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Salt Stress Alleviation in Field Crops Through Nutritional Supplementation of Silicon

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Abstract: Soil salinity is a huge problem negatively affecting physiological and metabolic processes in plant life, ultimately diminishing growth and yield. Salts taken up by the plants influence the plant growth by inducing adverse effects on different physiological and biochemical processes, including turgor, photosynthesis and enzymatic activities. Mechanisms responsible for reduction in plant growth under salt stress are: (1) Osmotic stress, (2) Specific ion toxicity, (3) Nutritional imbalance and (4) Oxidative stress. Different approaches such as introduction of new genes into genotypes responsible for salt tolerance, screening of large international collections and conduct of field trials on selected genotypes, conventional and non-conventional breeding methods and adequate regulation of mineral nutrients have been employed to enhance salinity tolerance in plants. Saline agriculture and exogenous application of mineral elements including Si has been professed as cost effective approach to ameliorate the salt stress in cereal crops like wheat. Si is categorized as a beneficial element in plant biology. It is unquestionably an important requirement for the normal growth of many plants and must be called as "Quasi essential". Si amendment also plays a pivotal role to enhance chlorophyll content, stomatal conductance, photosynthesis and rigidity of plants under stressful conditions. There are different mechanisms by which Si mediates salinity tolerance in plants. It maintains the plant water status under saline conditions. It reduces uptake of Na⁺ by improving K⁺: Na⁺ and also alleviates the toxicity of other heavy metals. Its application helps to improve the defensive system of the plants by producing anti-oxidants which in turn detoxify reactive oxygen species. Morphological and physiological improvements in plants were observed due to Si deposition within plant body under salt stress conditions. Silicon improves growth and dry matter production under salt stress conditions. Its application also enhances the crop performance against biotic stress. It is, therefore, suggested that supplemental application of Si must be included in salt stress alleviation management techniques.

Key words: Salt stress, management techniques, silicon, nutritional supplementation

INTRODUCTION

Salinity is one of the major factors responsible for soil degradation. Approximately, one third of the world's land surface is arid or semiarid (4.8 x 10⁹ ha), of which half is estimated to be affected by salinity (Croughan and Rains, 1982) that accounts for about 7% of the world's total land area (Szaboles, 1989). Approximately 6.67 Mha of total agricultural land area in Pakistan is also affected by salinity/sodicity to various degrees (Khan, 1998). Salinity is a major abiotic stress at present (Rueda-Puente *et al.*, 2007) and is one of the most severe environmental problems affecting crop growth (Lopez *et al.*, 2002) and in concert with drought seems to be one of the world's most serious problems in agriculture.

Plant growth under salt stress conditions is a complex mechanism and the way it is affected by the stress is not fully understood because the response of plants to excessive salinity is multifaceted and involves changes

in plant's morphology, physiology and metabolism (Hilal *et al.*, 1998; Rhoades, 1993), ultimately diminishing growth and yield (Ashraf and Harris, 2004). Excess of soluble salts in root zone negatively affects plant growth and yield through osmotic effects, nutritional imbalances and specific ion toxicities (Grattan and Grieve, 1999; Munns, 2005; Tahir *et al.*, 2006).

Salinity influences plant physiology by changing the water and ionic status of the cells (Sultana *et al.*, 1999; Hasegawa *et al.*, 2000). Salts present in the soil solution exert an osmotic pressure and reduce the soil water potential making water unavailable to plants as reported by Munns *et al.* (2006). Ionic imbalance takes place in the cells due to excessive buildup of Na⁺ and Cl⁻, which affects the uptake of other mineral nutrients (Cramer and Nowak, 1992; Khan, 1998; Grattan and Grieve 1999; Lutts *et al.*, 1996). High Na⁺ disturbs K⁺ nutrition and inhibits activities of many enzymes (Jaleel *et al.*, 2007).

The primary cause of growth reduction under salt stress due to the uptake of certain ions (Na^+ and Cl^-) upto supra-optimal level is termed as specific ion toxicity (Chinnusamy *et al.*, 2005). Salt stress due to ion toxicity inhibits the plant growth for a longer time than water stress (Jacoby, 1993).

