Silicon as a Beneficial Element and as an Essential Plant Nutrient: An Outlook

Ibrahim H. Elsokkary[1]

ABSTRACT

Silicon application has been known to enhance the plant tolerance against several biotic and abiotic stresses. The mechanisms of alleviation of UV-radiation, drought, salt, and heavy metal stresses have been investigated but still definitely unknown. As a consequence, the needs for understanding the role of Si in the physiological and biochemical processes in plants are of a major importance. In most cases, the published data supported the role of Si in regulation and alleviation the adverse effects of several environmental stresses under specific conditions and for specific plant species.

The physiological functions of Si in plants have been studied and showed that Si influx and efflux is regulated by specific genes in plasma membrane of plant cells. The role of these genes in Si transport and alleviation several stress conditions is still poorly understood.

The occurrence of high Si content in tissues of graminaceous plants (rice, barley and maize) has positively activated physiological, physical and biochemical defense mechanisms for increasing stress balance, such as decreased lipid peroxidation, reduced membrane permeability, and stimulation of defense enzymes activities. The activities of stress defense enzymes, also called antioxidative enzymes (ascorbate peroxidase, catalase, peroxidase, and superoxide dismutase), have been found to be linked to Si nutrition especially under abiotic stress conditions.

There are genotypic differences controls the accumulation of Si within a specific plant species, such as rice. These differences are originated from variations in abundance of certain transporters of Si in roots or/and shoot of plant. These genotypic differences allow the plant to facilitate high growth under abiotic stress conditions. However, the responsible genes for Si accumulation in plant varieties have not yet been well characterized.

Harvesting cultivated high Si – accumulator plant species results in removal of large quantity of available Si from soil. In order to replenish the needed amount of available Si from such soil, application of Si – fertilizer would improve its status in soil and maintain appreciable amount of available Si in this soil. Fertilization of soil by the required and safe rate of Si has been found to improve the chemical, physical and biological properties of plant and soil. Tests for available Si in soil and for Si content in specific plant tissue in combination with evaluation of the quantitative relationship between both would be reliable guides for Si–fertilization. In this concern, whether Si is known as a beneficial element or as an essential plant nutrient, the use of Si compounds as a fertilizer or as an amendment has been proved to be of a major importance in the present and near future.

Key words: Silicon, Deposition, Antioxidant enzymes, Drought stress, Heavy metals, Fertilization

INTRODUCTION

Silicon is a beneficial element to plant growth. It is indispensable to plant life cycle but has not been proved to be essential to all higher plants. Early researchers considered silicon as an essential element for plants because it constitutes a high proportion of plant contents (Table 1). Other researchers reported that it may he essential only to some plant species including rice, barley, and sugarcane. Several research studies considered Si as a major inorganic constituent in higher plants and its application is very important for production of many crop species.

Silicon occurs in soils as silica (silicon dioxide: SiO_2), silica gel (a form of silica which has a highly porous structure capable of adsorbing 40% of its weight water from the saturated vapour), silicate (a salt of silicic acid, H_2SiO_3, that occurs in a very large number of rocks, earths) and other minerals consist of silicate of calcium, aluminium, magnesium and/or other elements. It occurs also in the form of meta-silicic acid ($SiO_2.H_2O$) and ortho silicic acid ($SiO_2.2H_2O$).

Silicon is a non-metal of 28.086 atomic weight, 14 atomic number and occurs in two allotropic forms: a brown amorphous powder and a dark gray crystal, of specific gravity of 2.42 and melting point of 1420°C.

Table 1.Average values of the contents of some elements in higher plants

Element	mg kg^{-1} DM	Element	mg kg^{-1} DM
N	1.5	Ca	0.2
K	1.0	Mg	0.5
P	0.2	S	0.2
		Si	1.2

Silicones are compounds having the general formula: R_2SiO, where R stands for hydrocarbon radicals, and defined as polymeric organic silicones of the general type: $(R_2SiO)_n$.

---

[1] Department of Soil and Water Sciences, Faculty of Agriculture,
El-Shatby, Alexandria University, Egypt
E-mail address: elsokkary35@gmail.com

Received September 05, 2018, Accepted September 30, 2018

The primary significance of Si is consecrated with certain groups of plant species, i.e, monocotyledons such as cereals. Small amounts of this element have been shown to be of a vital role in plants. Because old soils can be depleted from adequate levels of available Si, the determination of this portion in soils could permit quantitative estimation of Si supplementation need of the plant. The objectives of this article, therefore, were to investigate the role of Si in the growth performance of different plant species, in alleviation of different abiotic stresses on plant, and in amelioration and fertilization of soils.

Silicon in soils

Silicon is the second abundant element in the lithosphere after oxygen. In soils, its concentration varies from 5 to 40%Wt (Kovda, 1973), while the common concentrations vary from 23 to 35%Wt with an average value of 32.0% (Lindsay, 1979). Wedepohl (1995) reported an average value of 28.8%Wt of Si content in most soils.

Despite its abundant in soil, it is not usually occurred in a free element but it is always combined with other elements forming oxides and silicates (Richmond and Sussman, 2003). As a result, silicon dioxide (SiO_2) comprises from 50 to 70%Wt of the soil mass (Ma and Yamaji, 2006).

In spite of its high total content in soil, most Si compounds are insoluble in soil solution and are resistant to weathering and decomposition. This makes the concentration of Si in soil solution is extremely low and normally in the range from 0.1 to 0.6 $mMSiL^{-1}$ (Epstein, 1994; Sommer et al., 2006).

Silicon exists in soil in both the solid and liquid phase. The solid phase can be divided into crystalline, poorly crystalline and amorphous (Sauer et al., 2006). The amorphous silica consists from pedogenic amorphous inorganic silica, such as opal, and biogenic silica including phytoliths which is opal polymerized in plant (Iller, 1979). The phytoliths consists of about 92%Wt silica and 6%Wt water in addition to small amounts of carbon and traces of Fe and Al (Richmond and Sussman, 2003). The phytuliths contents in soils vary from 0.03 to 0.06%Wt (Desplanques et al., 2006). The crystalline forms of silicates are usually bio-geochemistry inert (Savant et al., 1999).

The different compounds of Si have different dissolution limits, i.e, the solubility of quartz is low compared to that of the easily soluble amorphous silica and diatomaceous earth (Savant et al., 1999). The solubility of inorganic silicate in soil, generally, is in the range 1.8 – 2.0 $mMSiL^{-1}$ (Karathananasis, 2002) but commonly from 0.1 to 0.6 $mMSiL^{-1}$ (Faure, 1991), while that of quartz is in the range 0.10 – 0.25 mM (Iller, 1979; Lindsay, 1979; Drees et al., 1989).

The solubility of biogenic silica is 17 times higher than that of quartz (Fraysse et al., 2006), while the solubility of polymorphs silica is constant between pH 2.0 – 8.5, but increases rapidly near pH 9.0 (Fraysse et al., 2006).

The chemically active Si in soil solution is represented by monosilicic acid ($SiOH_4$), polysilicic acid as well as Si – complexes with inorganic and organic compounds, i.e, organosilicates (Matichenkov and Ammosova, 1996; Berthelesem et al., 2001; Matichenkov and calvert, 2002; Carnelies et al., 2011).

The solubility of Si in soil is affected by several dynamic factors such as particle size and surface area of Si–fertilizer, soil pH, organic complexes, the presence of Al, Fe, P ions, temperature, moisture content in soil and precipitation/dissolution reactions (Berthelsen et al., 2001). When the concentration of Si OH_4 in soil solution exceeds 65 $mgSiL^{-1}$, silicic acid is polymerized forming Si-gel (Savant et al., 1999).

Silicon Content and Uptake in Plant

Plant differs widely in their capacity to absorb and accumulate Si in their tissues. As a result, Si concentration in plant shoot greatly varies according to plant species and ranges from 0.1 to 10.0% DM (Raven, 1983; Epstein, 1994, 1999; Marschner, 1995; Ma and Takahashi, 2002; Richmond and Sussman, 2003; Hodson et al., 2005, Ma and Yamaji, 2006).

Based on Si concentration in shoot, plants are classified into accumulator, intermediate and excluder (Takahashi et al., 1990). Plant species containing more than 1.0% Si are Si – accumulators, those containing between 0.5 and 1.0% Si are Si-mediators and those containing less than 0.5% are Si–excluders (Table 2). These variations have been attributed to difference in Si uptake ability by plant roots (Ma and Yamaji, 2006). The majority of Si – accumulators is belonging to the monocotyledons, i.e, rice, sorghum and sugarcane (Ma et al., 2001; Ma and Takahashi, 2002). For most plant species, Si content in plant tends to increase with plant age (Jones and Handreek, 1967) and usually high Si concentration is found in older leaves.

Silicon is taken up by plant roots in the form of unchanged monosilicic acid ($H_4SiO_4°$) and is transported from roots to shoots via the xylem (Casey et al., 2003). The wide variations of Si concentrations in the different plant species are attributed to differences in the mechanisms of Si uptake by roots and its transport from roots to shoots. Active uptake has been demonstrated in graminaceous such as rice (Takahashi et al., 1990; Ma et al., 2001; Rains et al., 2006), barley

Table 2. Silicon concentration in shoot of different plant species*

Plant species	Common name	Si%Wt
Lactuca serriola	Lettuce	0.97
Helianthus	Sunflower	1.88
Glycine max	Soybean	1.39
Lupines nanus	Lupine	0.28
Phaseolus vulgaris	Bean	0.95
Menthe longifolia	Mint	0.73
Menthe piperita	Peppermint	1.22
Allium fistulosum	Onion	0.31
Musa basjoo	Banana	0.98
Hordeum vulgare	Barley	1.82
Oriza sativa	Rice	4.17
Saccharum officianum	Sugarcane	1.51
Sorghum bicolor	Sorghum	1.54
Triticum aestivum	Wheat	2.45
Zea mays	Maize	0.83

* : Ma and Takahashi (2002); Hodson et al. (2005)

(Barber and Shone, 1966) wheat (Rafi and Epstein, 1999; Casey et al., 2003), and maize (Liang et al., 2006 a). Passive uptake has been demonstrated in some dicotyledons (Takahashi et al., 1990; Ma et al., 2001; Mitani and Ma, 2005; Liang et al., 2005; Balakhnina and Borkowska, 2013). Both active and passive uptake mechanisms can coexist in rice, maize and sorghum depending upon Si concentration in the external solution (Liang et al., 2006 a; 2006 b). At high Si concentration, Si uptake by rice and maize is passive and at low Si concentration, the active mechanism is the dominant.

The Si content in plant root of 0.5% DM has been suggested to be the baseline for intermediate; passive uptake of Si, while Si content more than 0.5% DM has been indicated for active uptake (Ma et al., 2001).

