Journal of Pharmacognosy and Phytochemistry
Available online at www.phytojournal.com

E-ISSN: 2278-4136
P-ISSN: 2349-8234
www.phytojournal.com
JPP 2020; 9(4): 1374-1381
Received: 10-05-2020
Accepted: 12-06-2020

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Silicon nutrition for alleviation of abiotic stress in plants: A review

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Abstract
Silicon (Si) earth is known to have numerous beneficial effects on plants in alleviating diverse forms of abiotic and biotic stress. Available Si in soils refers to the amount of Si that can be taken up by plants during the growing season and usually considered an index of Si-supplying capacity of soils. The silicic acid (H_4SiO_4) is the plant-available form of soil silicon which is present in the soil solution at concentrations normally ranging from 0.1 to 0.6 millimolar (mM). Some important factors influencing availability of Si to plants include parent material and type of soil, land use pattern, soil pH, soil texture and soil redox potential. All terrestrial plants contain some silicon (Si) in their tissues and the concentration of Si in shoots varies greatly among plant species. By application of silicon solution externally plants lodging can be reduced. Abiotic stresses like heat, cold, drought, salt stress and heavy metal toxicity in plants can be alleviated with the application of silicon solution. Accumulated silicon can provide rigidity and roughness to the plant cell walls. Silicon plays a significant role in maintenance of the integrity of cell membranes during stress condition such as chilling, freezing, heat, drought, pollution etc. and therefore Si-treated plants acquire tolerance to these stress conditions.

Keywords: Abiotic stress, accumulation, availability, silicon

Introduction

Silicon (Si) is a ubiquitous, tetrahedral metalloid and the second most abundant element after oxygen, comprising approximately 27.7% of the Earth's crust. It was discovered by John Jocob Berzelius in 1824. Its atomic number is 14, molecular weight is 28.0855, valence is 4 and melting point is 1414°C. The name for silicon is taken from the *Latin* word 'silex' which means "flint".Most sources of Si in soil are present as crystalline forms, which are insoluble and not directly available for plants (Richmond and Sussman, 2003) [61]. The plant-available form of Si is monosilicic acid (H_4SiO_4), which is present in the soil solution at concentrations normally ranging from 0.1 to 0.6 millimolar (mM) (Gunnarsson and Arnórsson, 2000) [26], roughly two times higher than the concentrations of phosphorus (P) in soil solutions (Epstein 1994, 1999) [17, 18]. Even highly purified water contains about 20 micro molar (µM) Si (Werner and Roth, 1983) [81]. Total Si content in soil ranges normally from 25 to 35% with an average of 30%. But in highly weathered soils in the tropics Si content can be as low as less than 1% due to desilification and fersialitization processes. Silicon (Si) is known to have numerous beneficial effects on plants, alleviating diverse forms of abiotic and biotic stress. Research on Silicon in agriculture has accelerated in recent years and revealed multiple effects of Si in a range of plant species.

Despite its ubiquity and abundance in both soils and plants, Si has not yet been considered an 'essential' mineral element of any terrestrial higher plant, except the members of *Equisetaceae* (Diatoms). Epstein (1999) [18] considered Si as "Quasi-essential" element for many plant species. An element is defined as quasi-essential if it is ubiquitous in plants and if a deficiency of it can be severe enough to result in demonstrable adverse effects or abnormalities with respect to growth, development, reproduction or viability (Epstein, 1999) [18]. American Association of Plant Food Control Officials (AAPFCO) and the International Plant Nutrition Institute (IPNI) listed Si as a beneficial or quasi-essential element. Use of silicon in agriculture is not a new thing. Slag based Si fertilizer was used in middle ages in Europe. Liebig (1840) [45] first recommended Sodium silicate as Si fertilizer to improve crop productivity. Sachs (1865) [65] commented that 'Si is widely distributed in plants'. Onodera (1917) [56] published that a close relation exists between Si content in leaves and blast disease in rice. Suzuki (1935) [72] recommended 1.5 – 2.0 ton/ha of various source of Si to Si deficient paddy field to reduce blast intensity in Japan. Zhu and Chen (1963) [86] conducted extensive field trials with different blast furnace slags in different soil and crop and found increased yield and quality of various crops. However, it was not until the late 1980s that Si began to attract the attention of a broader group of plant scientists.

