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Silicon: The Most Under-appreciated Element in Horticultural Crops

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ABSTRACT

The most debatable and studied element over decades contributing to the betterment of agricultural as well as horticultural crops is silicon (Si). Soilless cultures used in horticultural plant production are devoid of this under-appreciated element (Si). Supplementation of Si to such crops through sub-irrigation or foliar spray has improved plant architecture. Silicon has been responsible for enhancing growth of various plants by providing mechanical strength on accumulation. Silicon application has been shown to enhance plant metabolism and leaf chlorophyll content and mitigate nutrient imbalance and metal toxicity in plants. It reinforces the plants and makes them tolerant to environmental stresses such as salt, drought and frost and protects them against pathogens and insects. Hence, addition of Si to the nutrient solution of plants has been an added advantage to the horticultural industry. The purpose of this review is to summarize the reports on effects of Si on horticultural crops which will further help to explore these plants to some extent.

Key words: Abiotic stress, drought, growing medium, horticultural crops, hydroponics, metal, salt, silicon

INTRODUCTION

The potentiality of silicon (Si) as an essential element has been questioned despite of decades of ongoing research on plants. Its beneficial effects on growth have been reported in a wide variety of crops, including horticultural crops (Cai and Qian, 1995). Silicon is the second richest element found on the surface of the earth's crust as well as in the soils (Liang *et al.*, 2007). In the soil solutions, Si is found as silicic acid at concentrations from 0.1 to 0.6 mM. The major form in which Si is absorbed and consumed by plants is monosilicic acid [$Si(OH)_4$] (Farmer, 1986; Epstein, 1994; Birchall, 1995; Ma and Yamaji, 2006). The plant roots absorb it and it is regularly stored in cell walls, intercellular spaces and a subcuticular layer outside the cell in the leaves as insoluble silica (Sangster *et al.*, 2001; Ma *et al.*, 2011). In various plant species, Si helps to combat both abiotic and biotic stresses. Also, excess of Si has no toxic reports so far (Epstein, 1994; Fauteux *et al.*, 2005; Ma and Yamaji, 2006).

The positive effects of Si observed in agronomic crops, such as rice, wheat, barley, etc., have generated interest for research with horticultural crops as well. To enhance the productivity of horticultural crops silicon fertilizers are used in many countries such as China, Japan, Korea and Europe (Chen *et al.*, 2000). Plant ash has been used as silicon fertilizer, for ages by many agriculturists. Addition of Si to the hydroponic solution of cucumber (*Cucumis sativus* L.) and roses (*Rosa* sp.) is a practice in the Netherlands, to circumvent negative effects when Si is not available to plants (De Kreij *et al.*, 1999). Si supplementations as fertilizer have enhanced the growth and quality of apples (Cai and Qian, 1995) and also the silicon-responsive ornamental plants (Chen *et al.*, 2001). Si has found its place as a fertilizer and it has frequently been used for rice (Datnoff *et al.*, 1997) and other Poaceae crops and it is also supplemented to cucumber, melon and lettuce grown hydroponically (Bae *et al.*, 2010). However, plant species and cultivars differ in their ability to benefit from Si supply (Frantz *et al.*, 2008), such as reported among cultivars of French marigold (Sivanesan *et al.*, 2010) and begonia and pansy (Lim *et al.*, 2012). Similarly, it was also reported that soybean cultivars absorbed Si differently (Lemes *et al.*, 2011).

Greenhouse production provides an alternative to field production. It is very well known that crops grown in greenhouses are mostly grown in containers using organic substrates such as peat, bark and coir dust combinations (soilless cultures). In greenhouse experiments severe growth and fruit yield reduction and chlorosis have been reported in absence of Si in non-accumulator species such as tomato (Miyake and Takahashi, 1978), cucumber (Miyake and Takahashi, 1983), soybean and strawberry plants (Miyake and Takahashi, 1985, 1986).

To determine the effect of Si in potted plants various studies have been done on horticultural crops as models. Silicon compounds are applied to plants by adding them to the nutrient solution in the root zone (Belanger *et al.*, 1995) or by foliar applications (Bowen *et al.*, 1992; Menzies *et al.*, 1992). The role of Si in rice and other agricultural crops are very well investigated in comparison to horticultural crops. Hence, the review covers the effect of Si on horticultural crops explored until now.

Si and horticultural crops: Si supplementation to the hydroponic nutrient solution is essential for few plant species as they are grown in inert substrates (Savvas *et al.*, 2007). The horticultural plants have been studied as models to decipher the effect of Si on growth parameters (plant height, dry matter, stem diameter, etc.) as well as quality of flowers or fruits. The following descriptions are reviews on these aspects in some major horticultural crops.