Plants such as tomato (Solanum lycopersicum) and beans (Phaseoulus vulgaris) are not able to absorb high levels of Si from soil and can exclude Si from uptake (Takahashi et al., 1990; Mitani and Ma, 2005; Liang et al., 2006a).

The active of Si transport from the cortical cells and the xylem is responsible for high accumulation of Si in the shoot of rice (Liang et al., 2006 a) while the lower Si concentration in the shoots of cucumber and tomato is related to both lower Si uptake and transport from the cortical cells to the xylem (Liang et al., 2006 a).

Silicon – accumulator, intermediator and excluder plant species take up Si from the external solution by a similar transporter and with a K_m (Michaelis constant) value of 0.15 mM but with different values of V_{max} (maximal transport rate) which can be arranged in the order: rice > cucumber > tomato. This indicates that the density of Si transportation differs among these three plant species and the transport process, therefore, is energy dependent (Ma and Yamaji, 2006). This leads to higher concentration of Si in the xylem sap of rice than in that of cucumber or tomato. This indicates that xylem Si loading in rice is mediated by specific transporter while that in cucumber or tomato is mediated by diffusion.

Silicon translocated from roots to shoots, via the xylem, is subjected to further concentration as a result of water loss by transpiration. In rice, Si concentration in xylem sap is high and the process of xylem loading with Si is mediated by specific transporters (Mitani and Ma, 2005). The concentration of Si in xylem sap of rice is usually 20 and 100 fold higher than that of cucumber and tomato, respectively (Mitani and Ma, 2005). Also, the concentration of Si in xylem sap of cucumner and tomato is mostly lower than its concentration in the external solution. This makes the polymerization rate of Si in shoots of cucumber and tomato is very low (Mitani and Ma, 2005). Under these conditions and with increasing the amount of silicic acid absorbed by plant roots, the concentration of Si is increased and consequently is polymerized to colloidal silica and then to silica gel ($SiO_2.nH_2O$). As a result, more than 90% of the total Si in shoot of rice is present in the form of silica gel. The accumulation of Si in shoot of cucumber behaves in similar pattern as that of rice but with lower concentration (Ma and Yamaji, 2006).

Silicon as a Beneficial / an Essential Element

In the early 1900S, Si was recognized as one of the 15 elements needed for plant life (Tubana et al., 2016).

In spite of its high accumulation in plant, it is not considered an essential nutrient element for higher plants (Lewin and Reimann 1969; Epstein, 1994; 1999; Ma and Takahashi, 2002). However, its beneficial effects have been proved for a wide varieties of higher plants (Ma et al., 2001; Korndorfer and Lepsch, 2001; Ma and Takahashi, 2002; Richmond and Sussman, 2003; Ma, 2004). On the other hand, its essentiality has been known to diatoms and some members of rushes and algae (Epstein, 1999). Silicon can improve the tolerance of plant to several varieties of abiotic stresses, such as salt stress (Liang et al., 2003; Ashraf et al., 2010), drought stress (Hattori et al., 2005; Chen et al., 2011), and heavy metals stress (Neumann and Nieden, 2001; Nwugo and Huerta, 2008).

The well known definition of the essentiality of an element based by Arnon and Stout (1939) has been modified recently by Epstein and bloom (2005). Accordingly, the essential plant nutrient element should fulfil one or both of the following criteria: (1) the element is a part of molecule which is an intrinsic component of the structure of metabolism of the plant, and (2) the plant can be so severely deficient in the element that it exhibits abnormalities in growth, development or production, i.e., performance compared to plants with lower deficiency. According to this recently newly definition, Si can be an essential element for higher plants, which can be generally adopted in the near future (Epstein and Bloom, 2005).

Savant et al, (1997; 1999) considered Si an agronomical essential element for sustainable production of rice. In the same sense, Si has been proved to be essential for the healthy growth and development of a wide varieties of plant species (Ma et al., 2001; Richmond and Sussman, 2003; Ma, 2004; Currie and Perry, 2007). This can be due to its linkage to some physiological, morphological, nutritional and molecular processes in plants (Ma, 2004; Epstein and Bloom, 2005; Ma and Yamaji, 2006; Gunes et al., 2007; Pereira et al., 2013). In this aspect, Si is the element that does not cause severe injury to plant when it is taken in excess levels because it can provide multiple benefits (Ma et al., 2001).

The beneficial effects of Si are decreased under optimum growth conditions and are more evident under stress conditions (Epstein, 1994; Ma et al., 2001). In this concern, there is no evidence for Si enolvement in plant metabolism and also no Si – bearing organic compounds has been identified in higher plants (Ma et al., 2001; Knight and Kinarde, 2001).

Silicon Deposition in Plant: The unchanged silicic acid ($H_4SiO_4^\circ$) taken up by plant root is deposited as an amorphous silica (SiO_2.n H_2O, i.e, opal, silica gel or phytoliths) in higher plants (Esptein, 1994; Ranganathan et al., 2006). The deposited opal takes place in plant cell wall, intercellular spaces of roots, leaves and reproductive organs (Inanaga and Okasaka, 1995; Harrison, 1996). In some cases, Si deposits are precipitates combined with Zn or Al (Neumann and Zur Nieden, 2001). This co-precipitate could be a part of mechanisms that allows plant to ameliorate heavy metal toxicity (Neumann and De Figueiredo, 2002; Richmond and Sussan, 2003).

Silicon deposition, as polymerized Si O_2 in apoplast root, restricts ions transport from roots to shoots (Epstein, 1999; Wang et al., 2004) and decreases apoplastic bypass flow. It also provides binding sites for heavy metals which lead to a decrease of metal transport from roots to shoots (Ma and Yamaji, 2006).

Due to water loss via transpiration, silicic acid is concentrated in the leaves and then after is polymerized forming colloidal silicic compounds, i.e, silica gel ($SiO_2.nH_2O$) which may account for 90% of total Si in shoots (Ma and Yamaji, 2006). Silicon is also deposited in the transpiration sites where polymerization of amorphous silica takes place forming phytoliths (Jones and Handreck, 1067; Raven, 1983; Sangster et al., 2001; Lux et al., 2003). Organo-matrix of Si deposits are also formed with organic macromolecules (Neumann and De Figueiredo, 2002). The deposited Si in the epidermis of leaves and endodermis of roots (Raven, 1983; Lux et al., 2003) is polymerized and became unavailable to translocate within the plant (Raven, 1983).

The higher deposition rate of Si in shoot of rice is attributed to higher transportation rate of Si from root cortical cells to xylem, while the lower Si deposition rate in leaves of cucumber and tomato is due to lower transportation rate from the root cortical cells to leaves via xylem (Mitani and Ma, 2005; Mitani et al., 2005).

Most of the deposited Si, in cell walls of roots, stems, leaves and hulls, forms a thin layer consisting of silica gel. It is found that more than 80% of total Si in grains of 41 barely varieties is located in the hull with amounts ranging from 15.34 to 27.09 mg Si kg^{-1} DM (Ma et al., 2003).

Plant Erection (Rigidity): One of great importance is the contribution of Si in reinforcement of cell walls by deposition of solid silica (Currie and Perry, 2007). Silicon application, therefore, improves plant architectures; i. e., making it more erect, improving the angle of leaves and light interception, avoiding excessive self – shading, increasing the structural rigidity of plant tissue, reducing lodging and delaying senescence (Ma and Yamaji, 2006; Gong and Chen, 2012). In the same sense, Si improves structure integrity of plant (Epstein, 1999; and Ma, 2004), reduces lodging and leaf freckling of sugarcane. According to Marschner (1995), Si contributes to cell wall rigidity and strengthens and also increases cell wall elasticity during extension growth.

Silicon provides mechanical support for monocotyledons, i.e, inhances suberization, lignification, and silicification of cell wall. The structural stability of monocots is due to the binding of Si with cell wall hemicellulose which is a beneficial mechanism under water deficit condition (Saqib et al., 2008; Ma et al., 2015; Coskun et al., 2016).

Biosilicication in plant involves polymerization of silicic acid within apoplast leading to formation of an amorphous silica barrier restricting penetration of toxic metal into symplast and transporation stream (Wang et al., 2004; Ma et al., 2015; Coskun et al., 2016).

Plant Growth: Under normal soil conditions, silicon addition showed no significant effect on plant growth (Wu et al., 2015) and its beneficial role is usually decreased (Epstein, 1994; Kaya et al., 2006; Ma and Yamaji, 2006). However, under stress conditions, the biomass and crop yield of plants have been found to increase as a result of Si addition (Liang and Chen, 1994; Ma et al., 2001; Liang et al., 2005; Zuccarini, 2008; Matichenkov and Bocharinkova, 2008; Reezi et al., 2009; Hashemi et al., 2010; Crusciol et al., 2013; Shi et al., 2013; Kim et al., 2014; Maamoun, 2014; Wu et al., 2015; Adrees et al., 2015; Farooq et al., 2016).

Silicon treatment stimulated the growth of most plant species and increased the dry weight, total fruit number, total marketable fruit yield of strawberry (Miyake and Takahashi, 1986), increased leaf area, plant height, root volume and biomass of alfalfa (Wang and Han, 2007), increased the yield of common bean (Zuccarini, 2008) and seed yield of soybean, common bean and peanut (Crusciol et al., 2013), simulated plant height and stem diameter of chrysanthemum (Sivanesan et al., 2013), enhanced plant height and shoot dry weight of three rice cultivars (Shi et al., 2013) and rice biomass and yield (Savant et al., 1997; Farooq et al., 2016), produced the highest grain yield of wheat (Maamoun, 2014). Silicon application significantly increased plant height, leaf area index, and grain yield of maize (Amin et al., 2016), improved plant height, number of branches and leaves, fresh and dry weight of sweet pepper (Tantawy et al., 2015), increased plant height and number of branches per plant, number of head per plant, number of seeds per head and straw end seed yield of Egyptian clover (Ibrahim et al., 2015), increased plant height, root length, leaf area index of cotton (Adrees et al., 2015), and improved biological yield of bean (Abou Baker et al., 2012). Application of Nano-silica enhanced the germination and growth development of common bean (Alsaeedi et al., 2017), and the number of leaves and branches and seed dry weight of soybean (Suciaty et al., 2018).

Macronutrients Contents: Silicon addition reduced Na^+ uptake and content in shoots and translocation from roots to shoots of tomato and spinach (Gune et al., 2007), of alfalfa (Wang and Han, 2007), of common bean (Zuccarini, 2008), of rice, wheat and barley (Savant et al., 1997; Liang, 1999; Tuna et al., 2008) and of wheat (Maamoun, 2014). It also decreased Na^+, Cl^- and B accumulation in the shoot of tomato and spinach (Gunes et al., 2007), decreased Cl^- accumulation in leaves of tomato (Shi et al., 2013), and reduced Na^+ and Cl^- uptake by tomato roots and translication to plant shoot (Liang et al., 2015).