Salt stress not only imposes the osmotic stress and ion toxicity, but also marked as an oxidative stress (Guetadahan *et al.*, 1998) which can stimulate the accumulation of Reactive Oxygen Species (ROS) such as superoxide, hydrogen peroxide, hydroxyl radical and singlet oxygen (Lee *et al.*, 2001). Reactive Oxygen Species (ROS) attack nucleic acids, proteins and lipids and the extent of damage depends on the equilibrium between creation of ROS and their elimination by the antioxidative scavenging systems (Menezes-Benavente *et al.*, 2004). Water stress is generally considered as one of the main reasons of oxidative stress and increased permeability of cell membrane of plants growing under salinity stress (Tabaei-Aghdaei *et al.*, 2000). Leaf senescence showing reduction in chlorophyll content is associated with elevated membrane permeability (Dhindsa *et al.*, 1981).

Studies on salt tolerance normally point to limited ion accumulation and synthesis of compatible (organic) solutes as a major adaptation in glycophytes (Greenway and Munns, 1980). Some mechanisms of salinity tolerance that prevent the accumulation of Na^+ ion in plant tissues were reported in various plant species. These mechanisms include exclusion, inclusion, compartmentation and homeostasis of ions (Marschner, 1995; Saqib *et al.*, 2005; Tahir *et al.*, 2006).

Several chemical, physical (engineering) and biological approaches are used for better crop production in saline soils. Most of the time, integrated use of these approaches is crucial due to economic and environmental limitations. Of all above approaches, exogenous application of nutrients was considered as a shotgun approach to alleviate the adverse effects of salt stress (Raza *et al.*, 2006). The damaging effects of salts have been ameliorated with exogenous application of K^+ in wheat (Akram *et al.*, 2007), N in *Phaseolus vulgaris* (Wagenet *et al.*, 1983) and Ca in snap bean (Awada *et al.*, 1995). Furthermore, some beneficial mineral nutrients have been studied that can counteract adverse effects of salt stress. Silicon, being a beneficial element provides significant benefits to plants at various growth stages.

Silicon (Si) is the 2nd most abundant element on the earth crust after oxygen. It is accumulated in plants at a rate comparable to those of macronutrient elements like calcium, magnesium and phosphorous (Epstein, 1999a). It is evident that Si is beneficial for growth of many plants under various abiotic (e.g. salt, drought and metal toxicity) and biotic (plant diseases and pests) stresses (Liang *et al.*, 2003; Ma, 2004).

A number of possible mechanisms are reported through which Si may increase salinity tolerance in plants (Liang *et al.*, 2005) including increased plant water status (Romero *et al.*, 2006), enhanced photosynthetic activity and maintenance of ultra structure of leaf organelles (Shu and Liu, 2001), stimulation of ROS scavenging system (Zhu *et al.*, 2004), immobilization of toxic Na^+ ion (Liang *et al.*, 2003), reduced Na^+ uptake in plants and enhanced K^+ uptake (Yeo *et al.*, 1999; Liang *et al.*, 2005; Tahir *et al.*, 2006) and higher $\text{K}^+:\text{Na}^+$ selectivity (Hasegawa *et al.*, 2000).

Adding Ca-silicate in salinity-stressed plants maintains membrane permeability, chlorophyll content, stomatal conductance, transpiration, net photosynthesis, intercellular CO_2 and increased K^+ in leaves with reduced Na^+ uptake by improving growth, physiological parameters, balanced nutrition and increased nutrient uptake in cowpea and kidney bean (Murillo-Amador *et al.*, 2007). Si application can moderate the salinity stress in plants and plays a multitude of roles in plant existence and crop performance. Si application reduces Na^+ uptake by making complex with Na^+ in soil (Ahmad *et al.*, 1992). Si is deposited in leaves leading towards decreased transpiration and hence dilutes salts accumulated in saline environment (Matoh *et al.*, 1986). Gramineaceous plants accumulate more Si in their tissues than other species (Matichenkov and Kosobrukhov, 2004). Wheat is a member of gramineae family and recently designated as Si accumulator. Wheat a glycophytic plant is adversely affected by salinity stress (Zhu, 2003). Yield losses up to 45% have been reported due to salinity stress in wheat (Qureshi and Barrett-Lennard, 1998). Wheat genotypes differ significantly in salinity tolerance (Munns, 2002; Flowers, 2004; Saqib *et al.*, 2005) as salt tolerant plants accumulate less Na^+ than salt sensitive, which maintains the ionic balance within plant tissues (Tahir *et al.*, 2006). These variations can be used to screen and develop more salt tolerant genotypes.