Rose: The most common and famous ornamental plant worldwide are Roses. It was found that addition of Si to recirculated nutrient solution in a closed hydroponic system, ameliorated most of the negative effects of recirculation on cut rose (*Rosa hybrida* L. 'Kardinal') production, resulting in better stem quality (Ehret *et al.*, 2005). It was found that the implementation of potassium metasilicate (200 mg L^{-1} of Si) in rose cultivation resulted in an increase in plant height and shoot dry matter production (Hwang *et al.*, 2005). Similarly, it was suggested that an increased Si supply is beneficial to roses grown in the soilless culture as it stimulates the vegetative growth of roses and improves flower quality.

Zinnia: Zinnia is popular for its range of colorful flowers. It belongs to family Asteraceae (Riaz *et al.*, 2008). Zinnia is known for its long vase life and disease resistant characteristics (Dole, 1999). Zinnia plants, grown in the greenhouse with weekly $NaSiO_3$ foliar spray at 100 mg L^{-1} Si moderately increased the leaf resistance against transpiration and flower diameter (Kamenidou *et al.*, 2009). It was concluded that the increased leaf resistance due to the reduced transpiration would have been the reason for the increase in flower diameter. This increased leaf resistance may further benefit floricultural commodities by improving the quality and shelf longevity of cut flowers.

Sunflower: *Helianthus annuus* L. belongs to family Asteraceae and is priced for its ornamental flowers, seed oil and medicinal value (Khursheed *et al*., 2009). It was found that 200 mg L^{-1} K_2SiO_3 treatment to sunflowers resulted in plants with thicker stems and more compact statues (Kamenidou *et al*., 2008). Kamenidou *et al.* (2008) reported most beneficial Si forms and concentrations for greenhouse production of sunflowers. The Si forms mentioned are rice husk ash incorporated in substrates (peat: perlite; 4:1 by volume), hydrous K_2SiO_3, weekly foliar sprays of $NaSiO_3$ and drenches of K_2SiO_3.

Tomato: *Lycopersicon esculentum* belongs to family Solanaceae which is an important source of vegetables and fruits (Ogwulumba *et al*., 2010). The effects of Si on yield, nutritional status and fruit quality in tomato crop grown in a closed hydroponic system were reported (Stamatakis *et al*., 2003). The Si was applied in the form of K_2SiO_3. It was found that the contents of total solid solutes such as beta-carotene, lutein and lycopene contents of the fruit were significantly increased by Si supplementation. The Si also enhanced the fruit firmness and vitamin C in the tomato fruit (Stamatakis *et al*., 2003).

Strawberry: Strawberries have traditionally been a popular delicious fruits for their flavor and taste, in the fresh, frozen and processed form and are highly valued as a desert fruit (Hasan *et al*., 2010). This commercially important berry fruit belongs to family Rosaceae and genus *Fragaria*. On foliar applications of K_2SiO_3, beneficial metabolic changes in strawberry plants (*Fragaria X ananassa* Duch) were reported (Wang and Galletta, 1998). Increase in plant growth and chlorophyll content was reported. It was concluded further that Si has beneficial effects on strawberry plant metabolism as increased contents of citric acid and malic acid, higher ratios of fatty acids in glycolipids and phospholipids and elevated levels of membrane lipids were noted. Sucrose, glucose, fructose and myoinositol levels were reduced (Wang and Galletta, 1998).

Gerbera: *Gerbera jamesonii* belongs to the Asteraceae family and are popular as cut and potted flowers. It has been ranked among the top ten cut flowers of the world (Kanwar and Kumar, 2008). Inclusion of Si to the nutrient solution of *Gerbera* resulted in improved overall crop quality with thicker flower stems and a higher percentage of flowers when compared to the plants grown with the standard nutrient solution (Savvas *et al*., 2002). It was found that foliar sprays of $NaSiO_3$ applied weekly at 50 or 100 mg L^{-1} Si benefited flower quality by increasing flower height, peduncles and diameter (Kamenidou *et al*., 2010).

Chrysanthemum: *Dendranthema grandiflora* is one of the most important ornamental crops in the world and has been cultivated and improved for more than 2000 years (Martin and Gonzalez-Benito, 2005). It belongs to Asteraceae family. Three chrysanthemum cultivars 'Coral Charm', 'White Reagan' and 'Indianapolis' were monitored after treatment with 800 mg kg^{-1} Si applied to substrate (soil: sand: commercial substrate: vermiculite; 2: 0.5: 1: 0.5 by volume) (Carvalho-Zanao *et al*., 2012). All the three cultivars of chrysanthemum were classified as Si accumulators, as per (Ma *et al*., 2001), as presence of Si in the leaves of the cultivars was found to be more than 10 g kg^{-1} per dry weight. The Si was unable to alter production and shelf life of any cultivars. The number of inflorescences per pot was noted to be greatest in 'White Reagan'.