Potassium concentrations in roots and shoots of barley, grown under salt stress, have been increased by Si addition (Liang, 1999). Maamoun (2014) found that Si addition increased K^+ content and decreased Na^+ content in the grains of wheat. Silicon increase nitrogen use efficiency and P utilization in rice (Savant et al., 1997; 1999), and maintained adequate levels of P, K, Ca and Mg in shoots and roots of oil seed rape (Liang and Chen, 1994). It also maintained adequate K^+ content and uptake and increased its contents in roots and shoots of barley (Liang, 1999) and of wheat (Tuna et al., 2008), and enhanced K^+ uptake and reduced Na^+ uptake and increased K / Na ratio in plants (Imtias et al., 2016). It has been also found that foliar spray by Si (diatomite) had increased N, P and K uptake and content in wheat plant grown in clay soil (Hellal et al., 2012).

Enzymes Activities: Addition of potassium silicate to barley plant increased ATP-ase activity by two-folds as compared to plant grown without Si addition (Liang, 1999). Silicon enhanced also the activities of antioxidant enzymes in plants grown under salt stress (Liang, 1999 Zhu et al., 2004; Al Aghabary et al., 2004; Gong et al., 2005; Liang et al., 2006 b; Qian et al., 2006; Wang et al., 2011), while the concentration of hydrogen peroxide (H_2O_2) was decreased (Gong et al., 2005). Wang et al. (2011) found that Si addition increased ascorbate peroxidase (APX) activity in roots, shoots and leaves, catalase (CAT) activity in leaves, and peroxidase (POD) activity in shoots of two alfalfa cultivars grown under Cd-stress.

Silicon application to spinach, grown under salinity stress, decreased hydrogen peroxide (H_2O_2) and lipid peroxidation (LPO) while increased superoxide dismutase and catalase activities (Eraslan et al., 2008). The SOD, CAT and APX enzymes activities in leaves of spinach and tomato plants were increased as a result of Si treatment (Gunes et al., 2007). The activities of sucrose phosphate synthase and sucrose synthase in tomato plant were increased due to Si addition (Lee et al., 2002).Bu et al. (2016) found also that Si treatment of cucumber seedlings increased the activities of SOD, CAT and APX.

Photosynthesis: One of the benefits of Si addition to plants is improving the photosynthetic efficiency process (Ma and Yamaji et al., 2006; 2008; Sacala, 2009; Shen et al., 2010; Gong and Chen, 2012) while plants grown in Si-deficient soil showed disturbance in leaf photosynthetic efficiency (Liang, 1998). It has been proved that Si addition improved chlorophyll content and ultrastructure of chloroplast (Liang, 1998; Liang et al., 2003; Kaya et al., 2006; Quan et al., 2006; Tuna et al., 2008). It has been found that photosynthetic rate in leaves of soybean has been increased by 21% as a result of Si addition (Shen et al., 2010).

Recently, studies showed that Si addition had increased the chlorophyll a and carotene contents in wheat (Hellal et al., 2012), the contents of photosynthetic pigments in wheat (Gong et al., 2005), the photosynthetic rate in maize (Amin et al., 2016) and in wheat (Hijiboland et al., 2017), the chlorophyll of chrysanthemum (Sivanesan et al., 2013). It has been also found that foliar spray by Si increased chlorophyll pigments, chlorophyll a, chlorophyll b and carotenoids in leaves of wheat (Ibrahim et al., 2016).

Cell Membrane Stability: Excessive cell membrane damage of soybean caused by UV – radiation, drought, or salt stress (Shen et al., 2010) and of rice (Feng et al., 2011) was ameliorated by Si treatment. Protecting cell membrane of maize grown under drought stress from damage has been maintained by Si application (Kaya et al., 2006). Silicon addition to gerbera (Gerbera jamesonii) cuts (Kazemi et al., 2012) and to rose (Rose x hyprida L.) cut (Reezi et al., 2009) protected cell membrane from damage and restored membrane integrity and function. Gunes et al. (2007) found that oxidative membrane damage was protected by Si treatment of tomato and spinach grown under toxicity of Na^+, B and salt.

Water content in Plant: Silicon application improved water status of rice (Savant et al., 1999), maize (Gao et al., 2004; Kaya et al., 2006; Amin et al., 2016), tomato (Romero-Aranda et al., 2006; Gao et al., 2006), wheat (Tuna et al., 2008; Ahmed et al., 2012), gerbera cut (Kazemi et al., 2012), bean (Abou-Baker et al., 2012), sorghum (Hattori et al., 2005; Ahmed et al., 2011 a; 2011 b), papper (Pereira et al., 2013), and soybean (Shen et al., 2010). The Si treated plants maintained higher water content than those without Si – treatment when grown under drought condition (Ma et al., 2001; Kaya et al., 2006; Gong and Chen, 2012).

Irrigation water use efficiency (IWUE), water use efficiency (WUE). Economic water productivity (EWP), and relative leaf water content have been found to increase as result of Si addition to plants grown under salt stress (Shen et al., 2010; Gong and Chen, 2012; Abou-Baker et al., 2012; Amin et al., 2016). Improvement of water status in plants leaves was maintained at high level as a result of Si addition (Lobato et al., 2009; Ahmed et al., 2011 a; 2011 b) which has been attributed to reduced water loss via transpiration. This low transpiration has been achieved through Si deposition, as silica gel layer, on the epidermal cell walls (Gao et al., 2004; 2006; Romero – Aranda et al., 2006; Kaya et al., 2006; Tuna et al., 2008). It is also found that the improved structure integrity, of plant treated with Si, increased water retention in leaf tissue and maintained plant water balance (Ma, 2004; Hattori et al., 2005; Lobato et al., 2009).

The source of Si compound is an important factor in improving water status in plant. Foliar spray by K-silicate was more effective than Mg-silicate for improving water content in plant. This is due to the role of K in mitigating Na^+ toxicity and salt stress (Abou-Baker et al., 2012). High water content in plant would lead to salt dilution in plant tissues and consequently mitigates salt toxicity and in turn leads to higher plant growth (Romero – Aranda et al., 2006).

Role of Silicon in Plant under Stress Conditions

It has been reported that silicon alleviates various abiotic stresses those adversely affect plant growth including: physical stress i. e., drought, radiation, high and low temperature and freezing, and chemical stress i. e., salt, metal toxicity and nutrient imbalance (Ma, 2004; Ma and Yamaji, 2006; Ashraf et al., 2010).

Under stress conditions, the reactive oxygen species (ROS) are generated in plants under certain conditions and can exceed the antioxidant potential of plant cell and consequently cause its oxidative damage (Ali et al., 2013).

In the absence of Si, stomatal resistance, membrane permeability, lipid peroxidation, hydrogen peroxide and proline concentration are increased (Gunes et al., 2007). Plants under water deficit and salt stress conditions contain higher levels of proline than that of the normal plants and therefore addition of Si to pepper plants decreased proline concentration as compared to plants without Si treatment (Pereira et al., 2013).

Silica deposition underneath leaf cuticles forms subcuticular double layer which contributes in the reduction of water loss via transpiration, which thereby improves water status in plant grown under stress (Lux et al., 2002; Hattori et al., 2005).

Radiation Stress: Ultraviolet – B radiation adversely affects plant cell biology causing the generation of reactive oxygen species (ROS) which leads to plant damage (Zancan et al., 2008; Lizana et al., 2009). It causes also intensification of lipid peroxidation (LPO) and cell membrane damage in soybean seedlings (Shen et al., 2010), and in rice (Feng et al., 2011). Reactive oxygen species – mediated lipid peroxidation is considered the most damaging process in living organisms (Gill and Tuteja, 2010).

Silicon addition to soybean and sorghum seedlings increased plants tolerance to UV-B radiation stress and reduced cell membrane damage (Shen et al., 2010; Feng et al., 2011). It has been suggested that Si can protect leaves of sugarcane from UV-B radiation damage by filtering the harmful ultraviolet rays. In addition, Si application to sugarcane has been found to increase the activity of SOD compounds in leaves of plant subjected to UV-B radiation.

Drought Stress: Drought stress in one of the main causes of crop loss that reduces the average crop yield. Silicon supplementation has been proved to increase drought tolerance of sorghum (Hattori et al., 2005), cucumber (Liang and Romhold, 2005), wheat (Gong et al., 2003; 2005), soybean (Shen et al., 2010) and rice (Mauad et al., 2016).

The role of Si in increasing drought stress occurs by several physical, physiological and biochemical processes, i. e. (i) maintaining erection of leaves and structure of xylem vessels, water balance and photosynthetic efficiency (Hattori et al., 2005; Liang et al., 2005; Ahmed et al., 2011 a; 2011 b), (ii) stimulating the activities of antioxidant enzymes (Gong et al., 2005; Kiang et al., 2005; Wang et al., 2011) and photosynthetic rate (Gong et al., 2005; Liang et al., 2005; Chen et al., 2010; Amin et al., 2016), and (iii) increasing the concentrations of antioxidant metabolites (Liang, 1999; Al-Aghabary, et al., 2004; Zhu et al., 2004; Liang et al., 2006 b; Qian et al., 2006).

Silicon application improved water status in soybean grown under drought stress by 30% relative to the control treatment (Shen et al., 2010). It increased also relative water content in leaves of wheat (Gong et al., 2003; 2005) and of maize (Kaya et al., 2006; Amin et al., 2016) grown under drought stress.

Silicon addition reduced membrane damage of plant cells (Kaya et al., 2006; Shen et al., 2010; Feng et al., 2011), Na^+ uptake by cucumber (Liang and Romheld, 2005), alfalfa (Wang and Han, 2007) and common bean (Zuccarini, 2008), the concentration of hydrogen peroxide (H_2O_2) in plant leaves (Gong et al., 2005), lipid peroxidation (LPO) and membrane permeability (Farooq et al., 2015).

Liang et al. (2005) concluded that drought tolerance mechanisms, due to Si addition, included stimulation of antioxidant system and alleviation of specific ion effect. Hattori et al. (2005) summarized the role of Si in improving the physiological growth attributes of sorghum grown under drought stress as a result of addition of 10% K – silicate (Table 3).