Research work on silicon are being done since 150 years in some countries like China, Japan, America and Europe but since the last two decade extensive works have been done and scientists are able to understand various roles played by silicon in plants. Si acts as physical or mechanical barrier and enhances plant resistance to toxic elements, reduces oxidative stress and helps in alleviating the salt damage, alleviate drought stress by improving plant water status, photosynthesis and mineral nutrient absorption, improves the yield and quality of some crops and helps in decreasing the susceptibility to disease and insect damage (Zhang *et al*., 2015). Hundreds of studies performed with several plant species and under diverse growth conditions have demonstrated the favorable benefits of Si fertilization, particularly in alleviating biotic and abiotic stresses (Fauteux *et al*., 2005) [21].

Availability of Silicon in Soil and Plant

Silicon remains in two forms: crystalline and amorphous. In general quartz is considered to be most stable SiO_2 mineral at normal temperature and pressure. The crystalline aluminosilicates or SiO_2 are highly weather resistant with the resistance depending largely upon their structure. Silica is synonymous with silicon dioxide (SiO_2). Silica is commonly found in nature as beach sand. It exists in many different forms that can be crystalline as well as non-crystalline (amorphous). Crystalline silica is hard, chemically inert and has a high melting point. Quartz is the most common form of crystalline silica and is the second most common mineral on the earth's surface. It is found in almost every type of rock i.e. igneous, metamorphic and sedimentary. Since it is so abundant, quartz is present in nearly all mining operations.

Available Si in soils refers to the amount of Si that can be taken up by plants during the growing season and usually considered an index of Si-supplying power or capacity of soils. Silicon is taken up by plants in the plant available form such as silicic acid or mono silicic acid (H_4SiO_4). The plant available Si found in soil varies considerably ranging from 10 ppm to over 100 ppm (Liang *et al*., 2015) [43]. Soils with less than 20 ppm of Si are considered as Si-poor and mostly advised to supplement with Si-fertilizers. Among several natural sources, Wollastonite is one of the most preferred and affordable sources for Si-supplementation. Wollastonite is a naturally occurring metasilicate of calcium ($CaSiO_3$), and contains a major portion of calcium (Ca, 34.3%) and Si (24.3%) with minor amounts of aluminium (Al), iron (Fe), manganese (Mn), magnesium (Mg), potassium (K), and sodium (Na) (Maxim *et al*., 2008) [52].The other less preferred natural Si-sources includes minerals such as calcite, diopside, garnet, idocrase and quartz. Additional sources used for Si supplementation in crop plants are steel slag, potassium silicate, sodium silicate and sugarcane bagasse, etc. (de Camargo *et al*., 2013; Tubana and Heckman, 2015) [11, 78]. The monomeric form of silicic acid is the plant available form of soil Si (Williams and Crerar, 1985) [83] whereas the polymeric form has a role in improving soil aggregation and water-holding capacity due to its property to link soil particles by creating silica bridges. Most of the Si present in soil is in an insoluble form and is of no use in agronomy and horticulture. Thus, for making the Si available to the plant, the soil is subjected to chemical and physical weathering. The weathering process of silicate minerals depends on environmental factors such as temperature and pH as well as the physicochemical characteristics of the minerals (Heaney *et al*., 1994; Gérard *et al*., 2002) [29, 24]. Moreover, the concentration of Si in plants mainly depends on the concentration of silicic acid in soil solution (Ding *et al*., 2005; Henriet *et al*., 2008) [12, 30] and not on the concentration of total Si present in the soil (Brenchley and Maskell, 1927) [6].