Carnation: The most explored ornamental plant for cut flower postharvest physiology is *Dianthus caryophyllus* L. (Casas *et al.*, 2010). It belongs to family Caryophyllaceae. In carnation 'Harlem' on treatment with K_2SiO_3 (100, 150, 200 mg L^{-1}) it produced less ethylene, therefore, internal reservoir structures would have been maintained for a longer period and this in turn was responsible for lower carbohydrates and higher dry weight of Si-treated flowers (Jamali and Rahemi, 2011). Thus, it was confirmed that inhibitory effect of Si on ethylene production increases the postharvest quality and longevity of carnations.

Cucumber: *Cucumis sativus* is an economically important crop belonging to family Cucurbitaceae. Cucumber has always served as a model for sex determination studies and plant vascular biology (Huang *et al.*, 2009). In cucumber, it was reported that the addition of Si (100 mg L^{-1}) could increase the chlorophyll content, RuBP carboxylase activity (ribulose-bis-phosphate), root fresh weight and dry weight in cucumber plants grown in a recirculating nutrient solution (Adatia and Besford, 1986). The Si may act as beneficial element under conditions of nutrient imbalances such as in phosphorus (P) and zinc (Zn) supply (high or low) and P-induced Zn deficiency has been accounted (Marschner *et al.*, 1990), where cucumber were grown in a nutrient solution with 1.7 mM Si.

Marigold: *Tagetes patula* L. commonly known as French marigold is mainly cultivated for ornamental purposes and belongs to family Asteraceae. The Si effect on the growth of marigold 'Boy Orange' and 'Yellow Boy' seedlings have been investigated by Sivanesan *et al.* (2010). In both cultivars it was found that supplementation of Si significantly increased stem diameter, number of lateral shoots, root length, chlorophyll content and fresh and dry weights and addressed further that Si improves growth of these cultivars.

Sugarcane: *Saccharum officinarum* L. belongs to Poaceae family and is an economically important cash crop. Sugarcane accounts for approximately 70% of the world's sugar. With Si fertilizers, it was reported that productivity increased from 17-30% in field and greenhouse experiments, whereas production of sugar increased from 23-58% with increasing Si fertilization (Matichenkov and Calvert, 2002). It was found that higher yield of sugarcane was related to higher concentration of Si in the leaves.

Citrus: Citrus is one of the most economically important fruit crops in the world belonging to Rutaceae family. Si fertilization enhances the growth of citrus by 30-80% and the fruit yield as well (Taranovskaia, 1939). It was reported that Si may play an important role in citrus tree growth and development directly (Matichenkov *et al.*, 1999). They also confirmed a relationship between content of plant available Si in the soil and the content of Si in leaves and the health of citrus tree (Matichenkov *et al.*, 1999, 2000). It was further added with a study on citrus grown in the greenhouse with Si supplementation that Si nutrition was responsible for significant increase in mass of roots (Matichenkov *et al.*, 2001).

Kalanchoe: Kalanchoes belongs to family Crassulaceae, famous as ornamentals, rock or succulent garden plants. In a greenhouse study on rooted terminal cuttings of *Kalanchoe blossfeldiana* 'Peperu' an experiment was conducted with three sources of silicon viz., $CaSiO_3$, Na_2SiO_3 and K_2SiO_3 supplied through subirrigational feeding or foliar sprays (Son *et al.*, 2012). It was revealed that

$CaSiO_3$ supplied through a subirrigation system increased shoot tissue contents of Si and chlorophyll content, confirming that $CaSiO_3$ could improve plant quality of 'Peperu' making compact potted plants.

The Si supplementation has been reported to increase plant height when horticultural plants were grown in the peat-based substrate and treated with weekly K_2SiO_3 drenches at 100 mg L^{-1} (Mattson and Leatherwood, 2010). It was reported in New Guinea impatiens, *Lobelia erinus* L. and *Portulaca grandiflora* Hook that addition of Si significantly affected their heights. Calibrachoa 'Celebration Blue', *Fuchsia, Petunia, Portulaca, Scaevola* and *Torenia* were reported to have an increase in flower diameters while *Bacopa, Petunia, Scaevola* and *Verbena* had thicker leaves with Si supplements (Mattson and Leatherwood, 2010).

In vitro studies have also been done with Si supplementations on *Begonia* and pansy plants. *Begonias* are classic bedding plants and pansies are garden flowers. *In vitro* growth of *Begonia* (*Begonia semperflorens* Link et Otto) 'Super Olympia Red' and 'Super Olympia Rose' and pansy (*Viola*×*wittrockiana* Hort.) cultivars 'Matrix White Blotch' and 'Matrix Yellow Blotch' was investigated on K_2SiO_3 supplementation (Lim *et al.*, 2012). It was found that both cultivars of begonia and pansy were influenced by supplementation of Si, where growth, biomass and chlorophyll content were enhanced in both plants but varied among cultivars.

