preventive control than a control to reduce initial incidence. Silicon has been reported to prevent the incidence of powdery mildew disease, which is caused by *Sphaerotheca fuliginea*, in a number of plant species. Miyake and Takahashi (1983) reported that by increasing the Si concentration in the culture solution, the Si content in the cucumber shoot increased, resulting in a reduced incidence of powdery mildew disease. In strawberry, when the Si content of leaves increased proportionally to the increase of the Si concentration in the culture solution, the incidence of powdery mildew decreased (Kanto 2002).

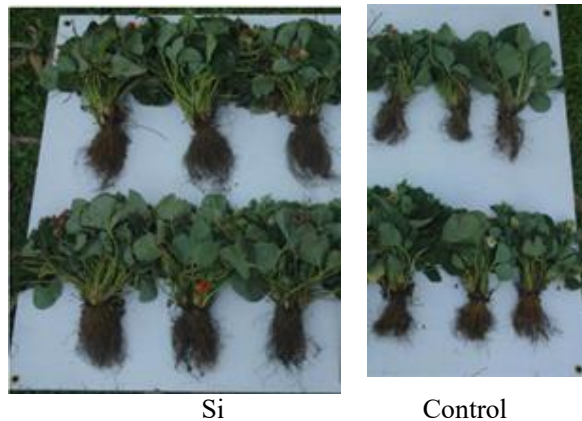
Silicon deficiency in barley and wheat leads to a poor growth habit and increased powdery mildew susceptibility (Zeyen 2002). Menzies *et al.*, (1992) found that infection efficiency, colony size, and germination of conidia were reduced when cucumbers were grown in nutrient solutions with high concentrations of Si.

Foliar application of Si has been reported to be effective in inhibiting powdery mildew development on cucumber, muskmelon, and grape leaves (Bowen *et al.*, 1992; Menzies *et al.*, 1992). Silicon applied to leaves may deposit on the surface of leaves and plays a similar role to that of Si taken up from the roots.



6.3. Silicon and other diseases

In addition to blast and powdery mildew, the occurrence of brown spot, stem rot, sheath brown rot on rice, fusarium wilt, and corynespora leaf spot on cucumber decreased by increasing the Si supply. In turf grass, several diseases were also suppressed by Si application (Datnoff *et al.*, 2002). Rice bacterial blight caused by *Xanthomonas oryzae* pv. *oryzae* (Xoo) is a serious disease worldwide. Chang *et al.*, (2002) reported that in the cultivar TNI which is susceptible to this disease the Si content in leaves was lower than that of the resistant breeding line, TSWY7 under the nutrient cultural system adopted.



Comparison between the control and Agripower Silica grown strawberries

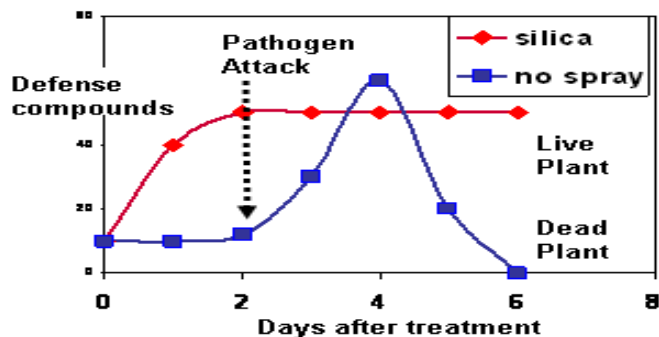
The degree of resistance to this disease increased in parallel with the increased amount of applied silicon. Si-induced decrease of soluble sugar content in the leaves seems to contribute to the field resistance of the disease. Silicon is also effective in increasing the resistance to the fungal diseases caused by *Pythium ultimum* and *P aphanidermatum* in cucumber roots (Cherif *et al.*, 1994).

6.4. Silicon and pests

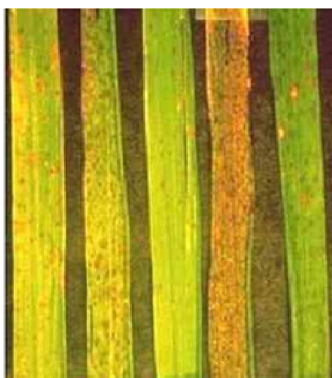
Silicon suppresses insect pests such as stem borer, brown plant hopper, rice green leaf hopper, and white backed plant hopper, and no insect pests such as leaf spider and mites (Savant *et al.*, 1997; Ma and Takashi, 2002). Stems attacked by the rice stem borer were found to contain a lower amount

of Si. In a field study, a positive relationship between the Si content of rice and resistance to the brown plant hopper has been observed (Rezende *et al.*, 2009).