Generally, Si is absorbed and transported by plants in the form of monosilicic acid [$Si(OH)_4$]. However, in the soil solution $Si(OH)_4$ is easily polymerized into polysilicic acid which is in dynamic equilibrium with amorphous and crystalline silicate. Thus available Si in soils includes monosilicic acid in soil solution and parts of silicate compound that can be easily converted into monosilicic acid such as polysilicic acid. The availability of Si in soil is determined by the rate of replenishment of Si in soil solution and the rate of Si uptake during plant growth (Marschner, 1995) [48].

In nature, microbes convert unavailable forms of silicon into silicic acid which is a bioavailable form of silicon. Microorganisms are known to play major role in dissolution of minerals like silicates and phosphates (Lee *et al*., 2019) [38]. Several beneficial microbes have been reported for their positive impacts on plant under different stress conditions through better uptake of these minerals (Rogers and Bennett, 2004; Lee *et al*., 2019) [63, 38]. Solubilisation of insoluble silicon due to organic acid production by microbes is known to enhance their availability to plants (Ameen *et al*., 2019) [3]. Various studies have reported weathering of silicates by bacteria for its dissolution to make it available to the plants (Chandrakala *et al*., 2019) [7]. Number of bacterial strains of genus *Bacillus*, *Pseudomonas*, *Proteus*, *Rhizobia*, *Burkholderia*, and *Enterobacter* are known to release silicon from silicates and promote plant growth (Wang *et al*., 2015; Kang *et al*., 2017; Kumawat *et al*., 2017; Chandrakala *et al*., 2019; Lee *et al*., 2019) [79, 36, 37, 7,38].

Factors influencing Si Availability in soil

Parent material and type of soil: Soil availability and Si-supplying power vary with soil types, depending mainly on the type of parent materials, weathering and eluviation and illuviation. Soils derived from granite and peats are prone to Si deficiency, while those developed from basalt and volcanic ashes are Si sufficient. Upland soils (i.e. ultisol and oxisol soil orders) which are often leached, acidic and highly weathered in the humid tropical areas are more prone to Si deficiency compared to lowland paddy soils, (Winslow *et al*. 1997) [84]. Li *et al.* (1999) [42] reported three categories of soils in terms of Si availability. The first is the soils derived from granite, quartzite and alluvial deposits and because of their sandy texture and strong leaching loss, they had lowest averaged available Si contents. The second is the soils developed from red sandstone, perlite, lacustrine deposits and quaternary red earth. These soils, mainly due to desilification and fersialitization, had lower average available Si; these soils are deficient or severely deficient in Si. The third is the soils had higher available Si content due to their clayey soil texture. These are the soils derived from purple rock and limestone

Land use pattern: Agricultural activities as land use can significantly alter the biogeochemical silica cycle, thus affecting terrestrial silica mobilization and the availability of Si for the growth of terrestrial plants and oceanic phytoplankton blooms (Struyf *et al*., 2010) [70].

Soil pH: The concentration of monosilicic acid is strongly dependent upon soil pH. The lowest concentration is observed at pH 8–9, below or above which the concentration of monosilicic acid increases significantly. Si concentration in soil solution may rise sharply when pH value decreases from 7 to 2 (Beckwith and Reeve, 1963) [5]. Soil-available Si content in acid soils increased with increasing pH, organic matter and clay content (Qin *et al.*, 2012) [60].

Soil texture: Many studies have shown that soils with light or sandy texture are usually deficient in available Si and thus have low Si-supplying power, while those with heavy or clayey texture are Si sufficient (Li *et al.*, 1999) [42]. Soil-available Si content is positively correlated with clay content in soils (Dai *et al.*, 2004) [10] as soil clay minerals with high specific surface have a high capacity to adsorb silicates.