In view of above considerations, the current theoretical study was accomplished with the objectives (i) to optimize the level of Si under saline environment, (ii) to study the biochemical insight due to Si under salinity stress, (iii) to study the role of Si in soil media by observing the impact of Si on plant water economy under salt stress and (v) the effect of Si application on yield and ionic composition.

Effects of salinity on crop production: Salinity is one of the major yield limiting factors for crop plants mainly in arid and semiarid regions of the world (Munns, 2005). Agriculture is the basis of economy of Pakistan. In Pakistan about 40,000 ha arable land is ruined annually due to salinization (Ghafoor *et al.*, 2004) and approximately 8% of the total agricultural area has turned into salt affected phase (Khan, 1998). Most of this

is naturally saline occurring in arid and semiarid areas and have low productive potential and if cropped suffer structural problems and become more prone to surface erosion. Wheat is usually grown in these regions, therefore, its growth and yield is severely affected due to salt stress.

Salts taken up by the plants influence the plant growth by inducing adverse effects on different physiological and biochemical processes (Zeng and Shannon, 2000), including turgor, photosynthesis and enzymatic activities (Munns, 1993). Meinzer *et al.* (1994) found that the decreased plant growth under salinity stress was due to reduced photosynthetic efficiency and certain specific changes that take place in the plant leaf. Increased salinity is negatively correlated with stomatal conductance and photosynthetic rate leading towards decreased net assimilation (Rozeff, 1995; Wagenet *et al.*, 1983). Cheeseman (1988) reported that when plants were grown in saline rooting medium, it resulted in reduction of turgor pressure that caused the stomatal closure and ultimately photosynthesis. This reduction in photosynthesis under salinity stress might be due to decrease in chlorophyll content and the inhibitory effect of salt stress on the translocation and assimilation of photosynthates and finally decline in crop productivity occurs (Long and Baker, 1986). Reduction in leaf area expansion and lower light interception under salinity stress also causes growth reduction as studied in radish (*Raphanus sativus* L.) (Marcelis and Hooijdonk, 1999).

Javid *et al.* (2000) reported that the anatomical changes in leaf induced by salinity stress are smaller leaves, reduced stomatal frequency and changed mesophyll area. There was a close relationship among all these factors and, therefore, played a drastic role in reduction of growth under salt stress. Adverse effects of salt stress on cell division and expansion are directly attributed to decreased turgor pressure in the cells of cell expansion zone of growing leaves (Greenway and Munns, 1980). Prolonged exposure of plants to NaCl induced shrinkage and even completes distortion of chloroplast. Further, it is reported that NaCl caused plasmolysis and breakage of plasmodesmata of leaf cells.

Mechanisms of growth reduction under salt stress:

Plant growth under salt stress conditions is complex mechanism and the way in which it is affected by the stress is not fully understood. Soil salinity is a huge problem negatively affecting physiological and metabolic processes in plant life, ultimately diminishing growth and yield (Ashraf and Harris, 2004). Glycophytes, like wheat are negatively influenced by increased soil salinity resulting in significant reduction in their productivity. Salt stress induces specific changes in the morphology and anatomy of the cells, tissues and organs (Cheeseman, 1988; Shannon, 1997; Sairam and Tyagi, 2004; Flowers,

2004). Saline soils contain high ratios of Na^+ : Ca^{+2} , Na^+ : K^+ , Ca^{2+} : Mg^{2+} and Cl^- : NO_3^- which cause reduction in plant growth due to specific ion toxicities and ionic imbalances and induce changes in physiological and metabolic components of plant growth processes. Mechanisms responsible for reduction in plant growth under salt stress are: (1) Osmotic stress, (2) Specific ion toxicity, (3) Nutritional imbalance and (4) Oxidative stress.