Salt Stress: Salinity adversely affects plant growth via specific effects of particular ions or via raising the osmotic pressure of solution of the growth medium or by both. Salinity increases the indicative stress compounds, i.e., hydrogen peroxide (H_2O_2), proline concentration and lipid peroxidation (LPO) in spinach (Eraslan et al., 2008). In the absence of Si, stomatal resistance, membrane permeability, lipid peroxidation, hydrogen

Table 3. The values of physiological growth attributes of sorghum grown under drought stress as effected by addition of 10% K-silicate (Hattori et al., 2005)

Physiological attribute		Treatment	
		- Si	+ Si
Crop growth rate	g m^{-2} day^{-1}	9.72	17.80
Relative growth rate	g m^{-2} day^{-1}	81.55	97.00
Net assimilation	g m^{-2} day^{-1}	3.37	5.71
Leaf area	cm^2	181.08	193.50
Leaf area index		0.815	1.380
Net photosynthesis	μ mole m^{-2} sec^{-1}	9.42	15.95
Transpiration rate	mole m^{-2} sec^{-1}	5.39	0.05
Stomal conductance	mole m^{-2} sec^{-1}	0.28	0.38
Leaf membrane stability index		74.68	79.88
Leaf succulence	mg m^{-2}	14.41	8.79
Relative water content		72.59	89.05
Drought resistance index		0.39	0.53

peroxide and proline are increased in tomato (Gunes et al., 2007) and spinach (Eraslan et al., 2008). Several mechanisms have been reported to be responsible in the ameliorative effects of Si under salt stress such as improvement of plants' ability to take up water and nutrients from the soil, and activation of antioxidative defense (Currie and Perry, 2007; Zhu and Gong, 2014).

Silicon addition to barley grown under salt stress maintained membrane integrity and decreased membrane permeability of plant (Liang et al., 2003).

Silicon supply simulated the activities of root plasma / membrane H^+ -ATPase and tonoplast H^+ - ATPase which enhanced Na^+ efflux and K^+ influx of barley plant (Liang, 1999; Liang et al., 2003; 2006b). Silicon had been found to simulate the activity of antioxidant defines enzymes: superoxide dismutase, peroxidase, catalase, glutathione reductase, and glutathione concentration in salt stressed plants (Liang et al., 2003; 2006b; Zhu et al., 2004; Al-Aghabary et al., 2004; Shi et al., 2016). Silicon decreased the concentration of malondialdehyde, the end product of lipid peroxidation in salt-stressed barley; which positively correlated with Na^+ content and negatively correlated with Ca^{2+} and K^+ uptake (Coskun et al., 2016). Under salt stress, Si decreased Na^+ uptake but increased K^+/Na^+ ratio, and alleviated Na^+ toxicity in barley (Liang, 1999).

Silicon application alleviated the adverse effect of salt stress on the growth and crop yield of barely (Liang et al., 2003), wheat (Saqib et al., 2008; Maamoun, 2014), rice (Shi et al., 2013), common bean (Zuccarini, 2008), cucumber (Zhu et al., 2004; Matichenlov and Bocharinkova, 2008), canola (Hashemi et al., 2010), tomato (Al-Aghabary et al., 2004; Gunes et al., 2007), spinach (Eraslam, 2008), alfalfa (Wang and Han, 2007), sugarcane (Ashraf et al., 2010), Egyptian clover (Ibrahim et al, 2015), and sorghum (Abdel-Latif and El-Demerdash, 2017).

Under salinity (120 mM/L NaCl), the activity of ATP-ase was decreased by 66% in salt-tolerant barely cultivar and by 75.8% in salt – sensitive one, compared with plant grown under non-saline condition. Silicon addition to the two barely cultivars increased enzyme activity by 2 folds as compared to plants grown without Si addition (Liang et al., 1999).

Lee et al. (2002) found that Si application to tomato, grown under salt stress, increased sucrose phosphate synthase and sucrose synthase activities.

Romero – Adranda et al (2006) found that Si addition to tomato, grown under salinity stress (80 mM/L^{-1} NaCl), increased plant water content by 40% and water use efficiency by 17% higher than the salinized plant without Si treatment. Gao et al. (2004) reported that Si addition improved water use efficiency of maize grown under salinity stress.

Silicon application to spinach, grown in saline soil, increased plant tolerance to salinity stress by enhancing antioxidant systems and protecting plant from oxidative damage, i.e. decreasing hydrogen peroxide (H_2O_2) and lipid peroxidation (Eraslan et al., 2008).

Several mechanisms have been suggested, to be responsible as an ameliorative agent for Si to improve plant growth under salt stress such as, improving plants' ability to take up nutrients and water from soil and activating antioxidative defense in plant (Currie and Perry, 2007; Zhu and Gong, 2014). Silicon application, to wheat grown under salt stress, decreased Na^+ in the cell sap and increased its concentration in the cell wall – bound fraction which indicates that the mechanism of Na+ detoxification is mediated by Si (Hajiboland et al., 2017).

Heavy metals Stress: Heavy metals toxicity causes inhibition of plant growth, disruption of physiological and biological processes in plant (Das et al., 1998; Song et al., 2009; Rizwan et al., 2012; Keller et al., 2015; Bu et al., 2016; Farooq et al., 2016). It also causes generation of reactive oxygen species (ROS), damage of membrane permeability and functions (Shah et al., 2001; Pal et al., 2007; Vaculik et al., 2009; 2012; Farooq et al., 2016). Cadmium inhibits photosynthesis rate in plant as a result of the decrease in both stomatal conductance and photosynthetic pigments concentration, and also alters leaf structure and reduces antioxidant enzyme activities (Shi and Cai, 2008; Mohsenzadeh et al., 2012; Kabir et al., 2016).

Silicon enhances plants' tolerance to toxic metals, i.e, Al, As, Cd, M, and Zn. The strategies of Si to alleviate the toxic effect of metal on plants can be achieved by: (i) Si deposition in roots, apoplasmic bypass flow is reduced which leads to a decrease of metal uptake and translocation in plant (Ma and Yamaji, 2006), (ii) altering sub-cellular distribution of metal and enhancing its binding to cell wall of roots, stems and leaves, and (iii) stimulating the activities of antioxidant enzymes and reducing membrane lipid peroxidation under toxic metal stress (Zhu et al., 2004; Shi et al., 2005; Mohsenzadah et al., 2012).

Silicon- mediated tolerance toxic metals can take place also by immobilizing the metal in the cell wall of plant root and inhibiting its transport to the cytosol. This can be achieved by the ability of Si to covalently bind with the metal and forming metal – silicate complex which subsequently suppresses metal toxicity (Song et sl., 2009; Greger et al., 2016; Lukacova et al., 2013; Adress et al., 2015; Wu et al., 2015; Kabir et al., 2016).

Silicon supplied to plant decreases Cd concentration in shoots and its translocation from roots to shoots of peanut (Shi and Cai, 2008), tomato (Wu et al., 2015), rice (Kim et al., 2014; Wang et al., 2016); alfalfa (Kabir et al., 2016). This could be due to blocking Cd absorption sites in roots and may be also to enhancement of Cd retention in roots by strengthening the exodermis tissues (Farooq et al., 2016) and may be also to physically blockage the apoplastic bypass flow and restraining apoplastic transport of Cd (Ma and Yamaji, 2006; Imtiaz et al., 2016).

Silicon enhanced the tolerance of wheat against the toxicity of Cd and Cu (Rizwan et al., 2012; Keller et al., 2015) of barley against Cr (Ali et al., 2013), of rice against Zn (Song et al., 2009), of cotton against Ni (Khaliq et al., 2016). In plant grown under heavy metal stress, Si application enhanced the activities of SOD, CAT and POD enzymes which reduced both the oxidative damage (Shen et al., 2010), and GSH content in plant (Liang et al., 2005; Bu et al., 2016).

Silicon Application and Future Prospective

Silicon Removal from Soil: Continuous cultivation of soil by different plant species with repeated application of N, P and K chemical fertilizers has been found to deplete the amount of available Si from soil (Meyer and Keeping, 2001; Ma and Yamaji, 2006). This will lead to the occurrence of unadequate level of available Si in soil for normal growth of most plant species especially Si – accumulator plants. Different plant species remove high quantities of Si from soil as well as N, P_2O_5 and K_2O(Table 4). In some cases, more Si is removed from soil as compared to that of N, P and K (Savant et al., 1997; Meyer and Keeping, 2001; Makabe et al., 2009). Low amounts of available Si occurred mostly in cultivated old soils.

The amount of Si removed from soil by crop can be greater than that supplied to soil via natural processes (Savant et al., 1997). With respect to plant need from Si, the fertilization of Si – deficient soil is becoming of great importance (Savant et al., 1997; 1999).

Under continuous cultivation of rice, the amounts of available Si in soil would be exhausted after short time, i.e., nearly five years (Desplanques et al., 2006). The decline in rice yield grown in such soil, has been declaired in many areas of the world (Savant et al., 1999). Therefore, soils which are intensively used for cropping should be fertilized on a regular basis with silicate amendments (Korndorfer and Lepsch, 2001).

Amelioration and Fertilization: Soil – Si (SiO_2, quartz) is unavailable to plant roots and is not always in a mobilizable form to sufficient extent to meet plant need. Thus, additional supply of soluble or readily mobilizable silicate is of a great concern. Because Si is not recycled like other nutrients i.e., N, P and K, application of Si – fertilizers is of major benefits for most plant species.

The activities of plant roots and soil microbes act for dissolving some of Si from SiO_2-soil into solution producing silicic acid ($H_4SiO_4°$) which is readily available to plant root. However, the capacity of soil is insufficient to satisfy crop need from Si. Currie and Perry (2007) found that fertilization by Si increased its concentration in plants (Table 5), and Hodson et al. (2005) found positive relationship between Si content and Productivity of different plant species (Table 6).

Table 4.The range values of the amounts of N, P_2O_5, K_2O and Si removed from cultivated soils by different plant species at harvest (kg ha^{-1} year^{-1})

Plant species	N*	P_2O_5*	K_2O*	Si**
Potatoes	105 – 200	70 – 85	300 – 112	50 – 70
Cereals	80 – 160	15 – 30	100 – 200	100 – 300
Rice	100 – 120	15 – 20	130 – 160	230 – 470
Sugarcane	160 – 220	25 – 35	218 – 280	500 – 700

* Cooke (1980)

** Savant et al., (1997).

Table 5. The Si content (mg Si kg^{-1} DW) in different plant species as a result of Si fertilization (Currie and Perry, 2007)

Plant species	Tested organ	Without Si	With Si
Pumpkin	leaf	700	3500
Corn	stem	1300	3300
Wheat	flag leaf	1530	11750
Rice	Polished grains	-	500
Rice	hull	-	230000

Table 6. Silicon concentration of most important crops ranked by production (Hodson et al., 2005)

crop	Production, ton ha^{-1}	Si% DW
Sugarcane	1,736	1.509
Corn	826	0.827
Rice	686	4.167
Wheat	683	2.455
Potatoes	326	0.400
Cassava	232	0.500
Soybean	231	1.339
Sugar beet	222	2.347
Barley	155	1.824

Several studies showed that Si – fertilization has positive effects on the chemical, physical and biological properties of soils via: (i) reducing the leaching of P and K, (ii) reducing heavy metals mobility in the soil due to allocation of the metal in more stable soil fraction such as organic matter and crystalline iron oxide (Cunha and Nascimento, 2009; Dresler et al., 2015), (iii) improving microbial activity, (iv) increasing the stability of soil organic matter, (v) improving soil texture, (vi) improving water holding capacity of soil, (vii) increasing soil stability against erosion, and (viii) increasing both cation exchange capacity of soil, and increasing the amounts of available Si, N, P and K in soil (Savant et al., 1997; Matichenkov and Calvert, 2002; Tubuna et al., 2016; Rashad 2017).