Soil Redox potential (E_h): Soil E_h is one of the most important factors that influence the solubility of soil Si. Flooding results in soil reduction, lowering soil E_h and normally leading to an increase in soil-available Si concentration with submergence time (Ponnamperuma, 1965) [59]. Liang *et al.* (1992) [44] added that Si concentration, after several months of submergence, Si concentration may be lower than at the beginning. However, Wei *et al.* (1997) [80] reported that effect of Eh on Si availability depended upon soil types.

Si accumulation in plants

Higher plants differ characteristically in their capacity to take up silicon (Marschner, 1966) [49]. Some plants absorb more silica than they require and this gets deposited on tissues as it cannot be excreted (Esan, 1953) [19]. Depending on their SiO_2 content, they can be divided into three major groups: wetland Graminaeae, such as wetland rice or horsetails (Equisetum), 10–15%; dryland Graminaeae, such as sugarcane and most of the cereal species and a few dicotyledons, 1–3%; and most dicotyledons, especially legumes, <0.5% (Takahashi and Miyake, 1977) [74].

Among the plants, silica concentration is found to be higher in monocotyledons than in dicotyledons and its level shows an increase from legumes < fruit crops < vegetables< grasses < grain crops (Thiagalingam *et al.*, 1977) [76]. The aerial plant parts accumulate more Si than roots. In general the Si content of shoots tends to decline in following order: liver worts>horsetails>clubmosses>mosses>angiosperms>gymnos perms>ferns (Hodson *et al.*, 2005) [31]. Plants take up different quantities of silica according to the species (Russel, 1973) [64]. Rice, oat, rye and wheat seed coat accumulate most of the silica and grain the least (Gallo *et al.*, 1974) [23]. It was observed that the leaves and stems of maize and sorghum and the leaves of sugarcane and bamboo had more silica than other plant parts. It was reported that silica content of rice straw ranged from4 to 20% with an average of 11% (Ishizuka, 1971) [34]. Plants of the family Poaceae, Equisetaceae and Cyperaceae exhibit high silicon accumulation (>4% Si), the Cucurbitales, Uritcales and Commellinaceae show intermediate levels (2–4% Si) while most other species contain less silicon (<2% Si).

Response of crop to Si application during abiotic stress

Silicon nutrition alleviates many abiotic stresses including physical stress like lodging, drought, radiation, high temperature, freezing, UV and chemical stress like salt, metal toxicity, nutrient imbalance and many others (Epstein, 1994) [17].The roles of Si in alleviating the abiotic stress in plants are presented in Table 1.

Table 1: Role of Si in alleviating the abiotic stress in plants

Abiotic stress	Crops	References
Physical stress		
Lodging		
Drought	All crops	Marschner *et al.*, 1999 [50]
Radiation		
High temeperature		
Freezing		
UV etc		
Chemical stress		
Salinity	Rice	Natoh *et al*., 1986 [55]
	Wheat	Zaheer Ahmad and Ismail,1992 [85]
Mn toxicity	Bean	Horst and Marschner, 1978; Horiguchi, 1988 [33, 32]
Al toxicity	Rice	Li *et al*., 1989 [41]
Fe toxicity	Leaf freckle in sugarcane	Fox *et al*., 1967 [22]
Cd toxicity	Wheat, rice, maize	Rizwan *et al*., 2012 [62]

(Meena *et al*., 2014) [53]