Osmotic stress: Salts present in the soil solution exert an osmotic pressure and reduce the soil water potential making water unavailable to plants. Munns *et al.* (2006) reported that the presence of excessive salts in soil solution reduced the ability of plants to take up water ultimately causing the slower plant growth. The primary cause of growth reduction due to the excess of salts is the energy required for growth which is utilized by plants to acquire water from the soil and to make metabolic adjustments (Akram *et al.*, 2002). The reduction in dry matter yield under salt stress could be due to inadequate availability of nutrients present in growth medium and the decreased water entry rate into the plants. As a result, less water is taken up by the roots and transported into shoot for various physiological and metabolic processes (Lopez and Satti, 1996). An efficient exclusion of Na^+ from leaves through transpiration stream and the transport of other ions to the leaves could assist in the osmotic adjustment of sugarcane, hence, the higher salinity tolerance of sugarcane genotype, H69-8235, could be interpreted on the basis of its hydraulic conductivity resulting in higher transpiration rate, not associated with reduced leaf water potential (Plaut *et al.*, 2000). Saqib *et al.* (2004) reported that the decreased the growth of wheat under saline conditions was largely attributed to the loss of turgor that resulted in reduced gas exchange and photosynthesis and also had detrimental effects on cell division and elongation.

Specific ion toxicity: The primary cause of growth reduction under salt stress due to the uptake of certain ions (Na^+ and Cl^-) at supra-optimal level is termed as specific ion toxicity (Chinnusamy *et al.*, 2005). Salt stress due to ion toxicity inhibits the plant growth for a longer time than water stress as described by Jacoby (1993). Na^+ and Cl^- accumulated in leaves up to toxic levels hamper the metabolic processes going on in cytoplasm and retard the growth and development of wheat plants. It had been shown that leaf injury and loss due to excessive salt accumulation might be an important factor controlling the active size of canopy (Francois and Maas, 1993).

Na^+ and Cl^- ions penetrate the hydration shells and interfere with non-covalent interaction between their amino acids inducing conformational changes and loss

of function of proteins due to ion cytotoxicity, caused by the replacement of K^+ with Na^+ in biochemical reactions. Dionisio and Tobita (2000) found that the salinity stress increased concentration of Na^+ that suppressed the leaf gas exchange and PSII photochemical activity and consequently inhibited the growth and development of plants.

Nutritional imbalance: The plant growth and development affected by salinity stress induces nutritional imbalance (Grattan and Grieve, 1994; Rogers *et al.*, 2003; Hu and Schmidhalter, 2005) induced as a result of the effect of salinity on relative nutrient availability, competitive uptake and transport or partitioning within the plant that may be caused by physiological inactivation of a given nutrient resulting in an increased plant's internal requirement for that essential element (Marschner, 1995). It is notable that one or more of these processes may occur simultaneously and whether they affect the crop yield or quality depends on the toxic level, composition of salts, the crop species and number of environmental factors (Grattan and Grieve, 1999).

Decreased nitrogen uptake under saline conditions occurs due to interaction between Na^+ and NH_4^+ and/or between Cl^- and NO_3^- that ultimately reduce the growth and yield of the crop (Rozeff, 1995). Many laboratory and greenhouse experiments have demonstrated that salinity could reduce N accumulation in plants (Passarakli and Tucker, 1988; Feigin *et al.*, 1991). This reduction in NO_3^- uptake is associated with Cl^- antagonism (Feigin *et al.*, 1987; Bar *et al.*, 1997) while others attribute this to reduced water uptake under saline conditions (Lea-Cox and Syvertsen, 1993). The availability of phosphate was reduced in saline soils due to (a) ionic strength effects that reduced the activity of phosphate, (b) phosphate concentrations in soil solution was tightly controlled by sorption processes and (c) low solubility of Ca-P minerals. Hence, it is noteworthy that phosphate concentration in field grown agronomic crops decreased as salinity increased (Sharpley *et al.*, 1992; Qadir and Schubert, 2002). It is observed in many cases that P concentration in plant tissue is decreased by 20 to 50%; however, there is no evidence of P deficiency in the crops. Root membrane integrity and selectivity is disrupted under saline conditions due to high levels of Na^+ in soil solution that also interferes with K^+ acquisition by the roots. A number of studies in many crops have shown that K^+ concentration in plant tissues, expressed on dry matter basis, reduces as the Na^+/Ca^{2+} in the root media increases (Asch *et al.*, 2000; Hu and Schmidhalter, 2005). High level of external Na^+ caused a decrease in both K^+ and Ca^{2+} concentrations in the plant tissues of many plant species (Hu and Schmidhalter, 1997). This reduction in K^+ concentration in plant tissue might be due to the antagonism of Na^+

and K^+ at uptake sites in the roots, the influence of Na^+ on the K^+ transport into xylem (Lynch and Lauchli, 1984) or the inhibition of uptake processes (Suhayda *et al.*, 1990).