The required quantities of Si – fertilizer, to be applied, vary widely for different plant species and therefore the determination of the amount available Si in soil permits a quantitative estimation of plant requirement from the applied Si – fertilizer. It is common to test soil, plant and fertilizer for their contents of Si in order to justify Si management and recommendation (Anderson et al., 1991; Savant et al., 1997; 1999; Berthelsen et al., 2001). The most common methods for extracting available Si from soils are neutral solution of 0.01 M $CaCl_2$ or alkaline solution of NH_4OH or $NaHCO_3$ (Tubana et al., 2016).

Usage of silicon fertilizers has been begun in Japan in 1950, by applying rice straw and industrial slags in soils (Guntzer et al., 2012). As expected, the most common recommended Si – fertilizers must contain soluble silicic acid or soluble salicates.

The characteristics of silicon fertilizers must meet a number of criteria including solubility, availability, suitable physical properties (i.e., high surface area), and free from contaminants. Commonly, the most used Si-fertilizers are (i) liquid sodium silicate and potassium silicate, (ii) calcium metasilicate; after is refered as calcium silicate and occurs naturally as "Wollastonite", (iii) silicate slag: contains high concentrations of total Si and low proportion of easily solubilized Si, (iv) magnesium silicate, and (v) basalt dust. The advantage of most silicate fertilizers is that they contain other nutrient elements such as Ca^{2+}.

The degree of Si solubility, of various silicon materials, is dependent on their particle size, surface area, and chemical composition. For example; calcium metasilicate is much more soluble and readily available to sugarcane than calcium orthosilicate.

Diatomaceous earth is a natural source of Si and has a large surface area and is readily soluble due to its amorphous nature. Application of NPK mineral fertilizers in combination with diatomaceous earth decreased N, P and K leaching from soils by 54% for N, 60% for P and 60% for K, improved crop production, increased nitrogen use efficiency, and increased NH_4^+ retention by soil.

Silicon can be applied as a soil amendment or as a foliar spray depending on the form of Si – fertilizer. Foliar spray by K-silicate is less efficient than soil amendment by Ca-silicate. Silicon application of wollastonite or slag to rice was most effective in increasing Si content in rice thatn by foliar spray by Si (Agostinho et al., 2017). It has been also recommended that soil application of Si fertilizers must be added to the soil before planting (Savant et al., 1999). Potassium silicate is the most soluble silicate but it can be polymerized at higher concentration (>50 mg Si L^{-1}) and therely is changed to slow Si-release form in soil.

It has been found that silicon application rate to the soils is controlled mainly by both the chemical composition of Si source, amount of available Si in the soil, and plant species (Savant et al., 1999). High Si – accumulator plants showed large and rapid growth and yield and high response to Si fertilization than low and moderate accumulator plant species (Epstein, 1999).

Silicon fertilization improved the vigor, growth, P nutrition, and increased sugar yield of sugarcane (Ayres, 1965; Berthelsen et al., 2001), increased iceberg lettuce growth, N, P, K, Ca and Mg contents (Olla, 2017), increased nitrogen use efficiency and P utilization in rice (Savant et al., 1997), increased N, P, and K contents in wheat (Hellal et al., 2012), increased N, P and K contents in sesame and wheat (Rashad, 2017).

It is also found that soil application of K – silicate increased the straw and seed yields of Egyptian clover (Ibrahim et al., 2015), increased the biomass of peanut (Shi et al., 2008). In the same sense, foliar spray of K – silicate increased the yield of cucumber (Matichenkov and Bocharnikova, 2008), soybean (Crusciol et al., 2013), bean (Abu-Baker et al., 2012), and rice (Wang et al., 2014).

High rate of Si applied to fodder plants produces high crop yield and large Si content in the plant. This high Si-fodder plants is harmful to animals because Si is presented in the form of needle – shaped residues which cause injuries to their digestive trac. In this concern, safe Si management for crop production should include the plant need from Si. This can be achieved by the determination of available Si in soil, its contents in plant, the interactions between N, P and K fertilization and Si supply in plants grown under environmental and soil stresses.

REFERENCES

Abdel-Latif, A. and F. M. El-Demerdash. 2017. The ameliorative effects of silicon on salt-stressed sorghum seedlings and its influence on the activities of sucrose synthase and PEP carboxylase. J. Plant Physiol. Pathol. 5: 1 – 8

Abou-Baker, N. H., M.Abd-Eladl. and T. H. Eied. 2012. Silicon and water regime response in bean production under soil saline conditions. J. Applied Sci. Res. 8: 5698 – 5707

Adrees, M. Ali, Sh., M. Rizwan, M. Zia-ur-Rehman, M. Ibrahim, F. Abbas, M. Farid, M. F.Qayyam and M. K. Irshad. 2015. Mechanisms of silicon – mediated alleviation of heavy metal toxicity. Ecotoxicology Environ Safety. 119: 186 – 197

Agostinho, F. B., B. S. Tubana, M. S. Martins and L. E. Datnoff. 2017. Effect of different silicon sources on yield and silicon uptake of rice grown under varying phosphorus rates. Plants. 6: 1 – 17

Ahmed, M., F. U. Hassan, U. Qadeer and M. A. Aslam. 2011 a. Silicon application and drought tolerance mechanism of sorghum. African, J. Agric. Res. 6: 594 – 607

Ahmed, M., F. U. Hassan and Y. Khurshid. 2011 b. Does silicon and irrigation have impact on drought tolerance mechanism of sorghum. Agric. Water Manage. 98: 1808 – 1812.

Ahmed, M., M.Asif and A. Goyal. 2012. Silicon the non-essential beneficial plant nutrient to enhance drought stress in wheat. Chapt. 2. In: Crop Plant. Goyal, A. (ed.). INTECH. pp: 31 – 48. In Tech. Croatia.

Al-Aghabary, Zhu. K. and Q. H. Shi.2004. Influence of silicon supply on chlorophyll content, chlorophyll fluorescence and antioxidative enzyme activities in tomato under salt stress. J. Plant. Nutr. 27: 2101 – 2115

Ali, S., M. A.Farooq, S.Yasmeen, M. S.Arif, F. Abbas, S. A. Bharwana and G. Zhang, 2013. The influence of silicon on barley growth, photosynthesis, and ultra-structure under chromium stress. Ecotoxicology. Environ. Safety. 89: 66 – 72

Alsaeedi, A., H. El-Ramady, T. Alshaal and M. Almohsen. 2017. Enhancing seed germination and seedlings development of common bean (*Phaseolus vulgaris*) by SiO_2 nanoparticles. Egypt. J. Soil Sci. 97: 407 – 415

Amin, M., R. Ahmed, A. Ali, M. Aslam and D. J. Lee. 2016. Silicon fertilization improves the maize (*Zea mays L.*) performance under limited moisture supply. Cereal Res. Commun., 44: 172 – 185

Andreson, D. L. 1991. Soil and leaf nutrient interactions following application of calcium silicate slag to sugarcane. Fertilizer Res. 30: 9 – 18

Arnon, D. I. and P. R. Stout. 1939. The essentiality of certain elements in minute quantity for plants with special reference to copper. Plant Physiol. 14: 371 – 375

Ashraf, M., M. Afzal, R. Ahmed, M. A. Magsoud, S. M. Shahazad, A. Aziz and N. Akhtar.2010. Silicon management for mitigating abiotic stress effects in plants. Plant Stress. 4: 104 – 114

Ashraf, M., M. Afzal, R. Ahmed, F. Mujeeb, A. Sarwar

and L. Ali. 2010. Alleviation of detrimental effect of NaCl by silicon nutrition in salt – sensitive and salt – tolerance genotypes of sugarcane (*Saccharum officinarum* L.). Plant Soil. 326: 381 – 391

Ayres, A. S. 1965. Calcium silicate slag as a growth stimulant for sugarcane on low silicon soil. Soil Sci, 101: 216 – 232

Balakhnina, T., A. Borkowska. 2013. Effects of silicon on plant resistance to environmental stress: review. Int. Agrophys. 27: 225 – 232

Barber, D. A., M. G. T. Shone.1966. The absorption of silica from aqueous solution by plants. J. Exp. Bot. 17: 569 – 578

Berthelsen, S., A. D. Noble and A. L. Garside. 2001. Silicon research: past, present and future. In: Datnoff, L. E., Snyder, G. J., Komdorfer, G. H. (eds). Silicon deposition in higher plants. Silicon in Agriculture, Elsevier Sci. pp: 241 – 255

Bu, R., J. Xie, J. Yu, W. Liao, X. Xiao, J. Lv, C. Wang, J. Ye and A. Calderon-Urrea. 2016.Autotoxicity in cucumber (*Cucumis sativus L.)* seedlings is alleviated by silicon through an increase in the activity of antioxidant enzymes and by mitigating lipid peroxidation. J. Plant Biol. 59: 247 – 259

Casey, W. H., D. S. Kinrage, C. T. G. Knight, D. W. Rains and E. Epstein.2003. Aqueous silicate complexes in wheat (*Triticum aesticum L.*). Plant Cell Environ. 27: 51 – 54

Carnelies, A. L., M. Madella and J. P. Theurillant. 2011. Biogenic silica production in selected alpine plant species and plant communities. Ann. Bot., 87: 425 – 434

Chen, W., X. Yao, K. Cal and J. Chen.2011. Silicon alleviates drought stress of rice plants by improving plant water status, photosynthesis and mineral nutrient absorption. Biol. Trace Elements Res. 142: 67 – 76

Cooke, G. W. 1980. Fertilizing For Maximum Yield. Grand Publishing Limited, St. Albans, Herts Great Britain.