Two hypotheses for the Si-enhanced resistance to diseases and pests have been proposed. One is that Si deposited on the tissue surface acts as a physical barrier. It prevents physical penetration and / or makes the plant cells less susceptible to enzymatic degradation by fungal pathogens. This mechanism is supported by the positive correlation between the Si content and the degree of suppression of diseases and pests. The other one is that Si functions as a signal to induce the production of phytoalexin (Cherif *et al.*, 1994).



Si application to cucumber resulted in the stimulation of the chitinase activity and rapid activation of peroxidases and polyphenoloxidases after infection with *Pythium* spp. Glycosidically bound phenolics extracted from Si-treated plants when subjected to acid or, β -glucosidase hydrolysis displayed a strong fungistatic activity. However, in oat attacked by *Blumeria graminis*, Si deficiency promoted the synthesis of phenolic compounds (Carver *et al.*, 1998). The phenylalanine ammonia-lyase activity was enhanced by Si deficiency. The reason why Si deficiency exerts opposite effects on the synthesis of phenolic compounds, as a disease response in different plant species, has not been elucidated. Recently, Kauss *et al.*, (2003) reported that during the induction of systemic acquired resistance (SAR) in cucumber, the expression of a gene encoding a novel proline-rich protein was enhanced. This protein has C-terminal repetitive sequences containing an unusually high amount of lysine and arginine. The synthetic peptide derived from the repetitive sequences was able to polymerize orthosilicic acid to insoluble silica, which is known to be involved in cell wall reinforcement, at the site of the attempted penetration of fungi into epidermal cells. This study provided a biochemical and molecular basis of Si-enhanced resistance to diseases.



Brown spots on leaves (IRRI).

7. Summary

Silica is the scientific name for a group of minerals made of silicon and oxygen. Silica is found in most mineral deposits in the world in both crystalline and non-crystalline (amorphous) forms. Silicates soil amendments provide effective and efficient means to correct a number of soil chemical imbalances, nutrient deficiencies and toxicity issues. Soil treatment with biogeochemically active Si substances optimizes soil fertility through improved water, physical and chemical soil properties and

maintenance of nutrients in plant-available forms. Uptake of Si from external solution and its transport through roots might be an active or a passive (diffusion) process. Once silicon is absorbed by the plant, it actively contributes to a balanced state of nutrient availability through uptake processes and micro-distribution of mineral ions. As a result of increasing silicon concentrations in plant tissues the mechanical strength may be improved. The Si content in plant tissue varies greatly among the species and can range from 0.1 to 10% on a dry weight basis. Rice is a typical Si accumulator and its uptake is about twice that of nitrogen.

Application of silicon as a soil amendment has been reported to result in elevated concentrations of chlorophyll per unit area of leaf tissue, resulting in improved photosynthetic efficiency. Si is effective in mitigating salinity in different plant species, (barley, cucumber, tomato). Some possible mechanisms through which silicon may increase salinity tolerance in plants include immobilization of toxic sodium ion and enhanced potassium uptake. In plants growing under salt-stress conditions, added silicon helps in maintaining an adequate supply of essential nutrients and reduces sodium uptake and its transport to shoots. Important aspects of silicon fertilization that have gained interest are increased drought resistance. Reduction of transpiration rate (or increase of leaf resistance) has been attributed to silicon.

An alleviative function of Si on Mn toxicity has been observed in rice, barley, and pumpkin. Silicon may be responsible for the alleviation of Zn and Fe excess toxicity in rice roots. Si-enhanced tolerance to Cd and this was attributed that not only to Cd immobilization caused by silicate-induced pH rise in the soils but also to Si-mediated detoxification of Cd in the plants.

Several studies have shown that Si is effective in enhancing the resistance to diseases and pests. Silicon reduces the epidemics of both leaf and panicle blast at different growth stages. Silicon has been reported to prevent the incidence of powdery mildew disease, brown spot, stem rot, sheath brown rot on rice, fusarium wilt, and corynespora leaf spot on cucumber. Silicon suppresses insect pests such as stem borer, brown plant hopper, rice green leaf hopper, and white backed plant hopper, and no insect pests such as leaf spider and mites. It prevents physical penetration and / or makes the plant cells less susceptible to enzymatic degradation by fungal pathogens.

