

SILICON
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Silicon, (Si) an element abundantly available on earth's crust is second only to oxygen (Ehrlich, 1981). It is the eight most abundant elements in universe. Its content in soils vary greatly and ranges from <1 to 45% by dry weight (Sommer *et al.*2006.). Silica (SiO₂) content of soils varies from less than 10% to almost 100%. Silicon dioxide (SiO₂/ silica) comprises 50-70% of the soil mass. As a consequence all plants rooting in soil contain some Si in their tissues. Silicon is considered a plant nutrient "anomaly" because it is not essential for plant growth and development. However soluble Si has enhanced the growth development and yield of many plants. The content of silica in plants is equivalent to or more than the major nutrients N, P, K supplied through fertilizers. Plants may not be that much foolish to accumulate an element without any specific role in nutrition or physiology. Perhaps with the available knowledge man is not able to pin point its exact role, requirements etc., even though he could observe its beneficial effects on crop growth, pest and disease suppression and yield.

Although it is 146 times more abundant than carbon on earth's crust it rarely appears in biological materials. It shares many properties of carbon which form the backbone of most organic molecules but seldom forms an integral component of any biomolecules as the Si-Si bonds are considerably weaker than C-C bonds and many Si-H bonds are relatively unstable and react readily with oxygen. The larger size of silicon atom compared to carbon also render it unsuitable as a building block despite the fact that it can also form bonds with four other atoms creating a three dimensional network similar to carbon. Yet a few organisms absorb and accumulate silicon. The most notable ones are diatoms, chrysophytes, silicoflagellates, some xanthophytes, radiolarians, plants, insects and vertebrates (Heinen, 1962).

Among the plants silica concentration are found to be higher in monocotyledons than in dicotyledons and its level increased from legumes < fruit crops < vegetables < grasses < grain crops (Thiagalingam et al., 1977). Grasses accumulates 2 to 20 percent foliar dry weight as hydrated polymer or silica gel. Rice accumulates 4-20 percent silicon in straw and almost every part of rice contains this element which is not at all added exogenously as fertilizer as done with nitrogen, phosphorus and potassium the trinity of nutrients.

Man ignored exogenous application of this element with the belief, that the soil itself can sustain its supply. Unfortunately the silica that occurs in soil is in an unavailable polymerized form and for its absorption by plants it has to be depolymerized and rendered soluble by means of biological or chemical reactions in soil. Plants absorb Si exclusively as mono silicic acid (*ortho*- silicic acid) by the diffusion and also by the influence of transpiration induced root absorption (mass flow). The soil silicates are the source of silica. Applications of metal silicates to rice in Japan and to sugar cane in Brazil have been extensively adapted. By looking at the amazing quantity of silicon removed from world arable soils which are estimated to the tune of 210-224 million tons annually (Table.1) one cannot remain silent without making any effort to render it available from *in situ* or applied through silicon fertilizer.

Table.1 Removal of Silicon and major nutrients from soil

Crop	Plant available Si* (kg Si/ ha)	Major nutrients(kg/ha) @		
		N	P	K
Rice	230-470	34	22	67
Sugarcane	500-700	90	17	202
Cereals	100-300	-	-	-
Potatoes	50-70	-	-	-

* Si removed globally from arable soils 210-224 million tons of silicon (FAO estimate); conversion factor for Si to SiO₂ - 2.1 and for Si to SiO₃ - 2.6

@ Nutrients removed as per the ICAR handbook of Agriculture,1997.

SILICON IN PLANTS

Silicon does not form a constituent of any cellular components but primarily deposited on the walls of epidermis and vascular tissues conferring strength, rigidity and resistance to pests and diseases. Although no biochemical role has been positively identified in the development of plants, it has been proposed that enzyme silicon complexes formed are found to protect or regulate photosynthesis. Silicon was found to suppress the activity of certain enzymes and suppression of invertase particularly resulted in greater sucrose production in sugarcane and the reduction in phosphatase provided a greater supply of essential high energy precursors needed for optimum growth. It was also suggested that silica in plants filter harmful ultraviolet radiation reaching leaf surface with leaf cells acting as 'windows' transmitting the light energy to photosynthetic mesophyll and cortical tissues beneath epidermis, than that would occur if silica were absent (Tisdale et al., 1985).