Na^+/Ca^{2+} interactions under salinity stress from physiological perspective indicates decreased Ca^{2+} availability in the presence of salinity as described in the recent review summarized by Hu and Schmidhalter (2005). Lower Ca^{2+}/Na^+ ratio was observed under saline conditions indicating reduced Ca^{2+} availability, because Na^+ readily displaced Ca^{2+} from its extra cellular binding sites (Cramer *et al.*, 1988). Moreover, it is reported that the decreased uptake of Ca^{2+} under saline conditions might be due to its precipitation and the increase in ionic strength that reduced its activity. Low Ca^+ uptake by plants can impair the activity and the integrity of cell membrane and promotes the passive accumulation of Na^+ in plant tissues. Furthermore, the low Ca^{2+}/Na^+ ratio in saline media plays a significant role in inhibiting the plant growth as well as causing morphological and anatomical changes in plants (Cakmak, 2005). Hu and Schmidhalter (1997) stated that Mg^{2+} concentration decreased in wheat leaves under saline conditions.

The availability of micronutrients in saline soils is dependent on the solubility of micronutrients, the pH of soil solution, redox potential of the soil solution and the nature of binding sites on the organic and inorganic particle surfaces. In addition, salinity can differently affect the micronutrient concentrations in plants depending upon crop species and salinity level (Oertli, 1991). Micronutrient deficiencies are very common under salt stress owing to high pH (Zhu *et al.*, 2004).

Oxidative stress: In addition to osmotic stress and ion toxicity, salt stress also exerts an oxidative stress and all these factors contribute to its deleterious effects (Comba *et al.*, 1998; Hernandez and Almansa, 2002; Vronova *et al.*, 2002). Under salt stress conditions stomatal closure occurs, which reduces the CO_2/O_2 ratio in leaves and inhibited CO_2 fixation. Consequently, it increases the concentration of ROS like superoxide radical (O_2^-), hydrogen peroxide (H_2O_2), hydroxyl radical (OH^{\cdot}) and singlet oxygen (1O_2) which are generated naturally in a number of cellular metabolic pathways (Becana *et al.*, 2000) like photorespiration, photosynthesis (Noctor *et al.*, 2000), senescence and fatty acid oxidation and (Vitoria *et al.*, 2001). ROS attack on many cellular components including membranes and essential macro-molecules such as photosynthetic pigments, proteins, nucleic acids and lipids (Foyer *et al.*, 1994; Lin and Kao, 2000) due to their interaction with free electrons (Sharma *et al.*, 2005). They are usually produced with in chloroplast and mitochondria because of sustained flow of electrons in these organelles. In normal conditions, up to 20% of the total photosynthetic electron flux is transferred to molecular O_2 converting it

into ROS (Cakmak, 2005). When the conversion of light energy into CO₂ fixation is limited under salt stress, the flow of electrons to O₂ is intensified, resulting in a greater accumulation of ROS in chloroplast. Under these conditions, the excitation energy is also transferred to O₂ to form highly toxic ¹O₂ (Cakmak, 2005; Choi *et al.*, 2002). Shalata and Tal (1998) stated that an unfortunate consequence of salinity stress in plants is the excessive production of ROS. The excessive production of ROS under salt stress occurred due to impaired electron transport processes in chloroplast and mitochondria as well as from pathways such as photorespiration causing membrane damage, chlorophyll degradation and responsible for the development of leaf chlorosis and necrosis (Choi *et al.*, 2002).

Various approaches to improve salt tolerance:

Different approaches such as introduction of new genes into genotypes responsible for salt tolerance, screening of large international collections and conduct of field trials on selected genotypes, conventional and non-conventional breeding methods and adequate regulation of mineral nutrients have been employed to enhance salinity tolerance in plants (Munns *et al.*, 2006). Saline agriculture and exogenous application of mineral elements including Si has been professed as cost effective approach to ameliorate the salt stress in cereal crops like wheat.