References

- Abou-Baker, N.H., M. Abd-Eladl, and T.A. Eid, 2012. Silicon and water regime responses in bean production under soil saline condition. *Journal of Applied Sciences Research*, 8(12): 5698-5707.
- Agarie, S., N. Hanaoka, O. Ueno, A. Miyazaki, F. Kubota, W. Agata, and P.B. Kaufman, 1998. Effect of silicon on tolerance to water deficit and heat stress in rice plants (*Oryza sativa* L.), monitored by electrolyte leakage. *Plant Prod. Sci.*, 1: 96-103
- Ahmad A., M. Afzal, A. Ahmad and M. Tahir, 2013. Effect of Foliar Application of Silicon on Yield and Quality of Rice (*Oryza Sativa* L.) *Cercetari agronomice in Moldova*, 46(3):21–28, ISSN (Online) 2067-1865, DOI: 10.2478/v10298-012-0089-3.
- Ahmad, S. and R. Haddad, 2011. Study of Silicon Effects on Antioxidant Enzyme Activities and Osmotic Adjustment of Wheat under Drought Stress *Czech J. Genet. Plant Breed.*, 47(1): 17–27
- Al-Aghabary, K., Z. Zhu, and Q. Shi, 2004. Influence of silicon supply on chlorophyll content, chlorophyll fluorescence, and antioxidative enzyme activities in tomato plants under salt stress. *Journal of Plant Nutrition* 12: 2101–2115.
- Arab, L., A. Ehsanpour, and N. Jwa 2013. Co-treatment effect of triadimefon and salt stress on antioxidant responses, NHX1 and LEA expression in two alfalfa cultivars (*Medicago sativa* L.) under *in vitro* culture
- Balakhnina, T. and A. Borkowska, 2013. Effect of silicon on plant resistance to environmental stresses: review. *International Agrophysics*, 27: 225-232.
- Benavides, M.P., S.M. Gallego, and M.L. Tomaro, 2005. Cadmium toxicity in plants. *Braz. J. Plant Physiol.* 17: 21-34.
- Bonman, J.M., B.A. Estrada, and J.A. Bandong, 1989. Leaf and neck blast resistance in tropical lowland rice cultivars. *Plant Dis.*, 73: 388-390