Silicon supply increased the photo assimilation of carbon and also promoted the assimilated carbon to the panicle in rice (Takahashi and Miyake., 1982). Silica also plays a role in phosphorus nutrition and there is an interrelationship with phosphorus (Silva, 1971). Considering all these favorable effects, earlier workers investigated the role of exogenous application of siliceous materials to rice and sugarcane and the response varied with the soil types (Padmaja and Verghese., 1972; Elawad *et al.*, 1982).

Plants take up different quantities of silica according to their species (Russell., 1973). Gallo et al (1974) observed that in rice, oat, rye and wheat, seed coat accumulate the most silica and grain the least. They also observed that leaves and stems of maize and sorghum and the leaves of sugarcane and bamboo had highest leaves than other plant parts.

Ishizuka (1971) reported that silica content of straw ranged from 4-20 percent with an average of 11 percent. Yoshida (1975) reported that rice plant absorbs silica in the form of ortho-silicic acid (H_4SiO_4 or $Si(OH)_4$) along with water from the growing medium and the water is lost through transpiration. Because of continued absorption and transpiration the silica concentration increases and at higher levels *ortho*-silicic acid polymerizes into silica gel ($SiO_2.nH_2O$) through a non-enzymatic reaction. In rice leaf blades 90% or more of silicic acid exists as silica gel (polysilicic acid) and 0.5% as low molecular weight

silicic acids (largely composed of ortho-silicic acid). It was found that silica content of rice plant increased with the age of the crop from transplanting to harvest (Nayar et al., 1982a). The silica content of rice straw at harvest ranged from 4.8 to 13.5 % in dry season and from 4.3 to 10.3 % in wet season (Nayar et al., 1982b).

SILICA HAS A SUPRISINGLY LARGE NUMBER OF FUNCTIONS IN PLANTS

- *The strengthening of epidermal cells in leaves and stems. Confers non lodging*
- *It is important constituent of DNA and RNA, i.e. Silica deficiency decreases the synthesis of proteins and chlorophyll.*
- **Decreasing toxicity:** *Silica regulates plants uptake of iron, manganese and aluminium. The infamous toxicity of these elements in acid soil can be counteracted with soluble silica.*
- **Water balance:** *Low silica content increases the transpiration rate (water loss through leaves) creating poor water-use efficiency.*
- **Improved plant growth and yield.:** *Published research catalogues increased root growth in grasses, spectacular yield increases for cucumbers (1500%), 30% to 50% in cane, and substantial increased yield in beets.*
- **Increased rates of photosynthesis** *partially due to stronger stems producing more erect leaves, which capture more sunlight.*
- **Improved reproduction:** *Studies have found enhanced pollination in tomatoes and better pollen fertility in cucurbits.*
- **Increases pest and disease resistance.**
- **Increases the grain yield and reduces chaffiness.**

SILICA SOLUBILIZING BACTERIA

Soil contains a variety of micro organisms but a few are capable of solubilizing silicates. A virulent Silicate Solubilizing Bacterium (**Si SOL B**) was isolated and tested on a variety of crops in different soils. Inoculation of SSB was found to release soluble silica in soils and also from silicate minerals. This bacterium is used as a biofertilizer and found to enhance the growth, suppress pest and diseases and increase the yield (Muralikannan 1996, Muralikannan and Anthoni Raj, 1998). Soil incubation studies revealed that inoculation of Si Sol B to sterile and unsterile soil solubilized silica in water and enhanced the available silica in soils (Table2 & 3).