Salvia splendens: It is the most common ornamental plant, also known as sage plant. The genus *Salvia* belongs to family Lamiaceae. *In vitro* studies under salt stress have been reported on this important plant. At 50 mM NaCl, 50 or 100 mg L^{-1} of K_2SiO_3 helped to overcome the salt effect and maximize the plant growth. The supplementation of Si enhanced tolerance and significantly affected the plant growth (Soundararajan *et al.*, 2013).

Cotoneaster wilsonii: Many species of cotoneaster are popular ornamentals due to their diversity in form, abundant flowers and attractive fruits. The genus *Cotoneaster* belongs to Rosaceae. A common problem hyperhydricity reported during its micropropagation has been significantly reduced by supplementation of Si. Inclusion of 50 or 100 mg L^{-1} of K_2SiO_3 to the medium significantly reduced the hyperhydricity of *in vitro*-raised plants (Sivanesan *et al.*, 2011). Hence, the problem of hyperhydricity can be overcome by addition of silicon.

Silicon has been beneficial in soilless cultures in the greenhouse as well as *in vitro* cultures. Thus, inclusion of this element seems to be promising in horticultural crops. Some positive effects of the element have been summarized in Fig. 1.

Si uptake in horticultural crops: The uptake of Si has been reported in cucumber (Liang *et al.*, 2005; Hou *et al.*, 2006), strawberry (Lanning, 1960) and tomato (Miyake and Takahashi, 1978). Citrus is a non-Si accumulator (Wutscher, 1989). In hydroponic experiments with *Cucumis sativus*, it was concluded that Si uptake was active and transport is independent of external Si concentrations (Liang *et al.*, 2005). It was found that differences in the leaf Si content of chrysanthemum cultivars were related to the capacity for Si accumulation (Carvalho-Zanao *et al.*, 2012). It appears from the various reports that the capability of plants to benefit from Si supply is related to the uptake of Si into the root symplast. This hypothesis has been well documented by many studies with different crops exhibiting varied degrees of Si uptake (Epstein, 1994; Jones and Handreck, 1967; Miyake and Takahashi, 1978; Hodson *et al.*, 2005). It is known that the amount of Si absorbed by the plant is directly related to the utilization by the plant for its growth. Contrary

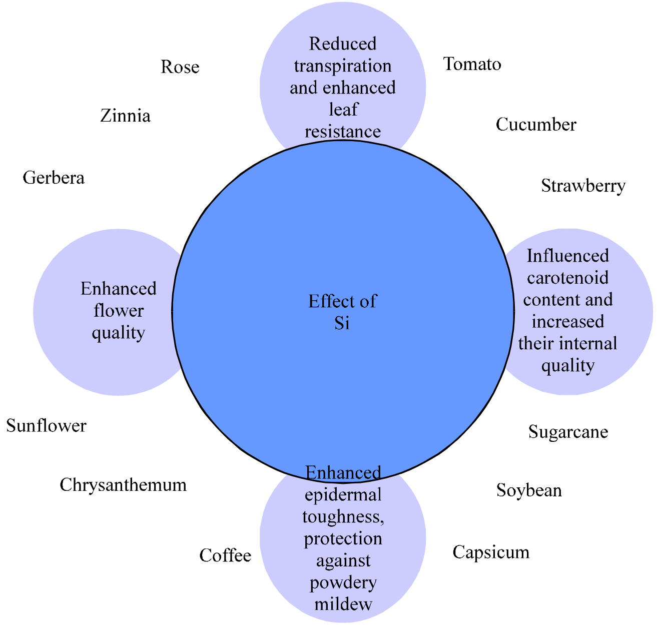

Fig. 1: Some positive effects of silicon on horticultural crops

to this, in a study with 21 cultivars of floriculture crops, it has been found that cultivars which did not accumulate Si did exhibit morphological responses. Thus, it can be concluded that there is no correlation between Si accumulation and its morphological responses seen in plants (Mattson and Leatherwood, 2010). Phalaenopsis orchid liners have been reported as Si accumulators with active uptake system (Vendrame *et al.*, 2010). Indeed, Si is accumulated by broad range of floriculture species.

To detect the uptake of Si, 14 floriculture plants were examined for Si accumulation or uptake (Frantz *et al.*, 2008). The Si was detected and quantified using electron beam analysis (EBA; scanning electron microscopy coupled with energy dispersive X-ray analysis), Inductively Coupled Plasma-Optical Emission Spectroscopy (ICP-OES) and colorimetric methods in economically important floriculture species, i.e., *Dianthus* spp. 'Floral Lace White', *Tagetes erecta* L. 'African Atlantis Primerose', *Zinnia elegans* L. 'Oklahoma White', *Begonia* 'Prelude white', *Verbena X hybrid* Voss 'Tukana White', *Vinca* 'Pacifica', *Impatiens wallerana* Hook. 'Super elfin white', *Impatiens hawker* Bull. 'Sonic Light Lavendar', *Euphorbia pulcharima* 'Freedom Red' and *Calibrachoa X hybrida* 'Colorburst Violet'. It was concluded that these species took up and accumulated Si in significant concentrations throughout their leaves, trichomes or leaf margins (Frantz *et al.*, 2008). However, Si was not detected in other floriculture species tested such as Geranium, *Antirrinum majus* L., *Petunia hybrida* and *Salvia divinorum*.