- Bowen, P., J. Menzies, and D. Ehret, 1992. Soluble silicon sprays inhibit powdery mildew development on grape leaves. 1. *Am. Soc. Hortic. Sci.*, 117:906-912
- Brogowski, Z., 2000. Silicon in soil and its role in plant nutrition. *Post. Nauk Rol.*, 6: 9-16. (in Polish)
- Carver, T.L.W., M.P. Robbins, B.J. Thomas, K. Troth, N. Raistrick, and R.J. Zeyen, 1998. Silicon deprivation enhances localized autofluorescent responses and phenylalanine ammonia-lyase activity in oat attacked by *Blumeria graminis*. *Physiol. Mol. Plant Pathol.*, 52: 245-257
- Cavins, T., S. Marek, and S. Kamenidou, 2010. Impact of silicon on plant growth c.f. *Greenhouse Management Magazine* October 28, 2013 online
- Chang, S.J., D.D. Tzeng, and C.C. Li, 2002. Effect of silicon nutrient on bacterial blight resistance of rice (*Oryza sativa* L.). Abstract of Second Silicon in Agriculture Conference, 31.
- Cherif, M., A. Asselin, and R.R. Belanger, 1994. Defense responses induced by soluble silicon in cucumber roots infected by *Pythium* spp. *Phytopathology*, 84: 236-242
- Cocker, K.M., D.E. Evans, and M.J. Hodson, 1998. The amelioration of aluminium toxicity by silicon in higher plants: solution chemistry or an in planta mechanism? *Physiol. Plant*, 104: 608-614.
- Datnoff, L.E., M.O. Brecht, T.A. Kucharek, and R.T. Nagata, 2002. The role of silicon in turfgrass disease management. Abstract of Second Silicon in Agriculture Conference, 105-110
- Datnoff, L.E., C.W. Deren, and G.H. Snyder, 1997. Silicon fertilization for disease management of rice in Florida. *Crop Protect.*, 16: 525-531
- Datnoff, L.E., G.H. Snyder, and G.H. Korndorfer, 2001. *Silicon in Agriculture*. Elsevier, Amsterdam.
- Desingh, R. and G. Kanagaraj, 2007. Influence of salinity stress on photosynthesis and anti-oxidative systems in two cotton varieties. *Gen. Appl. Plant Physiol.*, 33: 221-234.
- Elzbieta S., 2009. Role of silicon in plant resistance to water stress, *J. Elementol.*, 14(3):619-630.
- Epstein, E., 1994. The anomaly of silicon in plant biology. *Proc. Natl. Acad. Sci.*, 91: 11-17.
- Epstein, E., 1999. Silicon, Annual review of plant physiology and plant molecular biology. *Plant Biol.*, 50: 641-664.
- Epstein, E. and A.J. Bloom, 2003. *Mineral Nutrition of Plants: Principles and Perspectives*, 2nd Ed., John Wiley & Sons, New York.
- Gao, X., C.H. Zou, L. Wang, and F. Zhang, 2006. Silicon decreases transpiration rate and conductance from stomata of maize plants. *J. Plant Nutr.*, 29: 1637-1649.
- Gong, H., X. Zhu, K. Chen, S. Wang, and C. Zhang, 2005. Silicon alleviates oxidative damage of wheat plants in pots under drought. *Plant Science*, 169: 313-321.
- Gong, H.J., D.P. Randall, and T.J. Flowers, 2006. Silicon deposition in the root reduces sodium uptake in rice (*Oryza sativa* L.) seedlings by reducing bypass low. *Plant Cell Environ.*, 29:1970-1979.
- Gunes, A., A. Inaj, G. Bagcie, and D.J. Pijbeam, 2007b. Silicon-mediated changes of some physiological and enzymatic parameters symptomatic for oxidative stress in spinach and tomato grown in sodic-B toxic soil. *Plant Soil*, 290: 103-114.
- Gunes, A., A. Inaj, G. Bagcie, S. Coban, and O. Sahin, 2007a. Silicon increases boron tolerance and reduces oxidative damage of wheat grown in soil with excess of boron. *Biol. Plant*, 51: 571-574.
- Hasegawa, P.M., R.A. Bressan, J.K. Zhu, and H.J. Bohnert, 2000. Plant cellular and molecular responses to high salinity. *Ann. Rev. Pl. Physiol. Pl. Mol. Biol.*, 51: 463-99.
- Hashemi, A., A. Abdolzade, and H. Sadeghipour, 2010. Beneficial effects of silicon nutrition in alleviating salinity stress in hydroponically grown canola, *Brassica napus* L., plants. *Soil Science & Plant Nutrition*, 56(2): 244-253
- Hattori, T., S. Inanaga, H. Araki, P. An, S. Morita, M. Luxova, and A. Lux, 2005. Application of silicon enhanced drought tolerance in sorghum bicolor. *Physiologia Plantarum*, 123: 459-466.
- Hattori, T., S. Inanaga, E. Tanimoto, A. Lux, M. Luxova, and Y. Sugimoto, 2003. Silicon-induced changes in viscoelastic properties of sorghum root cell walls. *Plant Cell Physiology*, 44: 743-749.
- Heckman, J.R. and M. Provance-Bowley, 2011. *Silicon in Soil Fertility and Crop Production; Ten years of Research*. Northeast Branch Crops, Soils and Agronomy Meeting Abstracts. c.f. *The Soil Profile*, 20, 2012
- Henriet, C., X. Draye, L. Oppitz, R. Swennen, and B. Delvaux, 2006. Effects, distribution and uptake of silicon in banana (*Musa* spp.) under controlled conditions. *Plant Soil*, 287: 359-374.