Table.2 Available silica(mg/l) in water from different soils inoculated with Si Sol B

Sl.no.	Treatments	Red soil		Clay soil		Sand	
		0	4	0	4	0	4
1	sterile soil	203	210	119	215	173	176
2	sterile soil + SSB	302	321	278	326	258	330
3	unsterile soil	287	291	152	225	230	258
4	unsterile soil +SSB	327	363	284	328	248	306

0: Initial ; 4: after 4 weeks; (Muralikannan, 1996)

Table.3 Release of available silica (ppm) in different soils inoculated with Si Sol B

Sl.no.	Treatments	Red Soil		Clay Soil		Sand	
		0	4	0	4	0	4
1	sterile soil	105	106	73	75	430	430
2	sterile soil + SSB	105	135	73	105	430	494
3	unsterile soil	105	110	73	105	430	453
4	unsterile soil +SSB	105	145	73	129	430	496

0: Initial; 4: after weeks; (Muralikannan, 1996)

Field trials conducted with SSB showed that this bacterium enhanced the growth, chlorophyll content, thousand grain weight, filled grains, biomass and yield in rice(Table 4). The inoculation of SSB with organosiliceous material like rice straw, husk and husk ash (black char/ash) augmented the grain in rice. The use of SSB as a component of inoculum to hasten the decomposition of rice straw left after harvesting by combined harvester was also demonstrated.

The ability of the isolates to solubilize silicate minerals was demonstrated by plant assay liquid culture. The *in vitro* studies of certain isolates of SSB showed that some of these cultures were acid producers, some made the medium alkaline and a few others produced polysaccharides. Organic acids like 2 keto-gluconic acid, alkalis and polysaccharides were implicated in dissolution of silicates. Ciobanu (1961) found that 'Azotobacterin' and 'Silicabacterin' when applied simultaneously increased the yields of raw cotton by 50-34%. The beneficial effects of Si Sol B on lucerne and maize were also shown by Vintikova (1964).

The solubilized silicon has a larger interaction with other nutrients particularly phosphorus. The Si in solution renders phosphorus available to plants reversing its fixation as Si itself competes for phosphorus fixation sites in soil. It is to be noted here to some degree Si acts as a substitute for P in plant system. In soil system also application of silicates released more of phosphorus (Chinnasami and Chandrasekaran, 1978).

Table.5 Influence of Si Sol B inoculation on the yield parameters in Rice

Treatments	No. of grains Per panicle	1000 grain Weight(g)	Fully filled grains (%)	Biomass (t/ha)	Grain yield (kg/ha)
Control	54	22.14	76.7	10.24	3400
SSB	62	22.84	78.1	11.27	3800

RESPONSE TO SILICON APPLICATION

The response of crops to silicon application particularly rice and sugarcane have been extensively investigated both in solution and soil culture by several investigations (Ota et al., 1957; Padmaja and Verghese., 1972, Dong et al., 1981).

Silicon tends to maintain erectness of rice leaves and clumps there by increasing the photosynthesis because of better light interception. The oxidizing power of rice roots and accompanying tolerance to high levels of iron and manganese are found to be depending on silicon nutrition. Heavy application of nitrogen render rice plants more susceptible to fungal attack at low silicon concentration in straw. Supplemental silicon has been provided to be beneficial when silica concentration falls below one percent in straw and to avoid this problem silicon bearing materials have been recommended for field application (Tisdale et al., 1985).

Application of silica to rice was found to increase the grain yield under both upland and water logged conditions (Datta and shinde, 1985). The application of silicate not only augmented its absorption by rice plant but had a significant interrelationship with the other nutrients as well. With adequate silicon the uptake of nitrogen was increased (Okomota, 1969; Sadanandan and Verghese, 1969). However, decreased in nitrogen content was also reported in

rice in response to silicon addition to solution culture (Islam and Saha, 1969; Horiguchi, 1988).

Greenhouse and field experiments showed sustainable benefits of Si fertilization for rice, barley, wheat, corn, sugarcane, cucumber, tomato, citrus and other crops (Epstein, 1999; Metchinkov *et al.*, 1999).