Coskum, D., D. T. Britto, W. Q. Huynh and H. J. Kronzucker. 2016. The role of silicon in higher plants under salinity and drought stress. Front Plant Sci. 7: 1072: 1 – 7

Crusciol, C. A. C., R. P. Soretto, G. S. A. Castro, C. H. M. D. Costa and N. J. Ferrari. 2013. Foliar application of stabilized silicic acid on soybean common bean and peanut. Revista Ciencia Agronomica. 44: 404 – 410

Cunha, K. P. V. and C. W. A. Nascimento. 2009. Silicon effects on metal tolerance and structural changes in maize (*Zea mays L.*) grown on a cadmium and zinc enriched soil. Water Air Soil Pollut. 197: 323 – 330

Currie, H. A. and C. C. Perry. 2007. Silica in plants: Biological and chemical studies. Ann. Bot. 100: 1383 – 1389

Das, P., S. Samantary and G. R. Rout. 1998. Studies on cadmium toxicity in plants: a review. Environ. Pollut. 98: 29 – 36

Desplanques, V., L. Cary, J. C. Mouret, F. Troland, G. Bourrle and J. D. Grauby. 2006.Silicon transfers in a rice field in Camargue. J. Geochem, Explor. 88: 190 – 193

Drees, L. R., L. P.Wilding, N. E. Smeek and A. L. Senkayi. 1989) Silica in soil: quartz and disorders polymorphs. In: Mineral in Soil Environment, Soil Sci. Soc. Am. Madison. Wisconson, USA: 914 – 974

Dresler, S., M. Wojcik, W. Bednarek, A. Hanaka and A. Tukiendorf. 2015. The effect of silicon on maize growth under cadmium stress. Russian J. Plant Physiol. 62: 86 – 92

Epstein, E. 1994. The anomaly of silicon in plant biology. Proc. Natl. Acad. Sci. USA, 91: 11 – 17

Epstein, E. 1999. Silicon. Ann. Rev. Plant Physiol. 50: 641 – 664

Epstein, E. and A. J. Bloom. 2005. Mineral Nutrition of Plants: Principals and Prespectives. 2 nd. ed. Sinauer Sunderland. MA.

Eraslan, F., A. Inal, D. J. Pilbeam and A. Gunes. 2008. Interactive effects of salicylic acid and silicon on oxidative damage and antioxidant activity of spinach (*Spinacia oleracea L.* cv. Matador) grown under boron toxicity and salinity. Plant Growth Regul. 55: 207 – 219

Farooq, M. A., A. Detterbeck, S. Clemens and K. J. Dietz. 2016. Silicon – induced reversibility of cadmium toxicity in rice. J. Exp. Bot. 67: 3573 – 3585

Faure, G. 1991. Principles and Application of Inorganic Geochemistry, MacMillan, New York.

Fauteux, F., W. Remus-Borel, J. G. Menzies and R. R Belanger. 2005. Silicon and plant disease resistance against pathogens fungi: mini review. FEMS. Microbiol. Lett.: 249: 1 – 6

Feng, Ch.-X., Q. S. Wang, Y. Yu, L. K. Huang, X. Ch. Wu and W. X. Liu.2011. Silicon and its uptaking gene Lsil in regulation of rice UV-B tolerance. Acta. Agron. Sin. 37: 1005 – 1011

Fraysse, F., O. S. Pokrovsky, J. Schott and J. D. Meunier. 2006. Surface peoperties, solubility and dissolution kinetics od bamboo phytoliths. Geochim. Cosmochim Act. 70: 1939 – 1951

Gao, X., Cu Zou, L. Wang and F. Zhang. 2004. Silicon improves water use efficiency in maize plants. J. Plant Nutr. 27: 1457 – 1470

Gao, X., Cu Zou, L. Wang and F. Zhang. 2006. Silicon decreases transpiration rate and conductance from tomato and maize plants. J. Plant Nutr. 29: 1637 – 1647

Gill, S. S. and N. Tuteja. 2010. Reactive oxygen species and antioxidant machinery in abiotic stress tolerance in crop plants. Plant Physiol. Biochem. 48: 909 – 930

Gong, H. J., K. M. Chen, G. C. Chen, S. M. Wang and C. L. Zhang. 2003. Effect of silicon on growth of wheat under drought. J. Plant Nutr. 26: 1055 – 1063

Gong, H. J., K. M. Chen, G. C. Chen, S. M. Wang and C. L. Zhang. 2005. Silicon alleviates oxidative damage of wheat plants on pots under drought. Plant Soil, 169: 313 – 321

Gong, H. J. and K. M. Chen. 2012. The regulatory role of silicon on water relations, photosynthetic gas exchange, and carboxylation activities of wheat leaves in field under drought conditions. Act. Physiol. Plant. 34: 1589 – 1594

Greger, M., A. H. Kabir, T. Landberg, P. J. Maity and S. Lindberg. 2016. Silicate resuces cadmium uptake into cells of wheat. Environ. Pollut. 211: 90 – 97

Gunes, A., A. Inal, E. G. Bagci and D. J. Pilbeam. 2007. Silicon – mediated changes of some physiological and enzymatic parameters symptomatic for oxidative stress in spinach and tomato grown in sodic – B toxic soil. Plant Soil, 290: 103 – 114

Guntzer, F., C. Keller and J. D. Meunier. 2012. Benefits of plant silicon for crops: a review – Agron, Sustain. Dev. 32: 201 – 213

Harrison, C. C. 1996. Evidence for intramineral macromolecules containing protein from plant silicates. Phytochemistry. 41: 37 – 42

Hashemi, A., A. Abdolzahed and H. R. Sadeghipour. 2010. Beneficial effects of silicon nutrition in alleviating salinity stress in hydroponically grown canola (*Brassica napus L.*) Plants. Soil. Sci. Plant Nutr. (Tokyo).56: 244 – 253

Hattori, T., S. Inanaga, H. Araki, P. An, S. Mortia, M. Luxova and A. Lux. 2005. Application of silicon enhanced drought tolerance in sorghum bicolor. Physiologia Plantarum. 123: 459 – 466

Haynes, R. J. 2014. A contemporary overview of silicon availability in agricultural soils. J. Plant Nutr. Soil. Sci. 177: 831 – 844

Hellal F. A., R. M. Zeweny and A. A. Yassen. 2012. Evaluation of nitrogen and silicon application for enhancing yield production and nutrient uptake by wheat in clay soil. J. Applied Sci. Res. 8: 686 – 692

Hijiboland, R., L. Cherghvarch, F. Dashtebani. 2017. Effects of silicon supplementation on wheat plant under salt stress. J. Plant Process Function. 5: 1 – 11

Hodson, M. I., P. J. White, A. Mead and M. R. Broadley. 2005. Phylogenetic variation in the silicon composition of plants. Ann. Bot. 96: 1027 – 1046

Ibrahim, H. I. M., A. M.Sallam and Kh. A. Shaban. 2015. Impact of irrigation rates and potassium silicate fertilizer on seed production and quality of Fahl Egyptian clover and soil properties under saline conditions. Am. Eurasion J. Agric. Environ. Su. 15: 1245 – 1255

Ibrahim, M. A., A. M. Merwad, E. A. Elanka, C. L. Burras and L. Follett.2016. Application of silicon ameliorated salinity stress and improved wheat yield. J. Soil Sci. Environ. Manage. 7: 81 – 91

Iller, R. K. 1979. The Chemistry of Silica. Wiley – Interscience, New York.

Imtiaz, M., M. S. Rizwan and M. A. Mushtag. 2016. Silicon occurrence, uptake, transport and mechanism of heavy metals, minerals and salinity enhanced tolerance in plants with future prospects. A review. J. Environ. Manage. 183: 521 – 529

Inanaga, S. and A. Okasaka.1995. Calcium and silicon binding compounds in cell wall of rice shoots. Soil Sci. Plant Nutr. 41: 103 – 110

Jones, L. P. H. and K. A. Handreck. 1967. Silica in soils, plants and animals. Adv. Agron.19: 107 – 149

Kabir, A. H., M. M. Hossain, M. A. Khatun, A. Mandal, Haider, S. A. (2016). Role of silicon counteracting cadmium toxicity in alfalfa (*Medicage sativa L.*) Front Plant Sci. 7: 1 – 12 (dio: 10.3389/fpis. 2016. 01117)

Karathanasis, A. D. 2002. Mineral equilibria in environmental soil systems. In: Soil Mineralogy with Environmental Application, Soil Sci. Soc. Am., Madison. Wisconson, USA, 109 – 151

Kaya, C., L. Tuna and D. Higgs. 2006. Effect of silicon on plant growth and mineral nutrition of maize grown under – water stress conditions. J. Plant Nutr. 29: 1469 – 1480

Kazemi, M., M. Gholami and F. Hassanvand. 2012. Effects of silicon on antioxidative defence system and membrane lipid peroxidation in gerbera cut flower. Asain. J. Biochem. 7: 171 – 176

Keller, C., M. Rizwan, J – C. Davidian, O. S. Pokrovsky, M. Bovet, P. Chaurand and J – D. Meunier. 2015. Effect of silicon on wheat seedlings (*Triticum turgidum L.*) grown in hydroponics and exposed to 0 to 30 mM Cu. Planta, 241: 847 – 860

Khaliq, A., S. Ali, A. Hameed, M. A. Farooq, M. Farid, M. B. Shakoor, Kh. Mahmood, W. Ishaquw and M. Rizwan. 2016. Silicon alleciates nickel toxicity in cotton seedlings through enhancing growth, photosynthesis, and suppressing nickel uptake and oxidative stress. Archives Agron. Soil. Sci., 62: 633 – 647

Kim, Y. H., A. L. Khan, D. H. Kim, S. Y.Lee, K. M. Kim, M. Waqas, H. Y. Jung,n J. H. Shin, J. G. Kim and I. J. Lee .2014. Silicon mitigates heavy metal stress by regulating P-type heavy metal ATPase, Oryza sative low silicon genes, and endogenous photohormones. BMC Plant Biol. 14: 13 – 22

Knight, C. T. G. and S. D. Kinrade. 2001. A primer on the aqueous chemistry of silicon. In: Silicon in Agriculture. Elsevier. The Netherlands.: 57 – 84

Korndorfer, G. H. and I. Lepsch. 2001. Effect of silicon on plant growth and crop yield. In: Silicon in Agriculture.Elsevier. The Netherlands:133 – 147

Kovda, V. A. 1973. The bases of learning about soils. Nauka. 2: 377 – 428

Lee, J. W., Y. C. Kim, Y. Y. Kim, H. K. Yun and T. C. Seo. 2002. Influence of silicate application on the sucrose synthetic enzyme activity of tomato in perlite media culture. Plant Material Acta. Hort. 633: 259 – 262

Lewin, J. and B. E. F. Reimann.1969. Silicon and plant growth. Ann. Review Plant Physiol. 20: 289 – 304

Li, S., Sh. Zhang, L. Ding and R. Wang. 2013. Spraying silicon and/or cerium sols favourable mediated enhancement of Cd/Pb tolerance to lettuce grown in combined Cd/Pb contaminated soil. Procedia Environ. Sci. 18: 68 – 77

Liang, Y. C. and Z. G. Chen. 1994. Interaction of silicon and boron in oil seed rape plants. J. Plant Nutr. 17: 415 – 425