- Hinman, N.W. and R.F. Lindstrom, 1996. Seasonal changes in silicadeposition in hot spring systems. *Chemical Geology*, 132: 237-246.
- Horst, W.J., M. Fecht, A. Naumann, A.H. Wissemeier, and P. Maier, 1999. Physiology of manganese toxicity and tolerance in *Vigna unguiculata* (L.) Walp. 1. *Plant Nutr. Soil Sci. (Z. Pflanzenernahr)*, 162: 263-274.
- Hwang, S.J., M. Hamayun, H.Y. Kim, C.I. Na, K.U. Kim, D.H. Shin, S.Y. Kim, and I.J. Lee, 2008. Effect of nitrogen and silicon nutrition on bioactive gibberellin and growth of rice under field conditions. *Journal of Crop Science and Biotechnology*, 10: 281-286.
- Iwasaki, K. and A. Matsumura, 1999. Effect of silicon on alleviation of manganese toxicity in pumpkin (*Cucurbita moschata* Duch cv. Shintosa). *Soil Science and Plant Nutrition* 45, 4.
- Iwasaki, K., P. Maier, M. Fecht, and W.J. Horst, 2002a. Leaf apoplastic silicon enhances manganese tolerance of cowpea (*Vigna unguiculata*). 1. *Plant Physiol.*, 159: 167-173
- Iwasaki, K., P. Maier, M. Fecht, and W.J. Horst, 2002b. Effect of silicon supply on apoplastic manganese concentrations in leaves and their relation to manganese tolerance in cowpea (*Vigna unguiculata* L. Walp.). *Plant Soil*, 238: 281-288
- Kabata-Pendias, A., 2001. *Trace Elements in Soils and Plants*, Third Edition. Taylor & Francis, Dec 12, 2010 - Technology & Engineering - 432 pages
- Kanto, T., 2002. Research of silicate for improvement of plant defense against pathogens in Japan. *Abstract of Second Silicon in Agriculture Conference*, 22-26
- Kanto, T., A. Miyoshi, T. Ogawa, K. Maekawa, and M. Aino, 2006. Suppressive effect of liquid potassium silicate on powdery mildew of strawberry in soil, *J. Gen. Plant Pathol.*, 72:137-142.
- Kauss, H., K. Seehaus, R. Franke, S. Gilbert, R.A. Dietrich, and N. Kroger, 2003. Silica deposition by a strongly cationic proline-rich protein from systemically resistant cucumber plants. *Plant* 1, 33: 87-95.
- Kaya, C., L. Tuna, and D. Higgs, 2006. Effect of silicon on plant growth and mineral nutrition of maize grown under water-stress conditions. *J. Plant Nutr.*, 29: 1469-1480.
- Li Q, F., C.C. Ma, and Q.L. Shang, 2007. Effects of silicon on photosynthesis and antioxidative enzymes of maize under drought stress. *Chinese Journal of Applied Ecology*, 18: 531-536.
- Liang, Y., 1999. Effects of silicon on enzyme activity and sodium, potassium and calcium concentration in barley under salt stress. *Plant and Soil*, 209: 217-224.
- Liang, Y., Q. Chen, W. Zhang, and R. Ding, 2002. Exogenous silicon increases antioxidant enzyme activities and reduces lipid peroxidation in roots of salt-stressed barley (*Hordeum vulgare* L.). *Abstract of Second Silicon in Agriculture Conference*, 140-151
- Liang, Y., H. Hua, Y.G. Zhu, J. Zhang, C.H. Cheng, and V. Romheld, 2006a. Importance of plant species and external silicon concentration to active silicon uptake and transport. *New Phytol.*, 172: 63-72.
- Liang, Y., Q. Shen, Z. Shen, and T. Ma, 1996. Effects of silicon on salinity tolerance of two barley cultivars. 1. *Plant Nutr.*, 19: 173-183
- Liang, Y., J. Si, and V. Romheld, 2005a. Silicon uptake and transport is an active process in *Cucumis sativus*. *New Phytol.*, 167: 797-804.
- Liang, Y., W. Sun, Y.G. Zhu, and P. Christie, 2007. Mechanisms of silicon-mediated alleviation of abiotic stresses in higher plants: a review. *Environmental Pollution*, 147:422-428.
- Liang, Y.C., Q. Chen, Q. Liu, W. Zhang, and R. Ding, 2003. Exogenous silicon (Si) increases antioxidant enzyme activity and reduces lipid per-oxidation in roots of salt stressed. *Plant and Soil*, 255: 85-91.
- Liang, Y.C., W.Q. Zhang, J. Chen, and R. Ding, 2005. Effect of silicon on H⁺-ATPase and H⁺-PPase activity, fatty acid composition and fluidity of tonoplast vesicles from roots of salt-stressed barley (*Hordeum vulgare* L.). *Environmental and Experimental Botany*, 53: 29-37.
- Lux, A., M. Luxova, J. Abe, E. Tanimoto, T. Hattori, and S. Inanaga, 2003. The dynamics of silicon deposition in the sorghum root endodermis. *New Phytol.*, 158:437-441.
- Ma, J.F. and E. Takahashi, 1990a. Effect of silicon on growth and phosphorus uptake of rice. *Plant & Soil*, 126:115-119.
- Ma, J.F. and E. Takahashi, 1990b. The effect of silicic acid on rice in a P-deficient soil. *Plant & Soil*, 126:115-119.

