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Silicon nutrition in rice: A review

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Abstract
Silicon (Si) is considered as a beneficial element for crop growth, especially for crops under Poaceae family. Rice is a typical silicon accumulating plant and it benefits from silicon nutrition. Si is absorbed in the form of monosilicic acid and its transportation is governed by three genes *i.e.* LSi1, LSi2 and LSi6. Silicon is deposited beneath the cuticle as cuticle-silicon double layer in the form of silicic acid. Highly weathered soils are low in available silicon mainly due to leaching loss. Its supply is essential for healthy growth and economic yield of the rice crop. Silicon interacts favourably with other applied nutrients and improves their agronomic performance and efficiency in terms of yield response. Also it improves the tolerance of rice plants to abiotic and biotic stresses. Hence, silicon management is essential for increasing and sustaining rice productivity.

Keywords: silicon, rice, biotic stress, abiotic stress, yield, productivity

Introduction
Silicon (Si) is the second most abundant element in the earth's crust. It is not considered as an essential element, but is a beneficial element for crop growth, especially for Poaceae crops. Si concentration of plant shoots varies greatly among plant species, ranging from 0.1 to 10% Si on a dry weight basis. Silica strengthens the plant, protects the plant against pests and diseases, increases crop production and quality, stimulates active immune systems of plants, increases plant nutrition, increase plant salt resistance and neutralizes heavy metal toxicity in acid soils. Si fertilizer has a double effect on the soil–plant system. First, improved plant-silicon nutrition strengthens plant-protective properties against insect pests incidence, and unfavorable climatic conditions. Second, Si optimizes soil fertility through improved water, physico-chemical soil properties and maintenance of nutrients in plant-available forms.

Silicon in soils
In the soil solution, Si is present as Monosilicic acid and Polysilicic acid as well as complexes with organic and inorganic compounds such as aluminium oxides and hydroxides. While it is the PAS (plant available silicon) that is taken up by the plants and has a direct influence on crop growth. The solubility of Si in the soil is affected by a number of dynamic processes occurring in the soil including the particle size of the silicon fertilizer, the soil acidity (pH), organic complexes, presence of aluminium (Al), iron (Fe) and phosphate ions, dissolution reactions and soil moisture. Si improves physical, chemical and biological properties of soil.

Role of Silicon in Rice
Rice is a high silicon accumulating plant and the plant is benefited from Si nutrition. Rice crop can uptake Si in the range of 230-470 kg ha^{-1}. Si is a beneficial element for plant growth and is agronomically essential for improving and sustaining rice productivity. Besides rice yield increase, Si has many fold advantages of increasing nutrient availability (N, P, K, Ca, Mg, S, Zn), decreases nutrient toxicity (Fe, P, Al) and minimizing biotic and abiotic stress in plants. Hence, the application of Si to soil or plant is practically useful in laterite derived paddy soils, not only to increase yield but also to alleviate the Fe toxicity problems. Si increases the mechanical strength of the culm, thus reducing crop lodging (Savant *et al*., 1997) [10]. In soil, Si is not a much mobile element to plants. Therefore, a continued supply of this element would be required particularly for the healthy and productive development of plant during all growth stages.

Beneficial effects of silicon in rice
Decreases Lodging
Si in rice shoots enhanced the thickness of the culm wall and the size of the vascular bundles that result in reduction in lodging.

Thickening of the cell walls of the sclerenchyma tissue in the culm and/or shortening and thickening of internodes or increase in Si content of the lower internodes provides mechanical strength to enable the plant to resist lodging (Savant *et al.,* 1997) [10].

Increases crop growth and yield

Si promotes growth, strengthens culms, and favors early panicle formation, increases the number of spikelets per panicle and percentage of matured rice grains and helps to maintain erect leaves which are important for higher rate of photosynthesis. Si plays an important role in hull formation in rice, and, in turn, seems to influence grain quality (Bhaskaran, 2014) [2]. Ahmad *et al*., (2013) [1] reported that application of Si fertilizers enhanced the growth parameters, increased yield, yield attributes and quality of rice crop.

Improves availability of applied nutrients

Nitrogen

Fertilizing with nitrogen tends to make rice leaves droopy, whereas silicon keeps them erect. By adopting proper silicon management, erect leaves can easily account for a 10 % increase in the photosynthesis by crop (Yoshida, 1981) [14]. Therefore, the maintenance of erect leaves by proper silicon fertilization for higher photosynthetic efficiency becomes more important when rice is grown with liberal applications of nitrogenous fertilizers in lowland rice fields having highly weathered tropical soils, (Yoshida *et al.,* 1969).

Phosphorus

The application of calcium silicate to highly weathered soils enhanced upland rice response to applied phosphate. Ma *et al.* (1991) [6] reported that overall beneficial effect of Si may be attributed to a higher P: Mn ratio in the shoot due to the decreased manganese and iron uptake, and thus indirectly improved phosphorus utilization within the rice plants.