Liang, Y. 1998. Effect of silicon on leaf ultrastructure, chlorophyll content and photosynthetic activity in barley under salt stress. Pedosphere. 8: 289 – 296

Liang, Y. 1999. Effect of silicon on enzyme activity and sodium, potassium and calcium concentration in barley under salt stress. Plant Soil. 209: 217 – 224

Liang, Y., Q. Chen, Q. Liu, W. Zhang and R. Ding.2003. Exogenous silicon (Si) increases antioxidant enzyme activity and reduces lipid peroxidation in roots of salt – stressed barley (*Hordem vulgare L.*) J. Plant Physiol. 160: 1157 – 1164

Liang, Y.; Si, J.; Romheld, V. (2005). Silicon uptake and transport is an active process in cucumber sativus. New Phytologist. 167: 797 – 804

Liang, Y., J. W. C. Wong and L. Wei. 2005. Silicon-mediated enhancement of cadmium tolerance in maize (*Zea mays L.*) grown in cadmium contaminated soil. Chemosphere 58: 475 – 483

Liang, Y., H. Hua, Y. G. Zhu, J. Zhang, Ch. Cheng and V. Romheld. 2006 a. Importance of plant species and external silicon concentration to active silicon uptake and transport. New Phytol. 172: 63 – 72

Liang, Y., W. Zhang, Q. Chen, Y. Liu and R. Ding. 2006 b. Effect of exogenous silicon (Si) on H^+ ATPase activity, phospholipids and fluidity of plasma membrane in leaves of salt – stressed barley (*Hordeum vulgare, L.*) Environ. Expt. Bot. 57: 212 – 219

Liang, Y., M. Nikolic, R. Belanger, H. Gong and A. Song. 2015. Silicon in Agriculture, Dordrecht. Springer

Lindsay, W. L. 1979. Chemical Equilibrium in Soil. John Wiley and Sons. New York

Lizana, C., S. Hess and D. F. Calderini. 2009. Crop phenology modifies wheat response to increased UV-B radiation. Agr. Forest. Meteorol. 149: 1964 – 1974

Lobato, A. K. S., G. K. Coimbra, M. A. M. Neto, R. C. L.Costa, F. B. G.Santos, N. C. F. Oliveira, B. W. F. Pereira, G. A. R. Alves, B. S. Monteiro and C. A. Marochio. 2009). Protective action of silicon on water relations and photosynthetic pigments in pepper plant induced to water deficit. Res. J. Biol. Sci. 4: 617 – 623

Lukacova, Z., S R. vubova, J. Kohanova and A. Lux. 2013. Silicon mitigates the Cd toxicity in maize in relation to cadmium translocation, cell distribution, antioxidant enzymes simulation and enhanced endodermal apoplasmic barrier development. Plant Growth Regul. 70: 89 – 103

Lux, A., M. Luxova, J. Abe, E. Tanimoto, T. Hattori and S. Inanaga. 2003. The dynamics of silicon deposition in the sorghum root endodermis. New Phytol. 158: 437 – 441

Ma, J. E., Y. Miyake, and E. Takahashi. 2001. Silicon as beneficial element for crop plants. In: Silicon in Agriculture. Datnoff et al. (eds). New York. Elsevier Sci. Pub: 17 – 39

Ma, J. F. and E. Takahashi. 2002. Soil, Fertilizer and Plant Silicon Research in Japan. Elsevier. The Netherland

Ma, J. F., A. Higashitani, K. Sato and K. Takeda. 2003. Genotypic variation in silicon concentration of barley grain. Plant Soil. 249: 383 – 387

Ma, J. F. 2004. Role of silicon in enhancing the resistance of plants to biotic and abiotic stresses. Soil Sci. Plant Nutr. 50: 11 – 18

Ma, J. F.; Yamaji, N. (2006). Silicon uptake and accumulation in higher plants. Trends Plant Sci., 11: 342 – 397

Ma, J. F. and N. Yamaji. 2008. Functions and transport of silicon in plants, Cell. Molec. Life Sci. 65: 3049 – 3057

Ma, J., H. Cai, C. He, W. Zhang and L. Wang. 2015. A hemicellulose – bound form of silicon inhibits cadmium ion uptake in rice (*Oryza sativa*). New Phytol. 206: 1063 – 1074

Maamoun, H. 2014. Effect of silicon and saline irrigation water on productivity of two wheat cultivars at south Sinai, Egypt. Egypt. J. Soil Sci. 54: 319 – 336

Marschner, H. 1995. Mineral Nutrition of Higher Plants. Academic Press, 2nd ed. London

Matichenkov, V. V. and J. M. Ammosova. 1996. Effect of amorphous silica on soil properties of a sod – podzolic soil. Eurasian Soil Sci. 28: 87 – 99

Matichenkov, V. V. and D. V. Calvert. 2002. Silicon as beneficial element for sugarcane. J. Am. Soc. Sugarcane Technol. 22: 21 – 30

Matichenkov, V. V. and E. A. Bocharnikiva. 2008. New generation of silicon fertilizers, In: Silicon in Agriculture Conference, South Africa, Univ. Kwazulu-Natal. pp 71. Conference Abstract

Mauad, M., C. A. C. Crusciol, A. S. Nascente, H. G. Filho and G. P. P. Lima. 2016. Effect of silicon and drought stress on biochemical characteristics of leaves of upland rice cultivars. Revista Ciencia Agronomica. 47: 532 – 539

Meyer, J. H. and M. G. Keeping. 2001. Past, present and future research of the role of silicon for sugarcane in southern Africa. In: Silicon in Agriculture. Vol. 8, Studies in Plant Science, Datnoff et al. (eds), Amsterdam, The Netherlands, Elsevier. P: 257 – 275

Mitani, N., F. M. Jian and T. Iwashita.2005. Identification of the silicon form in xylum sap of rice (*Oryza sativa L.*). Plant Cell Physiol. 46: 279 – 283

Mitani, N. and J. F. Ma. 2005. Uptake system of silicon in different plant species. J. Expt. Bot. 56: 1235 – 1261

Miyake, Y. and E. Takahashi. 1986. Effect of silicon on the growth and fruit production of strawberry plants in a solution culture. Jap. Soc. Soil Sci. Plant Nutr. 32: 321 – 326

Mohsenzadeh, S., M. Shahrtash and J. A. T. Da silva. 2012. Silicon improves growth and alleviates toxicity of cadmium in maize seedlings. Plant Stress, 6: 39 – 43

Neumann, D. and U. Zur Nieden. 2001. Silicon and heavy metal tolerance of higher plants. Phytochemistry. 56: 685 – 692

Neumann, D. and C. De Figueriedo. 2002. A novel mechanism of silicon uptake. Protoplasma.220: 59 – 67

Nwugo, C. C. and A. J. Huerta.2008. Effects of silicon nutrition on cadmium uptake, growth and photosynthesis of rice plants exposed to low – level cadmium. Plant Soil. 311: 73 – 86

Olle, M. 2017 The effect of silicon on the organically grown iceberg lettuce growth and quality. J. Agric. Sci. 2: 82 – 86

Pal, M., E. Horvath, T. Landa, E. Bald and S. Gabriella. 2007. Physiological changes and defense mechanisms induced by cadmium stress in maize. J. Plant Nutr. Soil Sci. 169: 239 – 246

Pereira, T. S., A. K. Lobato, D. K. Y. Tan, D. V. Costa, E. B. Uchoa, R. N. Ferreira, E. S. Pereira, F. W. Avila, D. J. Marques and E. M. S. Guedes. 2013. Positive interference of silicon on relations, nitrogen metabolism and osmotic adjustment in two pepper (*Capeicum annum*) cultivars under water deficit. Austr. J. Crop Sci. 7: 1064 – 1071

Qian, Q., W. Zai, Z. Zhu and J. Yu. 2006. Effect of exogenous silicon on active oxygen scavenging systems in chloroplasts of cucumber (*Cucumis sativus L.*) seedlings under salt stress. J. Plant Physiol. Mol. Biol. 32: 107 – 112

Rafi, M. M. and E. Epstein. 1999. Silicon absorption by wheat (*Triticum aestivam L.)*. Plant Soil, 211: 223 – 230

Rains, D. W., E. Epstein, R. J. Zasoski and M. Aslam. 2006. Active silicon uptake by wheat. Plant Soil. 280: 223 – 228

Ranganathan, S., V. Suvarchala, Y. B. R. D. Rajesh, M. S. Prasad, A. P. Padmakumari and S. R. Voleti. 2006. Effects of silicon sources on its deposition, chlorophyll content, and disease and pest resistance to rice. Biol. Plantarum. 50: 713 – 716

Rashad, R. T. 2017. Relationship between the absorption behavior of iron and silicon by plant and the macronutrients affected by some sandy soil additives. Asian J. Soil Sci. Plant Nutr. 1: 1 – 12

Raven, J. A. 1983. The transport and function of silicon in plants. Biol. Rev. 58: 179 – 207

Reezi, S., M. Babalar and S. Kalantari. 2009. Silicon alleviates salt stress, decreases malondialdehyde content and affects petal color of salt stressed cut rose (Rosa x hybrid L.) "Hot Lady". African J. Biotechnol. 8: 1502 – 1508

Richmond, K. E. and M. Sussman. 2003. Get silicon? The non-essential beneficial plant nutrient. Current Opinion Plant Biol. 6: 268 – 272

Rizwan, M., J. D. Meunier, M. Helene and C. Keller. 2012. Effect of silicon on reducing cadmium toxicity in durum wheat (*Triticum turgidum L.* cv. Claudio W.) grown in a soil with aged contamination. J. Hazard Mater 209 – 210: 326 – 334

Romero-Aranda, M. R., O. Jurudo and J. Cuartero. 2006. Silicon alleviates the deleterious salt effect on tomato plant growth by improving water status. J. Plant Physiol. 163: 847 – 855

Sacala, E. 2009. Role of silicon in plant resistance to water stress. J. Elementol. 14: 619 – 630

Sangster, A. G., M. J. Hosdon and H. J. Tubb.2001. Silicon deposition in higher plants. In: Silicon in Agriculture, Elsevier, The Netherlands, 85 – 113

Saqib, M., C. Zorb and S. Schubert.2008. Silicon-mediated improvement in the salt resistance of wheat (*Triticum aestivum*) results from increased sodium exclusion and resistance to oxidative stress. Func Plant Biol. 35: 633 – 639

Sauer, D. L., D. J. Saccone, L. Conley, C. Herrmann and M. Sommer. 2006. Review of methodologies for extracting plant available and amorphous Si from soils and aquatic sediments. Biogeochemistry. 80: 89 – 108