Quantification of Si was also carried out using alkaline fusion technique which involves dry-ashing the samples and spectrophotometerical measurements of ten horticultural crops (Hogendorp *et al.*, 2012). It was concluded that *Zinnia elegans* and New England aster accumulated Si, confirming that zinnia which has initially high Si concentration may benefit from silicon-based fertilizer applications. According to Hogendorp *et al.* (2012) supplementation of silicon-based fertilizers may not be beneficial for Marigold (*Tagetes erecta*). Other horticultural plants studied such as *Heuchera hybrid* L., *Rosmarinus officinalis* L. and *Astilbe chinensis* (Maxim) Franch were reported to be 'silicon rejectors' on the basis of Si content category by Ma *et al.* (2011).

An experiment was conducted with 21 cultivars of floricultural crops grown in peat-based substrate and treated with weekly drenches of 100 mg L^{-1} K_2SiO_3 (Mattson and Leatherwood, 2010). It was reported that Si supplementation increased leaf Si concentrations from 13-145% as compared to the control. The cultivars having highest concentrations of Si were torenia, argyranthemum, verbena, petunia, calibrachoa (*Calibrachoa X hybrida* Cerv. 'Celebration Rose') and New Guinea impatiens. Seven cultivars have been reported to show no Si responses towards growth parameters and they were begonia (*Begonia X tuberhybrida* Voss 'Nonstop Rose Petticoat'), calibrachoa 'Celebration Rose', impatiens (*Impatiens wallerana* Hook. F 'Cameo Scarlet Surprise Improved'), ivy geranium (*Pelargonium peltatum* L. L'He´r. ex Aiton 'Global Ruby Red'), 'Global Soft Pink' ivy geranium, geranium (*Pelargonium X hortorum* L.H. Bailey 'Patriot Bright Red') and vinca 'Variegata' (Mattson and Leatherwood, 2010).

In vitro grown banana spp. (*M. acuminata* 'Grande Naine', *M. acuminate* spp. Banksii and *M. balbisiana* spp. Tani) when treated with 0-1.66 mM Si (Na_2SiO_3) in hydroponics revealed that it may be capable of Si accumulation depending on Si concentration of the nutrient solution and on the rate of water uptake. Confirmation of Si uptake in three genotypes of Musa was credited to transpiration when distribution of Si among shoot organs was recorded on the basis of dry weight (Henriet *et al.*, 2006).

Hence, it is significant to know which horticultural species accumulate Si element. This information on detection of Si and its uptake may help researchers to further explore these crops to improve growth as well as study various other mechanisms involved and yet unknown.

Role of Si in disease suppression

Biotic stress: Reports on the beneficial effects of Si on plant health are available for several plant pathogen combinations (Locke *et al.*, 2010; Gillman *et al.*, 2003; Van Bockhaven *et al.*, 2012). It is also a known fact that treating plants with soluble Si enhances fungal resistance (Menzies *et al.*, 1991). The Si, being dispersed through the plant via., the transpiration stream (Samuels *et al.*, 1991), inhibits fungal diseases through modifications of the epidermal layer of the leaves and fruits as well as by increasing presence of low-molecular-weight metabolites (Fawe *et al.*, 1998; Gillman *et al.*, 2003). Hence, epidermal and cell wall toughness is imparted by Si (Jones and Handreck, 1967; Sangster *et al.*, 2001) and consequently plant protection against abiotic and biotic stresses (Pilon-Smits *et al.*, 2009). Table 1 summarizes crops affected by pathogens and diseases which are treated by Si amendment.

The Si delayed the onset of diseases or reduced them to some extents and therefore, can be used as a preventive measure. Positive impacts of silicon have been on pest management, savings in fungicide and insecticide costs and reductions in fertilizer applications as well, as reported in rice that Si eliminates the need for fungicide (Datnoff *et al.*, 1997). There are also reports on increasing resistance by addition of Si against aphids.