SILICA NUTRITION REDUCES PEST INCIDENCE

The silicon in plants was found to alleviate many biotic and abiotic stresses, leading to application of silicates either directly to crops or incorporate it into the fertilizers applied. Use of ashes in home grown lab lab to control aphids is an age old practice followed in rural India. The deposition of silica on epidermal layers offers a physical barrier to insects. Sucking pests and leaf eating caterpillars have a low preference for the silicified tissues than low silica containing succulent parts. Both physical and or biochemical defence system operates.

Due to high silica content in silicon fertilized rice the penetration time of first instar larvae of yellow stem borer increased from 2.8 for 0.4 ppm Si to 21.2 for 47 ppm Si. When seedlings, in the nursery was fertilized with silicon through black-grey ash of burnt rice hulls the stem borer damage (dead heart) was reduced in the transplanted main field. The incidences of stem maggots, green leaf hopper, brown plant hopper and white backed plant hopper, leaf folder etc. were reduced due to silicon nutrition. Application of silicon to corn affected the biological development of the *Spodoptera*. In wheat and sorghum silicon negatively affected the preference and reduced reproduction rates of the green bug *Schizophis graminum* (Table.5)

Table.5 Pest suppressed by Si nutrition

Sl.no.	Pest	Scientific name	Reference
	Stem maggot	<i>Chlorops oryzae</i>	Sawant et al (1994)
Rice	Green leaf hopper	<i>Nephotettix bipunctatus</i>	Maxwell et al (1972)
	Brown plant hopper	<i>Nilaparvata lugens</i>	Sujatha et al (1987)
	White backed plant hopper	<i>Sogetella furcitera</i>	Salim and Saxena (1992)
	Leaf spider	<i>Tetranychus spp.</i>	Yoshida (1975)
		<i>Scizaphis graminum</i>	

Wheat	Green bug		Gomes <i>et al.</i> ,2005
Sorghum	Green bug	<i>Scizaphis graminum</i>	Carvalho <i>et al.</i> ,1999
Corn	Leaf aphid	<i>Rhopalosiphum maidis</i>	Goussain,2001
Sugarcane	Stalk borer	<i>Eldana saccharina</i>	Kvedaras <i>et al.</i> , 2005

White fly (*Bemisia tabaci*) is an important pest assuming greater portion now a days in several crops like cucumber, cotton, sugarcane etc. feeding and the excreted honey dew of this insect lead to the formation of sooty moulds which reduces photoreception mechanically and reduces yield. These insects also transmit viral diseases. Infestation by this aleyrodid pest can significantly inhibit plant growth leading to plant death (Rogerio *et al.*, 2005). Both soil and foliar application of silicon as calcium silicate increased the mortality by nymphs of white fly (Table.6)

Table.6 Mean number of eggs, 4th instar nymphs and survival rate (eggs to nymph) of *Bermisia tabaci* in cucumber plants treated with calcium silicate

Treatment	egg	Nymph	Survival%
Control	476.2±32.35	416.0±24.20	86.8±1.29
Soil CaSiO ₃ (3g/2kg of soil)	393.0 ±41.70	310 ±27.00	81.6± 2.36
Foliar CaSiO ₃ (1% solution 200ml/pot)	388.7 ±32.92	233.1 ±19.37	60.0± 2.72

(Rogerio *et al.*, 2005)

INDUCTION OF DISEASE RESISTANCE AND DISEASE SUPPRESSION

The mechanism for Si-induced resistance to diseases is due to (i) Si acting as a physical barrier and (ii) soluble Si acting as a modulator of host resistance to pathogen. Si is deposited beneath the cuticle to form a cuticle-Si double layer which mechanically impede penetration of fungi and thus disrupt the infection process. In rice-blast system increased resistance through Si application was associated with the density of silicified bulliform, long and short cells in leaf epidermis which acted as a barrier and decreased the number of blast lesion (Datnoff and Rodrigues, 2005). Silicon @ 1000kg, application of silicate reduced neckblast by 30.5% and brown spot by 15.0% over the control (Table.7).