Savant, N. K., L. E. Datnoff and G. H. Snyder. 1997. Depletion of plant available silicon in soils: a possible cause of declining rice yield. Commun. Soil Sci. Plant Anal. 28: 1245 – 1252

Savant, N. K., G. H. Snyder and L. E. Danhof. 1999. Silicon management and sustainable in rice production. Adv. Agron. 58: 151 – 199

Shah, K., R. G. Kumar, S. Verna and R. S. Dubey. 2001. Effect of cadmium on lipid peroxidation, superoxide anion generation and activities of antioxidant enzymes in growing rice seedlings. Plant Sci. 161: 1135 – 1144

Shen, X., Y. Zhou, L. Duan, Z. Li, A. E. Enej and J. Li. 2010. Silicon effects on photosynthesis and antioxidant parameters of soybean seedlings under drought and ultraviolet – B radiation. J. Plant Physiol., 167: 1248 – 1252

Shi, X., C. Zhang, H. Wang and F. Zhang. 2005. Effect of Si on the distribution of Cd in rice seedlings. Plant Soil, 272: 53 – 60

Shi, G. R.; Cai, Q. S. (2008). Photosynthetic and anatomic responses of peanut leaves to cadmium stress. Photosynthetica, 46: 627 – 630

Shi, Y., Y. Wang, T. J. Flowers and H. Gong. 2013. Silicon decreases chloride transport in rice (*Oryza sativa L.*) in saline conditions. J. Plant Physiol. 170: 847 – 853

Shi, Y., Y. Zhang, W. Han, R. Feng, Y. Hu and J. Guo.2016. Silicon enhances water stress tolerance by improving root hydraulic conductance in Solanum lycopersicum L. Front Plant Sci. 7: 196 . doi: 10 . 3389 / fpls – 2016 – 00196

Sivanesan, I., M. S. Son, J. Y.Song and B. R. Jeong. 2013. Silicon supply through the subirrigation system affects growth of three chrysanthemum cultivars. Hort. Environ. Biotechnol. 54: 14 – 19

Sommer, M., D. Kaczorek, Y. Kasyanov and J. Breuer. 2006. Silicon pools and fluxes in soils and landscapes – a review. J. Plant Nutr. Soil Sci. 169: 310 – 329

Song, A. L., Z. J. Li, J. Zhang, G. F. Xue, F. L. Fan and Y. C. Liang. 2009. Silicon enhances resistance to cadmium toxicity in Brassica chinensis L. is attributed to Si – suppressed cadmium uptake and transport and Si – enhanced antioxidant defense capacity. J. Hazard Mater.172: 74 – 83

Suciaty, T., D. Purnomo, A. T. Sakya and Supriyadi. 2018. The effect of Nano-silica fertilizer concentration and rice hull ash doses on soybean (*Glycine max (L.)* Merrill) growth and yield. IOP Conference Series, Earth Environ. Sci. 129: 1 – 7

Takahashi, E., J. F. Ma and Y. Miyake. 1990. The possibility of silicon as an essential element for higher plants. Comments Agric. Food Chem. 2: 99 – 122

Tantawy, A. S., Y. A. M. Salama, M. A. El Nemr, A. M. R. Abdel Mawgoud. 2015. Nano-silicon application improves salinity tolerance of sweet pepper plants. Inter. J. Chem. Tech. Res. 8: 11 – 17

Tubana, B. S., T. Babu and L. E. Datnoff. 2016. A review of silicon in soils and plants and its role in US agriculture: History and future prospective. Soil Sci. 181: 1 – 19

Tuna, A. L., C. Kaya, D. Higgs, B. Murillo – Amador, S. Aydemir, A. R. Girgin. 2008. Silicon improves salinity tolerance of wheat plants. Environ. Expt. Bot. 62: 10 – 16

Vaculik, M., A. Lux, M. Luxova, E. Tanimoto and I. Lichtscheidi. 2009. Silicon mitigates cadmium inhibitory effects in young maize plants. Environ. Exp. Bot. 63: 25 – 28

Vaculik, M., T. Landberg, M. Greger, M. Luxova, M. Stolarikova and A. Lux. 2012. Silicon medicates cadmium inhibitory effects in young maize plants. Environ. Exp. Bot. 67: 52 – 58

Wang, Y., A. Stass and W. Horst. 2004. Apoplastic binding of aluminum is involved in silicon-induced amelioration of aluminium toxicity in maize. Plant Physiol. 136: 3762 – 3770

Wang, X. S. and J. G. Han. 2007. Effect of NaCl and silicon on ion distribution in the roots and leaves of two alfalfa cultivars with different salt tolerance. Soil Sci. Plant Nutr. 53: 278 – 285

Wang, X., Z. Wel, D. Liu and G. Zhao. 2011. Effect of NaCl and silicon on activities of antioxidative enzymes in roots, shoots and leaves of alfalfa. Afric. J. Biotechnol. 10: 545 – 549

Wang, S., F. Wang and S. Gau. 2014. Foliar application with nano-silicon alleviates Cd toxicity in rice seedlings. Environ. Sci. Pollut. Res. 21: 1 – 9

Wang, H., S. L. Wen, P. Chen, L. Zhang, K. Cen and G-X. Sun. 2016. Mitigation of cadmium and arsenic in rice/grain by applying different silicon fertilizers in contaminated fields. Environ. Sci. Pollut. Res. 23: 3781 – 3788

Wedepohl, K. H. 1995. The composition of the continental crust. Geochim Cosmochim Act. 59: 1217 – 1232

Wu, J., J. Guo, Y. Hu and H. Gong. 2015. Distinct physiological responses of tomato and cucumber plants in silicon mediated alleviation of cadmium stress. Front Plant Sci. 6: 452 – 459

Zancan, S., I. Suglia, N. La Rocca and R. Shisi. 2008. Effects of UV-B radiation on antioxidant parameters of iron – deficient barley plants. Environ. Exp. Bot. 63: 71 – 79

Zhu, Z., G. Wei, J. Li, Q. Qian and I.Yu. 2004. Silicon alleviates salt stress and increases antioxidant enzymes activity in leaves of salt – stressed of cucumber (*Cucumis sativus L.*). Plant Soil, 167: 527 – 533

Zhu, Y. and H. Gong. 2014. Beneficial effect of silicon on salt and drought tolerance in plants. Agron. Sustain. Dev. 34: 455 – 472

Zuccarini, P. 2008. Effects of silicon on photosynthesis, water relations and nutrient uptake by phaseolus vulgaris under NaCl stress. Biologia

الملخص العربي

السيليكون كعنصر مفيد وكعنصر مغذى ضرورى للنبات: نظرة مستقبلية

إبراهيم حسين السكرى

تعمل إضافة السيليكون على تحفيز قدرة النبات على التعايش مع العديد من الإجهادات الحيوية والغير حيوية. وبالرغم من تفسير آليات الحد من تأثير الإجهاد الناتج عن الإشعاع، الملح، العناصر الثقيلة إلا أن هذه الآليات ما زالت غير معروفة بدقة. وبناء على ذلك كانت الحاجة إلى فهم دور السيليكون فى العمليات الحيوية والكيموحيوية فى النبات وهذه تعتبر من المتطلبات ذات الأهمية الكبيرة فى هذا المجال.

ولقد أوضحت معظم نتائج الدراسات المنشورة دور السيليكون فى تنظيم وتقليل التأثيرات الضارة الناتجة عن الإجهادات البيئية العديدة تحت ظروف محددة ولأنواع نباتية محددة.

أظهر الدور الفسيولوجى للسيليكون فى النبات أن تنظيم عمليات الدخول والخروج للأيونات عبر الغشاء البلازمى للخلايا النباتية يتحكم فيها مورث خاص ومع ذلك فإن دور هذا المورث فى انتقال السيليكون من الجذر إلى الأوراق وكذا تقليل حدة الإجهاد ما زال غير مفهوماً بحالة جيدة ويتطلب المزيد من الدراسة.

يؤدى وجود تركيزات مرتفعة من السيليكون فى أنسجة النباتات النجيلية، مثل الأرز والشعير والذرة، إلى تنشيط الآليات الدفاعية الفسيولوجية والفيزيائية والكيموحيوية بهدف زيادة اتزان قدرة النبات على الحد من أكسدة الدهون ونفاذية الأغشية مع العمل على تحفيز أنشطة الإنزيمات الدفاعية تناقص والتى تعرف باسم إنزيمات ضد الأكسدة مثل حامض الأسقربوط والكاتاليز. والتى يكون وجودها دائماً مرتبطاً بالتغذية بالسيليكون خاصة تحت ظروف إجهادات غير حيوية.

توجد عوامل وراثية تتحكم فى تراكم السيليكون فى نباتات معينة مثل الأرز. والتى عادة تكون ناتجة عن الاختلافات والتباين فى سيادة ناقلات حيوية محددة للسيليكون والتى توجد فى الجذر أو الساق أو فى الإثنين معاً. وتعمل هذه الاختلافات الوراثية على تهيئة النبات للنمو الجيد عندما ينمو تحت إجهاد غير حيوى. ومع ذلك فإن المورث المسئول عن تراكم السيليكون فى الأنواع النباتية المختلفة ما زال غير معروفاً ولم تحدد خواصه.

يؤدى حصاد الأنواع النباتية ذات القدرة العالية على امتصاص السيليكون الصالح للنبات من الأرض وتراكمه داخلها إلى إزالة كمية كبيرة من هذا السيليكون واستنزافه من الأرض و لكى تعوض هذه الكمية المفقودة من السيليكون يجب إضافة سماد السيليكون حيث يؤدى ذلك الي تحسين موقف السيليكون ويحافظ على توفر كمية من السيليكون الصالح للنبات بالأرض. ولقد وجد أن التسميد بالمعدل الصحيح والمقدر وكذلك الآمن يؤدى إلى تحسين الخواص الكيميائية والفيزيائية والحيوية للأرض وكذلك تحسين جودة النبات للاستعمال فى الأغراض المختلفة. لذلك فإن إجراء اختبارات وفحوصات لتقدير محتوى الأرض من السيليكون الصالح للنبات وكذلك تقدير السيليكون فى أنسجة محددة من النبات مع إجراء علاقات الارتباط سوف يعتبر مؤشراً موثوقاً به لإجراء التسميد بالسيليكون والمحافظة على كل من صحة الأرض وصحة النبات والحيوان.

تؤدى المعرفة الوثيقة بدور السيليكون كعنصر مفيد أو كعنصر مغذى ضرورى للنبات إلى أن استخدام مركبات السيليكون سواءا كسماد أو كمحسن للتربة الزراعية قد أيقن أن هذا العنصر ذات أهمية كبيرة فى الحاضر والمستقبل.

كلمات المفتاح: السيليكون، الترسيب، إنزيمات ضد الأكسدة، جهد الجفاف، التسميد، العناصر الثقيلة.