- Ma, J.F. and E. Takahashi, 1991. Effect of silicate on phosphate availability of rice in a P-deficient soil. *Plant Soil*, 133:151-155.
- Ma, J.F. and E. Takahashi, 2002. *Soil, Fertilizer, and Plant Silicon Research in Japan*, Elsevier Science, Amsterdam.
- Ma, J.F. and N. Yamaji, 2006. Silicon uptake and accumulation in lower plants. *Trends. Plant Science*, 11(8): 392-397.
- Ma, J.F. and N. Yamaji, 2008. Functions and transport of silicon in plants. *Cellular and Molecular Life Sciences*. 65: 3049-3057. Maas EV, Hoffman GH, 1977. Crop salt tolerance current assessment. *Irrigation Derange J.*, 103: 115-134.
- Ma, J.F., 2004. Role of silicon in enhancing the resistance of plants to biotic and abiotic stresses. *Soil Sci Plant Nutr.*, 50: 11-18.
- Ma, J.F., Y. Miyake, and E. Takahashi, 2001a. Silicon as a beneficial element for crop plants. 111 *Silicon in Agriculture*, Ed. LE Datnoff, GH Snyder, and GH Korndorfer, p. 17-39, Elsevier Science, Amsterdam.
- Ma, J.F., M. Sasaki, and H. Matsumoto, 1997. Al-induced inhibition of root elongation in corn *Zea mays* L. is overcome by Si addition. *Plant Soil*, 188: 171-176.
- Ma, J.F., K. Tamai, N. Yamaji, N. Mitani, S. Konishi, M. Katsuhara, M. Ishiguro, Y. Murata, and M. Yano, 2006. A silicon transporter in rice. *Nature*, 440: 688-691
- Ma, L.Q., K.M. Komar, C. Tu, W. Zhang, Y. Cai, and E.D. Kennelley, 2001b. A fern that hyperaccumulates arsenic. *Nature (London)*, 409: 579-579.
- Maekawa, K., K. Ogawa, K. Watanabe, T. Kanto, M. Aino, and Y. Iwamoto, 2002. Silicon dependent promotion of superoxide generation following the inoculating of *Magnaporthe grisea* into rice leaves (in Japanese with English Summary). *Japan Soil Sci. Plant Nutr.*, 73: 509-514.
- Maekawa, K., K. Watanabe, M. Aino, and Y. Iwamoto, 2001. Suppression of rice seedling blast with some silicic acid materials in nursery box. *Ip. 1. Soil Sci. Sci. Plant Nutr.*, 72: 56-62.
- Mason, M.G., W.M. Porter, and W.J. Cox, 1994. Effect of an acidifying nitrogen fertilizer and lime on soil pH and wheat yields. 1. Soil Effect, *Australian Journal of Experimental Agriculture*, 34: 237-46.
- Matichenkov, V.V. and E.A. Bocharnikova, 2001. The relationship between silicon and soil physical and chemical properties. In: *Silicon in Agriculture*. Datnoff LE, Snyder DH, Korndorfer GH (Eds.). Elsevier Science B.V., Amsterdam, Netherlands
- Matichenkov, V.V. and E.A. Bocharnikova, 2010. Technology for natural water protection against pollution from cultivated areas", 2020 15th Annual Australian Agronomy Conference.
- Matoh, T., P. Kairusmee, and E. Takahashi, 1986. Salt-induced damage to rice plants and alleviation effect of silicate. *J. Soil Sci. Plant Nutr.*, 32: 295-304.
- McCord, J.M., 2000. The evolution of free radicals and oxidative stress. *Am. J. Med.* 108: 652- 659.
- Menzies, J., P. Bowen, and D. Ehret, 1992. Foliar application of potassium silicate reduces severity of powdery mildew on cucumber, muskmelon, and zucchini squash. 1. *Am. Soc. Harth'. Sci.*, 117: 902-905
- Mitani, N. and J.F. Ma, 2005. Uptake system of silicon in different plant species. *J. Exp. Bot.*, 56: 1255-1261.
- Miyake, Y. and E. Takahashi, 1983. Effect of silicon on the growth of solution-cultured cucumber plant. *Soil Sci. Plant Nutr.*, 29:71-83.
- Moussa, H.R., 2006. Influence of exogenous application of silicon on physiological response of salt-stressed maize (*Zea mays* L.). *International Journal of Agriculture and Biology*, 8: 293-297.
- Nagaoka, K., 1998. Study on interaction between P and Si in rice plants. Graduation Thesis, Kinki University.
- Neumann, D. and U. Zur Nieden, 2001. Silicon and heavy metal tolerance of higher plants. *Phytochemistry*, 56: 685-692.
- Ohyama, N., 1985. Effect of improvement in fertilization on the alleviation of cool-summer damage to rice. *Agriculture and Horticulture*, 11: 1385-1389.
- Oliveira, L.A., 2009. Silicon in bean and rice plants: absorption, transport, redistribution, and tolerance to cadmium [PhD. Thesis] Piracicaba, Escola Superior de Agricultura Luiz Queiroz, 1-157.