Table.7 Suppression of neck blast in rice due to silicon application (1000kg Si/ha)

Si (kg/ha)	Neck blast incidence (%)	Yield (kg/ha)
0	72	2284
1000	44	3445

Si as calcium silicate
Datnoff and Rodrigues,2005

It was also postulated that Si might form complexes with the organic compounds of cell walls of epidermal cells, thus increasing their resistance to enzymes elaborated by the pathogen. The soluble Si can produce phenolics and phytoalexins in response to infection by pathogen. The antifungal compounds like momilactones were found to accumulate in Si amended rice plants. These acted against blast pathogen. In cucumbers Si enhanced the activity of chitinases, peroxidases and polyphenol oxidases when cucumber roots were colonized by *Pythium*.

Silicon nutrition suppressed the leaf and neck blast, brown spot, sheath blight, leaf scald, grain coloration, stem rot, bacterial leaf blight and root knot nematode infection in rice. Silicon nutrition was found to suppress ring spot in sugarcane, powdery mildews in cucumber, wheat, barely etc. rust in cowpea (Table.8).

Table.8 Diseases suppressed by Si nutrition

Sl.No.	Disease	Pathogen	Reference
Rice	Leaf and neck blast	<i>Pyricularia oryzae</i>	Winslow (1992)
	Brown spot	<i>Bipolaris oryzae</i>	Dantnoff <i>et al</i> (1992)
	Sheat blight	<i>Rhizoctonia solani</i>	Dantnoff <i>et al</i> (1992)
	Leaf scald	<i>Gerlachia oryzae</i>	Winslow (1992)
	Grain discoloration	<i>Bipolaris fusarium</i>	Winslow (1992)
	Stem rot	<i>Sclerotium oryzae</i>	Elawad and Green (1979)
Sugarcane	Sugar rust	<i>Puccinia melanocephala</i>	Dean and Todd, 1979
	Ring spot	<i>Leptosphaeria Sacchari</i> <i>Phyllosticta</i> sp. [anamorph]	Raid <i>et al.</i> , 1991
Banana	Panama wilt	<i>Fusarium,oxysporium,f.sp.cubense</i>	
Cucumber	Powdery mildew	<i>Sphaerotheca fuliginea,Pythium.</i>	Adatia and Besford,1986
Wheat	Powdery mildew	<i>Erysiphe graminis, Oidium monilioides</i>	
		<i>Uromyces phaeseoli typia</i> Arth.	

Cowpea	rust		
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ROLE OF SILICON IN ALLEVIATING ABIOTIC STRESS

Silicon nutrition also alleviate many abiotic stresses including physical stress like lodging, drought, radiation, high temperatures, freezing, UV and chemical stress like salt, metal toxicity, nutrient imbalance and many others (Epstein, 1994). The beneficial effects are attributed to Si deposition in cell walls of roots, leaves, culms and hulls. Si deposition in roots reduces the binding sites for metals resulting in decreased uptake and translocation of salts and toxic metals from roots to shoot. Si alleviated effects have been associated with an increase in antioxidant defense abilities (Table.9).

Table.9 Role of silicon in mitigation of / alleviating the abiotic stress in plants

Abiotic stress	Plant/crop	Reference
Physical stress: Lodging Drought Radiation High temperature Freezing UV etc	All crops	Marschner <i>et al.</i> , 1990
Chemical stress: Salinity Mn toxicity Al toxicity Fe toxicity	Rice Wheat Mesquite Bean Rice Leaf freckle in sugarcane	Natoh <i>et al.</i> , 1986 Ahmad <i>et al.</i> , 1992 Bradbury and Ahmad, 1990 Horst and Marschner, 1978 Horiguchi, 1988 Li <i>et al.</i> , 1989 Fox <i>et al.</i> , 1967

SILICON NUTRITION AND YIELD

Silicon nutrition enhanced plant growth and yield. Application of organic siliceous materials like straw, husk, husk ash enhanced root length, shoot length, plant height, total and productive tillers per hill, filled grains and 1000 grain weight in rice. The increase was found in dry matter and yield. Inoculation of silicate solubilizing bacteria with these materials recorded further enhancement. Application of potassium, magnesium and calcium silicate to rice increased the yield. On an average 10-30% increased yields were recorded through silicate amendments.

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