Potassium

Silicification of cell walls seems to be linked with potassium nutrition. According to Nogushi and Sugawara (1966) [9], potassium deficiency reduces the accumulation of silicon in the epidermal cells of the leaf blades, thus increasing the susceptibility of the plant to rice blast. Therefore, silicon management integrated with potassium may be more important for sustaining rice yields in upland areas than in lowland areas.

Decrease metal toxicities of Fe and Al

Iron toxicity

In humid tropical and subtropical area, iron toxicity is one of the major physiological problems in rice growth. Silicon increases the oxidizing power of roots, which converts ferrous iron into ferric iron, thereby preventing a large uptake of iron and limiting its toxicity (Ma *et al.,* 2002) [7]. Silicon will regulate Fe uptake from acidic soils through the release of OH^- by roots (Wallace, 1993) [12].

Aluminium toxicity

Si application alleviates aluminium toxicity by creating inert aluminosilicates, stimulating phenolic exudation by roots or by sequestration in phytoliths (Guntzer *et al.,* 2012) [4].

Increases abiotic stress tolerance

Alleviate salt stress

Excessive salinity in cropping soil is a worldwide problem due mainly to rising water tables. Si may alleviate salt stress in higher plants either by improved photosynthetic activity, enhanced K/Na selectivity ratio, increased enzyme activity, and increased concentration of soluble substances in the xylem (Sahebi *et al.,* 2015) [11]. Si fertilizer application can also alleviate the adverse effects of salt stress on plants by increasing cell membrane integrity and stability through its ability to stimulate the plant's antioxidant system (Marafon *et al.*, 2013) [8].

Alleviate Drought stress

The deposition of Si in the culms, leaves, and hulls also decrease transpiration from the cuticle thus increasing resistance to drought stress. Drought stressed plants that were treated with Si fertilizer retained greater stomatal conductance, relative water content, and water potential than untreated plants. Si increased resistance to strong winds generated by typhoons, related to the increased rigidity of the shoots through silicification (Guntzer *et al.,* 2012) [4].

Increases biotic stress tolerance

Pest tolerance

Si increases the resistance of plants to many insects in rice like stem borer, leaf folder, brown plant hopper, etc. The deposition of silica on epidermal layers offers a physical barrier to insects by preventing the physical penetration by insects. Sucking and leaf eating caterpillars have a low preference for the silicified tissues than low silica containing succulent parts. Soluble silicic acid (as low as 0.01 mg/ml) in the sap of the rice plant acts as an inhibitor of the sucking activity of the brown plant hopper (Yoshihara *et al.,* 1979) [13]. Si increases the resistans=ce of plants to many insects in rice like stem borer, leaf folder, brown plant hopper, ets,

Disease tolerance

Si has been found to decrease several diseases in rice like sheath blight, brown spot, grain discoloration, etc. Si might form complexes with the organic compounds of cell walls of epidermal cells, thus increasing their resistance to the enzymes expounded by the pathogen. The antifungal compounds like momilactones were found to accumulate in Si treated rice plants and these acted against blast pathogen.

Silicon Deficiency

Si deficiency makes the rice plants susceptible to pests and diseases. Si deficiency is common in areas with poor soil fertility, and in highly weathered soils. Its deficiency also seen in organic soils with less Si reserves and also occurs in highly weathered soils. The critical level of Si in soil is 40 mg kg^{-1} and the critical level of Si in rice (leaf and straw) is 5%. Si deficiency leads to soft and droopy leaves, reduced photosynthetic activity, reduced grain yields, increased insect pest incidence, reduced number of panicles and filled spikelets per panicle (IRRI, 2016) [15].

Silicon Fertilizers

Calcium silicate, fine silica and sodium silicate, are mostly used silicon fertilizers. Potassium silicate, though expensive, is highly soluble and can be used in hydroponic culture and also applied through foliage. Rice husk, rice husk ash and straw are organic sources of Si. Rice straw hauled away from rice fields are used for various purposes, such as animal feed, biogas production, or mushroom cultivation, may maintain its nutrient value as a source of Si; thus the end products of these uses should be recycled. Si content in rice straw and rice husk ranges from 4-20% and 9-26% respectively. Silicon solubilising bacteria (SSB) is a bio-fertilizer which contains spores of the *Bacillus mucilaginosus*. It is used as an effective soil inoculant. It solubilizes silica and provides the plant with strength to tolerate biotic and abiotic stresses and improves its resistance to pest and disease attack. With the changes occurring in the global environment, the role of Silica will become more and more important for better and sustainable production of the crop. (Chinnasami *et al.*, 1978) [3].

Conclusion

Rice is a silicon accumulator, so adequate attention should be given to silicon nutrition. Highly weathered soils of the tropics and subtropics are low in available Silicon. Silicon management agenda includes silicon fertilization and recycling of silicon in rice crop residues. Silicon has manifold advantages. It is essential for healthy growth and productive development of the rice crop. Silicon increases the efficiency of applied nutrients, increases crop yield, increases resistance against lodging, biotic stresses, and abiotic stresses. Silicon management is essential for sustaining rice productivity in temperate, tropical, and subtropical soils.

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