Lodging: Accumulated silicon can provide rigidity and roughness to the walls of plant cells (Epstein and Bloom 2005) [16].Wiese *et al.* (2007) [82] explained in their study that silicon was transported passively in the transpiration stream, and deposited at sites of high transpiration.Rice requires large amounts silicon for its growth. It is estimated that nearly 20 kg of silicon is removed by rice plants from the soil for production of 100 kg brown rice (Dobermann and Fairhurst, 1997) [13]. Lodging is an important constraint in rice production especially in tall cultivars. It causes direct loss in grain yield and quality. Lodging may occur in vigorously growing rice plants after heading. Lodging resistance of a variety depends on its stem's resistance against external force, which is expressed as breaking resistance or strength, to represent the magnitude of force necessary to break the tissue. Breaking resistance can be measured with a bending hardness tester (Seko, 1962; Amano *et al.*, 1993) [67, 2]. The degree of lodging is reportedly positively correlated to length of culm, length of the basal internode, total length of the upper three leaf blades, length of the 6th internode from the top (N6); the basal internode is particularly important (Ookawa and Ishihara, 1992; Ookawa *et al.*, 1993) [57, 58]. Higher plant height, internode elongation, culm thickness, bending moment and break resistance were reported by Fallah (2012) [20] with the application of Silicon solution. As a result of application of higher concentration of Silicon solution (100 ppm) the lodging index was found to be significantly reduced compared to control (0 ppm Si), which indicated that lodging was reduced due to application of silicon in rice plants. This is due to the induced physical strength to the culm of rice by silicon.

Drought: Drought is one of the most limiting environmental stresses for plant production. The growth and development of plants experiencing occasionally periods of drought depend on the ability of stomata to control water loss. Plants respond to drought by closing their stomata, which reduces leaf transpiration and prevents excessive water loss from their tissues. The control on leaf stomata closure is a crucial mechanism for plants since it is essential for both CO_2 acquisition and desiccation prevention. In most cases, silicon does not appear to be beneficial to plants until some stress is imposed (Epstein and Bloom, 2005) [16]. Silicon (Si) plays an important role in plant health when plants are exposed to multiple stresses. As a physico-mechanical barrier, Si is part of the epidermal cell walls and vascular tissues. One major contribution of Si is a reinforcement of cell walls by deposition of solid silica. It is hypothesized that as water is transpires from the plant; silicic acid accumulates and forms colloidal silicic acid, then amorphous silica. These silica deposits in plants are called phytoliths, or plant opal. In addition to naturally occurring soluble Si in the soil, many crops respond positively to additions of supplemental Si. Chen *et al.* (2010) [8] reported that application of 1.5 mM silicon to drought-stressed rice significantly ($P<0.05$) increased total root length, surface area, volume, and root activity. In many cases these parameters were even equivalent to those observed in non-stressed plants.

Silica solubilizing microorganisms (SSM) are potentially useful in solubilizing insoluble forms of silicate. The application of Sodium silicate and silicate solubilizing bacteria (SSB-bio-silica) on oil palm seedling had a significant effect on stomatal opening in the period after drought stress treatment (Santi *et al.*, 2018) [66]. Application of silicon can significantly improve water status in non-irrigated crops.

Heat stress: Leakage of cytoplasmic solutes from plant tissues is often used as an indicator of cell membrane damage after exposure to stress condition such as chilling, freezing, high temperature, drought, pollution etc. Silicon plays a significant role in maintenance of the integrity of cell membranes and therefore Si-treated plants acquire tolerance to these stress conditions. Agarie *et al.* (1998) [1] reported that electrolytic leakage caused by high temperature (42.5°C) was lower in the rice leaves grown with Si than in the leaves grown without Si. They found the involvement of silicon in the thermal stability of lipids in cell membranes and suggested that silicon prevents the structural and functional deterioration of cell membranes when rice plants are exposed to environmental stress.

Chilling stress: Low soil temperature during winter is a major constraint for the cultivation of tropical and subtropical crops which is associated with inhibition of root growth and activity, affecting early growth and plant performance and final yield. Mitigation of oxidative stress is a major effect of Zn, Mn, and Si applied as cold stress protectants. Moradtalab *et al.* (2018) [54] reported that silicon and micronutrient Zn and Mn were associated with increased activity of superoxide dismutase, a key enzyme for detoxification of reactive oxygen species, depending on Zn and Mn as cofactors in shoot and roots increased tissue concentrations of phenolics, proline and antioxidants, but reduced levels of H_2O_2.