The possible mechanisms reported to confer resistance to hyphae and pest attack by Si in plants are: (1) Si accumulates and makes up a Si cellulose network in the cell walls which form mechanical barriers against pathogens and predator invasions (Yoshida *et al.*, 1969; Takahashi and Miyake, 1977), (2) The presence of Si crystals in these plant tissues hinders the feeding of the insect which damage their mandibles, (3) The interaction of Si in the water economy of the plant in terms of reducing moisture stress (Meyer and Keeping, 2005), (4) Si may enhance activity of chitinases, peroxidases and polyphenyloxidases (Cherif *et al.*, 1994) and (5) An increased formation of papillae and deposition of callose and hydrogen peroxide, also an upregulation of the phenylpropanoid

Table 1: Horticultural crops and diseases inhibited by Si applications

Crop	Silicon form	Pathogen	Disease	References
Zinnia elegans	K_2SiO_3	*Erysiphe cichoracearum*	Powdery mildew	Locke *et al*. (2010)
Rosa hybrida L. 'Meipelta'	K_2SiO_3	*Diplocarpon rosae*	Black spot	Gillman *et al*. (2003),
Miniature potted roses			Powdery mildew	Datnoff *et al*. (2006) and Larsen (2008)
Euphorbia pulcherrima Willd. ex. Klotzsch	Na_2SiO_3	Calcium deficiency	Bract necrosis	McAvoy and Bible (1996)
Cucurbita pepo L.	K_2SiO_3 foliar sprays	*Podosphaera xanthii*	Powdery mildew	Savvas *et al*. (2009) and
		Sphaerotheca fuliginea	Powdery mildew	Menzies *et al*. (1992)
Lycopersicon esculentum	K_2SiO_3	Calcium deficiency	Blossom end-rot	Stamatakis *et al*. (2003)
Strawberry	K_2SiO_3	*Sphaerotheca aphanis* (Wallr.)	Powdery mildew	Kanto *et al*. (2004, 2006)
Vitis vinifera L.	K_2SiO_3	*Uncinula necator*	Powdery mildew	Bowen *et al*. (1992)
Cucumis sativus	K_2SiO_3	*Sphaerotheca fuliginea*	Powdery mildew	Adatia and Besford (1986),
		Pythium aphanidermatum	Root rot	Menzies *et al*. (1992), Samuels *et al*. (1994), Fawe *et al*. (1998) and Cherif *et al*. (1994)
Cucumis melo	K_2SiO_3	*Sphaerotheca fuliginea*	Powdery mildew	Menzies *et al*. (1992)
Saccharum officinarum	$CaSiO_3$ slag	*Leptosphaeria sacchari*	Ringspot, sugarcane rust, leaf freckle	Matichenkov and Calvert (2002), Savant *et al*. (1999) and Raid *et al*. (1991)
Capsicum annum L.	K_2SiO_3 $CaSiO_3$	*Pytophthora capsici*	Root rot	Lee *et al*. (2004)
			Phytophthora blight	French-Monar *et al*. (2010)
Glycine max	K_2SiO_3	*Phakopsora pachyrhizi*	Soybean rust	Lemes *et al*. (2011)
'Hikmop Sorip'	K_2SiO_3	*P. pachyrhizi*	Soybean rust	Arsenault-Labrecque *et al*. (2012)
Coffea arabica cv. Mundo Novo	K_2SiO_3	*Hemileia vastatrix*	Coffee leaf rust	Martinati *et al*. (2008) and
Coffea arabica	$CaSiO_3$/$NaSiO_3$	*Cercospora coffeicola*	Brown eye spot	Botelho *et al*. (2005)

pathway (Shetty *et al*., 2011, 2012). Thus, from the reports it is quite clear that Si is potent enough to act as a biological inducer of plant innate defense responses other than being a mechanical barrier (Van Bockhaven *et al*., 2012). A compilation has been done from the available literature to summarize the effects of Si supplement against insect attack in Table 2.

Si combating abiotic stresses: Out of many abiotic stresses, salinity is a universal crisis which is a direct threat to soil and water world-wide. To exploit saline soils in future to enhance crop production has always received world-wide concern. Salt stress has been shown in many reports to be alleviated by Si (Bradbury and Ahmad, 1990; Liang *et al*., 1996; Tuna *et al*., 2008). It has been reported that Si may act to mitigate salt stress in plants by decreasing permeability of plasma membranes, lipid peroxidation and maintaining the membrane integrity and function (Liang, 1999). Salt toxicity is suppressed by water retention due to Si in tomato plants which permits growth rate and dilutes the salt concentration in plant, thus combating stress (Romero-Aranda *et al*., 2006).

Drought stress also causes decrease in crop production, inhibits photosynthesis of plants by inhibiting photochemical activities and decrease in activities of Calvin cycle enzyme (Gong *et al*.,

Table 2: Crops attacked by insects and effects of Si supplementation

Crop	Insect/Pest	Effect of Si	References
Dendranthema grandiflorum cv. Shinro	*Macrosiphoniellas anbornii*	K_2SiO_3 reduced colonies of aphids by 40-57%	Jeong *et al.* (2012)
Glycine max	Silver leaf whitefly *Bemisia tabaci* aggressive and virulent biotype B	Impaired nymphal development by reducing nymphal survival	Ferreira *et al.* (2011)
Zinnia elegans	*Myzus persicae* (Sulzer), the green peach aphid	K_2SiO_3 provides modest increase in resistance	Ranger *et al.* (2009)
Saccharum officinarum	Sugarcane stalk borer, *Eldana saccharina*	Resistance to insect	Savant *et al.* (1999) and Meyer and Keeping (2005)
Saccharum officinarum	Pyralid borer *Scirpophaga excerptalis*	K_2SiO_3 decreased the population and increased the sugarcane yield and sugar	Gupta *et al.* (1992)
Rosa hybrida	*Podosphaera pannosa*	Enhanced resistance	Shetty *et al.* (2011, 2012)
Cucumis sativus	*Pythium* spp.	Resistance to pest	Cherif *et al.* (1994)