- Parveen, A. and A. Ashraf, 2010. Role of Silicon in Mitigating the Adverse Effects of Salt Stress on Growth and Photosynthetic Attributes of Two Maize (*Zea mays* L.) Cultivars Grown Hydroponically. *Pak. J. Bot.*, 42(3): 1675-1684.
- Provance-Bowley, M., J.R. Heckman, and E.F. Durner, 2010. Calcium Silicate Suppresses Powdery Mildew and Increases Yield of Field Grown Wheat. *Soil Science Society America Journal*, 74:1652-1661.
- Rafi, M.M. and E. Epstein, 1999. Silicon absorption by wheat. *Plant Soil*. 211: 223-230.
- Ranganathan, S., V. Suvarchala, Y. Rajesh, M.S. Prasad, A. Padmakumari, and S. Voleti, 2006. Effects of silicon sources on its deposition, chlorophyll content and disease and pest resistance in rice. *Biol. Plant*, 50: 713-716.
- Rezanka, T. and K. Sigler, 2008. Biologically active compounds of semi-metals. *Phytochem.*, 69: 585-606.
- Rezende, D.C., F.A. Rodrigues, V. Carré, D.A. Schurt, I.K. Kawamura, and G.H. Korndorfer, 2009. Effect of root and foliar application of silicon on brown spot development in rice, *Australasian Plant pathology*, 38: 67-73.
- Rodrigues, F.A., F.X.R. Vale, G.H. Korndorfer, A.S. Prabhu, L.E. Datnoff, A.M.A. Oliveira, and L. Zambolim, 2005. Influence of silicon on sheath blight of rice in Brazil. *Crop Prot.*, 22: 23-29.
- Rodrigues, F.A., H.S.S. Duarte and G.P. Domiciano, 2009. Foliar application of potassium silicate reduces the intensity of soybean rust. *Aust Plant Pathol.*, 38:366-372.
- Romero-Aranda, M.R., O. Jurado, and J. Cuartero, 2006. Silicon alleviates the deleterious salt effect on tomato plant growth by improving plant water status. *Journal of Plant Physiology*, 163: 47-855.
- Saeed, R., M. Babalar, and S. Kalantari, 2009. Silicon alleviates salt stress, decreases malondialdehyde content and affects petal colour of salt-stressed cut rose (*Rosa xhybrida* L.) "Hot Lady", *African Journal of Biotechnology*, 8(8): 1502-1508.
- Sara, T. and H. Raheem, 2011. Study of silicon on effects on Antioxidant Enzyme Activities and Osmotic Adjustment of Wheat under Drought Stress, *Czech J.Genet. Plant Breed*, 47(1): 17-27.
- Sauer, D., L. Saccone, D.J. Conley, L. Herrmann, and M. Sommer, 2006. Review of methodologies for extracting plant available and amorphous Si from soils and aquatic sediments. *Biogeochemistry*, 80:89-108.
- Savant, N.K., G.H. Korndorfer, L.E. Datnoff, and G.H. Snyder, 1999. Silicon nutrition and sugarcane production: a review. *Journal of Plant Nutrition*, 22: 1853-1903.
- Savant, N.K., G.H. Snyder, and L.E. Datnoff, 1997.: Silicon management and sustainable rice production. *Adj'. Agron.*, 58 :151-199.
- Savvas, D., D. Giotis, E. Chatzieustraticu, M. Bekea, and G. Patakioutas, 2009. Silicon supply in soil-less cultivations of zucchini alleviates stress induced by salinity and powdery mildew infections. *Environ. Exp. Bot.*, 65: 11-17.
- Seebold, K.W., T.A. Kucharek, L.E. Datnoff, F.J. Correa-Victoria, and M.A. Marchetti, 2001.: The influence of silicon on components of resistance to blast in susceptible, partially resistant, and resistant cultivars of rice. *Phytopathology*, 91: 63-69.
- Sommer, M., D. Kaczorek, Y. Kuzyokov, and J. Breuer, 2006. Silicon pools and fluxes in soils and landscapes – a review. *J. Plant Nutr. Soil Sci.*, 169: 310-329.
- Tahir, M.A., T. Rahmatullah, M. Azia, S. Ashraf, Kanwal, and M.A. Maqsood, 2006. Beneficial effects of silicon in wheat (*Triticum aestivum* L.) Under Salinity Stress. *Pakistan Journal of Botany*, 38(5): 1715-1722.
- Tuna, A.L., C. Kaya, C.D. Higgs, B. Murillo-Amador, S. Aydemir, and A.R. Girgin, 2008. Silicon improves salinity tolerance in wheat plants. *Environmental and Experimental Botany*, 62: 10-16.
- Vaculik, M., T. Landberg, M. Greger, M. Luxova, M. Stolarikova, and A. Lux, 2009. Silicon modifies root anatomy and uptake and subcellular distribution of cadmium in young maize plants. *Ann. Bot.* 110, 433-443.
- Wang, X., Z.H. Wei, D. Liu, and G.U. Zhao, 2011. Effect of NaCl and silicon on activities of antioxidative enzymes in roots, shoots and leaves of alfalfa, *African Journal of Biotechnology*, 10(4): 545-549.