Salt stress: Silicon helps to reduce the ill effects of high salt concentration in soil. The role of Si in soybean growth and its effectiveness in salt stress alleviation was investigated by Lee *et al* (2010) [39]. Sodium chloride (NaCl) significantly decreased growth attributes and endogenous gibberellins levels. The plant growth attributes, i.e. root length, plant dry biomass, chlorophyll contents and endogenous gibberellins (GAs) level improved with 2.5 mM Si treatment. Scientists suggested that Si application alleviates the detrimental effect of salinity stress on growth and development of soybean.

Heavy metal toxicity

Cadmium: Cadmium (Cd) is one of the most toxic elements of the earth, released from natural and anthropogenic sources which pose detrimental hazardous effects both in plant and animal kingdoms. Cadmium possesses various degrees of phytotoxicity and exhibits potential health problems when accumulated in edible parts of crops plant. Cd threats seed germination and seedling growth disrupts, photosynthetic machinery and cellular redox damages meristem nucleoli and disrupts protein structure. Apart from these, Cd-induced growth inhibition, leaf rolling, chlorosis, necrosis, reduced water potential and even death are common phenomena. Cadmium induces oxidative stress indirectly by enhancing Reactive Oxygen Species (ROS) production; such as singlet oxygen ($^1O_2$), superoxide radical ($O_2^{\bar{}}$), hydrogen peroxide (H_2O_2), and hydroxyl radicals ($OH^·$). Cadmium toxicity was evident by an obvious oxidative stress through sharp increases in H_2O_2 content and lipid peroxidation (malondialdehyde, MDA content), and visible sign of superoxide. Exogenous application of Si in Cd treated seedlings reduced H_2O_2 and MDA contents and improved antioxidant defence mechanism through increasing the non-enzymatic and enzymatic antioxidants activity (Hasanuzzaman *et al.*, 2017) [28]. Thus Si reduced oxidative damage in plants to make more tolerant under Cd stress through augmentation of different antioxidant components. The presence of Si in plant growing medium decreases Cd uptake through root and then decreases the transfer of Cd to shoot which reduces Cd-induced cellular damages (Srivastava *et al.*, 2015; Tang *et al.*, 2015) [69, 75], decreasing Cd uptake and increasing antioxidant enzymes and photosynthesis.

Manganese: Manganese (Mn) is an important essential micronutrient for plant growth, but it easily becomes toxic above physiological levels. Mn toxicity occurs frequently in highly reduced paddy soils (waterlogged lowland soils) or in highly weathered acidic soils of tropical and subtropical areas. In general, the visual symptoms of Mn toxicity will vary with the plant species and plant sensitivity to excess Mn supply. Toxicity occurs at leaf Mn concentrations ranging from 200 to 5,300 mg/kg (Edwards and Asher, 1982; Clarkson, 1988) [15, 9]. Symptoms of Mn toxicity are quite diverse among plant species, but brown spots on older leaves near the main and secondary veins surrounded by chlorotic zones are the typical ones (Li *et al.*, 2012) [40]. At high Mn concentration (100 µM), Si-treated plants (+Si) showed a tendency to accumulate even higher Mn concentrations than non Si treated plants (-Si). Symptoms of Mn toxicity (e.g. brown spots, small chlorotic regions with necrosis) appeared in the older leaves of plants without Si treatment (-Si) plants subjected to excessive Mn. The symptoms of Mn toxicity were absent in the leaves of Si treated plants, in spite of the high level of Mn supply. It indicates that Si has protective effect under excess Mn (Iwasaki and Matsumura, 1999) [35].

Zinc: Experiment was conducted in China to elucidate the roles of silicon (Si) in enhancing tolerance to excess zinc (Zn) in two contrasting rice (*Oryza sativa* L.) cultivars: i.e. cv. TY-167 (Zn-resistant) and cv. FYY-326 (Zn-sensitive). Rice plants were grown in the nutrient solutions with normal (0.15 μM) and high (2 mM) Zn supply, without or with 1.5 mM Si. Significant inhibitory effects of high Zn treatment on plant growth were observed. Zinc concentration higher than normal (0.15 μM) can be causing detrimental effect on growth of plants. Significant inhibitory effects of high Zn treatment on plant growth were observed with high (2 mM) Zn supply. Supply of Si significantly decreased Zn concentration in shoots of rice indicating lower root-to-shoot translocation of Zn (Song *et al.*, 2011) [68]. Scientists suggest that Si-mediated alleviation of Zn toxicity is mainly attributed to Si-mediated antioxidant defence capacity and membrane integrity.