2005; Monakhova and Chernyadev, 2002). Plants treated with Si are reported to show reduced negative effects of water scarcity (Lobato *et al.*, 2009; Silva *et al.*, 2012). Avila *et al.* (2010) reported an increase in the levels of chlorophyll 'a' in *Oryza sativa* plants when Si and nitrogen interactions were investigated. Silicon supplementation showed changes in nitrogen metabolism (Watanabe *et al.*, 2002). As water is absorbed through root system, it conducts nitrogen and other nutrients. A decrease in the effects of drought stress in the transpiration rate, stomatal conductance and in the levels of total carbohydrates was observed in tomato plants (Silva *et al.*, 2012).

Metal toxicity: Usage of acid fertilizers results in soil acidification, decreasing soil pH and fertility. This directly enhances metal toxicity by increasing the availability of manganese (Mn). The Mn, a micronutrient essential for plant, becomes toxic when present in excess (Mukhopadhyay and Sharma, 1991). Metal toxicity has an impact on fruit yield and quality. Si can counterbalance nutrient elements in the plant tissue by inhibiting aluminium (Al), Mn and sodium (Na). It will facilitate the uptake of others such as phosphorus (P), magnesium (Mg), potassium (K), iron (Fe), copper (Cu) and zinc (Zn) (Chen *et al.*, 2000).

Previous studies have shown that Mn-excess has affected soybean (Suresh *et al.*, 1987) and citrus (Li *et al.*, 2010). Si is responsible for even distribution of Mn and not heavy deposition into selected areas of leaves, thus combating metal stress. The Si has been reported to increase plant tolerance to high Mn concentrations in *Phaseolus vulgaris* (Horst and Marschner, 1978), *Lactuca sativa* (Voogt and Sonneveld, 2001) and *Cucumis sativus* (Feng *et al.*, 2009). The Si has also been reported to decrease P uptake when P supply is high in strawberry (Miyake and Takahashi, 1986). It might form complexes with organic compounds, interacting with pectins and polyphenols (Currie and Perry, 2007) in the walls of epidermal cells, therefore increasing their resistance to degrading enzymes (Snyder *et al.*, 2007).

Aluminum (Al) toxicity is among the major problem of ion toxicity stress in plants. *Gossypium hirsutum* L. (cotton) is reported to be highly sensitive to Al toxicity. The Si at concentrations of 700-2800 μM in the nutrient solution has been reported to alleviate Al toxicity in cotton (Li *et al.*, 1989). Complex formed between aluminium and silicon has been attributed as a mechanism of Si-induced alleviation of Al toxicity to plants (Li *et al.*, 1996).

Silicon fertilizer has also been reported to increase frost tolerance of lemon (Taranovskaia, 1940) and sugarcane (Matichenkov and Calvert, 2002). Hence, Si improves the plant tolerance to abiotic stresses such as water deficit, salt stress, mineral stress and metal toxicity (Epstein, 1994, 1999; Gunes *et al.*, 2007). Table 3 summarizes the available current knowledge on the role of Si in combating various abiotic stresses reported in horticultural crops.