- Wang, X.D., O.U. Yang, Z. Ren Fan, S. Gao, F. Chen, and L. Tang, 2010. Effects of exogenous silicon on seed germination and antioxidant enzyme activities of *Momordica charantia* under salt stress, *Journal of Animal & Plant Sciences*, 6(3):700-708.
- Wang, Y., A. Stass, and W. Horst, 2004. Apoplastic binding of aluminium is involved in silicon-induced amelioration of aluminium toxicity in maize. *Plant Physiol.*, 136: 3762-3770.
- Yeo, A.R., S.A. Flowers, G. Rao, K. Welfare, N. Senanayake, and T.J. Flowers, 1999. Silicon reduces sodium uptake in rice (*Oryza sativa* L.) in saline conditions and this is accounted for by a reduction in the transpirational bypass flow. *Plant Cell Environ.*, 22: 559-565.
- Yongchao L., J.W.C. Wong, and W. Long, 2005. Silicon-mediated enhancement of cadmium tolerance in maize (*Zea mays* L.) grown in cadmium contaminated soil, *Chemosphere*, 58(4): 476-483.
- Yong, Y., S. Tai, and X. Bao, 2007. Effect of silicon on photosynthesis and antioxidative enzymes of maize under drought stress. *Plant Science*, 18:531-536.
- Yoshida S., Y. Ohnishi and K. Kitagishi, 1962. Chemical Forms, Mobility and Deposition of Silicon in Rice Plant. *Soil Science and Plant Nutrition*, Vol. 8, No.3, 15-21
- Zeyen, R.J., 2002. Silicon in plant cell defenses against cereal powdery mildew disease. Abstract of Second Silicon in Agriculture Conference, 15-21.
- Zhu, Z.J., G.Q. Wei, T. Li, Q.Q. Qian, and J.Q. Yu, 2004. Silicon alleviates salt stress and increases antioxidant enzymes activity in leaves of salt-stressed cucumber (*Curcumas sativa* L.). *Plant Science*, 167: 527-533.
- Zuccarini, P., 2008. Effects of silicon on photosynthesis, water relations and nutrient uptake of *Phaseolus vulgaris* under NaCl stress. *Biol. Plant*, 52: 157-160.