Arsenic: Silicon accumulate Arsenic (As) at higher levels than many other species, because as and silicic acid share the same carrier (Chen *et al.*, 2012) [9]. A higher level of as in plants demonstrates the potential use of Si in soil remediation techniques, such as phyto-stabilization and phyto-extraction. Scientists explain that Si changes the forms of as taken up by plants and accumulated in different plant parts. Thus vegetative growth is not affected and no toxicity symptoms are observed, even with higher as content in the tissue. The various chemical forms of as may represent different toxicity levels. The biotransformation of As^{3+} into the less toxic As^{5+} through oxidation, mainly using Fe and sulphates, is one of the mechanisms activated in both prokaryotic and eukaryotic microorganisms (Halter *et al.*, 2012) [27].

Other metal toxicities

The inclusion of Si to rice was found to significantly reduce Fe toxicity symptoms (Dufey *et al.*, 2014) [14]. Both Si pretreatment and continuous Si supply significantly helped to overcome the inhibitory effect of Al on root elongation in five varieties of *Stylosanthes* (Zhang *et al*., 2009) [87]. Si was found to be effective in mitigating Cr toxicity in rice (Tripathi *et al.*, 2012) [77]. Si supply alleviated the inhibitory effect of Pb on the growth of maize (Araujo *et al.*, 2011) [4]. All the symptoms of Zn toxicity in rice were significantly alleviated by the addition of Si (Song *et al*., 2011) [68]. Si accumulation in plants does not always have positive effects on dry matter product, but it can bring other beneficial effects, such as protection against physiological stress by improving the photosynthetic apparatus (Mattson and Leatherwood, 2010) [51].

Conclusion

Silicon (Si) is a ubiquitous, tetrahedral metalloid and the second most abundant element after oxygen, comprising approximately 27.7% of the Earth's crust. Despite its ubiquity and abundance in both soils and plants, Si has not yet been considered an 'essential' mineral element of any terrestrial higher plant, except the members of Equisetaceae (Diatoms). Si acts as physical or mechanical barrier and enhances plant resistance to toxic elements, reduces oxidative stress and helps in alleviating the salt damage, alleviates drought stress by improving plant water status, photosynthesis and mineral nutrient absorption, improves the yield and quality of some crops and helps in decreasing the susceptibility to disease and insect damage. The plant available Si-form found in soil varies considerably ranging from 10 ppm to over 100 ppm (Liang *et al*., 2015). Soils with less than 20 ppm of Si are considered as Si-poor and mostly advised to supplement with Si-fertilizers. Among several natural sources, Wollastonite (Si-24.3%) is one of the most preferred and affordable sources for Si-supplementation. Microorganisms are known to play major role in dissolution of silicon minerals. Several beneficial microbes have been reported for their positive impacts on plant under different stress conditions through better uptake of these minerals. Number of bacterial strains of genus *Bacillus*, *Pseudomonas*, *Proteus*, *Rhizobia*, *Burkholderia*, and *Enterobacter* are known to release silicon from silicates and promote plant growth.

Soil availability and Si-supplying power vary with soil types, depending mainly on the type of parent materials, weathering and eluviation and illuviation, soil type, land use, pH, texture and redox potential etc. All terrestrial plants contain some silicon (Si) in their tissues and the concentration of Si in shoots varies greatly among plant species. By application of silicon externally plants lodging can be reduced. Abiotic stresses like heat, cold, drought, salt stress and heavy metal toxicity in plants can be alleviated with the application of silicon.

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