Table 3: Plants grown under stress and their effects on Si supplementation

Crop	Stress	Si	Effects of Si treatment	References
Cucurbita pepo (Zucchini squash)	35 mM NaCl	1 mM K_2SiO_3	Tolerance to salinity, growth and yield controlled	Savvas *et al.* (2009)
Roses (*Rosa x hybrida*)	0.8 mM and 40 mM NaCl	0.3-2.0 mM K_2SiO_3	Improved overall plant appearance and higher number of marketable flowers per plant at the low salinity level	Savvas *et al.* (2007)
		1.5-2.0 mM in the root zone	Enhanced vegetative growth, flower production and quality	
Rosa x hybrida L. 'Hot Lady	25 mM NaCl	50 ppm Si as K_2SiO_3 50 and 100 ppm Si	Increased flower number, higher growth, quality and yield and reduced contents of malondialdehyde and chlorophyll of stressed plants, Alleviated dull flower color	Reezi *et al.* (2009)
Cucumis sativus	50 mM	1 mM K_2SiO_3	Higher activities of antioxidant enzymes SOD, GPX, APX, DHAR and GR, improved growth of plants	Zhu *et al.* (2004)
Lycopersicon esculentum 'Moneymaker'	0 or 80 mM NaCl	0 and 2.5 mM	Higher plant water content, dry weight, total leaf area, leaf turgor potential and photosynthesis rates	Romero-Aranda *et al.* (2006)
Tomato	100 mM	2.5 mM	Enhanced SOD, CAT and protein content in leaves	Al-Aghabary *et al.* (2005)
	NaCl electrical conductivity (EC) 4.8 dS m^{-1}	2.25 mM K_2SiO_3	Enhanced vitamin C content and fruit firmness	Stamatakis *et al.* (2003)
Helianthus annuus L.	60 or 100 mM	30 or 60 ppm Na_2SiO_3	Improved biomass production and increased tolerance to salinity	Saqib *et al.* (2011)
Capsicum annum L.	Drought/water deficiency	0.25-1.75 µM Na_2SiO_3	Leaf water retention increased, stomatal conductance reduced, total soluble proteins increased, total soluble amino acids and glycinebetaine decreased, Proline synthesis maximized	Lobato *et al.* (2009)
Lycopersicon esculentum cvs. 'Super Marmante' and 'Santa Cruz'	Drought	0.25 -1.75 μM Na_2SiO_3	Increase in chlorophyll 'a' and total chlorophyll levels	Silva *et al.* (2012)
Glycine max	NaCl (salt) PEG (drought)	100 or 200 mg L^{-1} Silicic acid	Improved growth attributes and mitigated adverse effects of stresses	Hamayun *et al.* (2010)
	Drought and UV-B stress	1.70-2.55 mM Na_2SiO_3	Ameliorates affects on seedling growth, photosynthesis and antioxidant parameters	Shi *et al.* (2005)

Table 3: Continue

Crop	Stress	Si	Effects of Si treatment	References
Solanum nigrum L.	Metal: cadmium	1.0 mM Na_2SiO_3	Strongly increased shoot length, root length and dry weight Lowered antioxidant activities of SOD, POD and CAT	Li *et al.* (2011)
Cucumis sativus L.	Manganese 10 µM and 600	1.0 mM K_2SiO_3	Decreased lipid peroxidation, inhibited appearance of Mn toxicity symptoms, improved plant growth Increased antioxidant activities of SOD, APX, DHAR, GR, ascorbate and glutathione Reversed chlorosis, increased photosynthetic activity, APX, DHAR and GR	Shi *et al.* (2005)
	600 µM $MnSO_4$	1.0 mM Na_2SiO_3	Reduced GPX activity in leaf chloroplast	Feng *et al.* (2009)
Cucumis sativus L. cv. Jinchun 4	Chilling temperature (15/8°C) and low light (100 µmol m^{-2} sec^{-1}) condition	0.1-1.0 mM K_2SiO_3	Greater deposition of endogenous silicon Increased antioxidant activities and reduced lipid peroxidation	Liu *et al.* (2009)

Silicon as an anomaly: There are few reports in which Si has shown detrimental effect. Flower deformations and stunted growth were observed in sunflower at 200 mg L^{-1} K_2SiO_3 treatment (Kamenidou *et al.*, 2008). Foliar sprays of Na_2SiO_3 at a rate of 150 mg L^{-1} Si on gerbera caused stem shortening and flower deformation (Kamenidou *et al.*, 2010). In soybean plants, application of Si has no effect on its vegetative development (Ferreira *et al.*, 2011).

Silicon-based fertilizers when applied to coleus (*Solenstemon scutellarioides* L.), fiddleleaf fig (*Ficus lyrata* Warb.) and poinsettia (*Euphorbia pulcherrima* Willd. ex Klotzsch) failed to fight against the citrus mealybug (*Planococcus citri* Risso) and greenhouse whitefly (*Trialeurodes vaporariorum* Westwood) (Hogendorp *et al.*, 2009a, b; 2010). In gerbera daisy, powdery mildew was reduced by neither K_2SiO_3 nor $CaSiO_3$ and it was concluded that Si may not be useful for managing this disease, due to low accumulation of Si by gerbera leaves (Moyer *et al.*, 2008). Reduced height has been observed in *Bracteantha bracteata* (Vent. Anderb. and Heagi 'Golden Beauty') grown in a soilless culture with Si supplementation (Mattson and Leatherwood, 2010).

CONCLUSION

The Si application to support growth and development of soil-grown horticultural crops has been increased many folds in a decade. Addition of Si to the nutrient solution of plants has been an added advantage to the horticultural industry. The Si application influences the quality of ornamental plants. The Si renders plants more resistant towards a wide range of abiotic and biotic stresses. Supplementation Si has helped to overcome the deleterious effects of abiotic stresses and improved the adaptation capability of plants to stressful environment. An increase in the resistance to aphids has been well recorded. The Si as a prophylactic measure can reduce and prevent losses against many pathogens and thus limit dependency on fungicides. Thus, usage of Si in horticultural production will ensure safe food production and environment protection. This review may help the researchers to carry on further experiments on horticultural crops with the help of this compiled information.

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