Silicon (Si): An introduction (properties, occurrence, discovery and nomenclature): Si exists in two allotropic forms a) shiny, grayish black needle-like or crystal plates b) amorphous brown powder (Datnoff *et al.*, 2001). The melting point of the crystalline allotrope is 1.41°C, its boiling point is 2.35°C and its density is 2.3 g/cm³. Si is the most plentiful element in the earth's crust, ranking second only to oxygen. According to an estimate, Si dioxide (SiO₂) comprises 50-70% of the soil mass and has also been detected in the sun and stars etc. Si never occurs free in nature, but usually exists as a compound with oxygen, calcium, magnesium, phosphorus and other elements. Those compounds that contain Si and oxygen with one or more other elements are known as silicates. The first successful effort in the search for Si was done by the Swedish chemist Jons Jakob Berzelius. The new element was named by the Scottish chemist Thomas Thomson (1773-1852) due to the presence of element in the mineral flint (*silex* or *silicis* in Latin). He added the ending-on because of the element's similarity to carbon. Si is categorized as a beneficial element in plant biology. It is unquestionably an important requirement for the normal growth of many plants and must be called as "Quasi essential" (Epstein, 1999a). A reasonable amount of literature supports that Si is beneficial element and its application may reduce the impact of

salt stress in plants. Published data on the role of Si against biotic and abiotic stresses, especially salinity in various plant species have been reviewed in following paragraphs:

Si in plant biology: Si is found in plant tissues growing in soil media. The element, Si shows an anomaly in plant physiology. In the soil solution, Si mainly present in the form of silicic acid (0.1-0.6 mM) and plants absorb most of Si in monosilicic acid form from the growing medium through transpiration stream. When silicic acid is accumulated over a critical level of (~100 ppm at biological pH), it is polymerized as phytoliths (SiO₂.nH₂O) bodies that comprise the bulk of a plant's Si content (Exley, 1998). As a result, all plants rooting in soil medium contain significant Si content in their tissues (Ma *et al.*, 2006). Si is deposited within cell wall forming silica-cuticle double layers and silica-cellulose double layer on the surfaces of leaves and stem (Raven, 2003). The leaf edges and awns of plants are smooth growing in Si-deprived medium, on the other hand, these were found quite rough in Si-repleted plants (Daren *et al.*, 1994).

Despite, the fact, that Si exists as ubiquitous and prominent constituent of plants; it is usually not recognized as an essential element for plant growth. Its role in plant biology is still poorly explored and lacks a direct evidence either it is a part of plant constituents or enzymes. The most of terrestrial plants complete their vegetative and reproductive growth in Si deprived growth medium (Epstein, 2001). The situation was made worse by the continuous reliance on an imperfect old definition of essentiality because of which Si does not meet the criteria of an essential element. Later on, the definition of essentiality was criticized and a new one was devised by Epstein and Bloom in (2005) as: An element would be essential if it qualifies either one or both of two criteria, (I) the element is part of a molecule which is an intrinsic component of the structure or metabolism of the plant and (II) the plants with severe deficiency in the element exhibit more abnormalities in growth, development, or reproduction, as compared to plants with a lower deficiency. Following this definition, Si is essential for higher plants because Si deficiency causes various abnormalities in the plant. Si-deficient plants are much more different from Si-enriched plants in structure, chemical composition, mechanical strength, yield and yield contributing factors, enzymatic activities, disease and pest resistance, metal toxicity, salt and drought tolerance etc. (Epstein, 2001).

The role of Si in plant growth and development remained overlooked until the beginning of the 20th century. The most plant physiologists ignored the positive effects of Si on plant body due to (I) Si is biologically un reactive element in soil plant system and (II) quantitative abundance of the element in nature and major inorganic

constituent of plants, therefore, visible symptoms of either Si deficiency or toxicity were not apparent (Richmond and Sussman, 2003). With the passage of time, repeated cropping and the constant application of chemical fertilizers have depleted the Si that was available to plants as a nutrient. This Si deficiency in soils is now recognized as a limiting factor for crop production, particularly in highly weathered soils (Datnoff, 2004).

However, awareness is scarce about the role of Si on the growth of plants grown on young *Aridisols* soil order that is relatively less Si-depleted. But ample information is present about the deficiency of Si in the *Aridisol* soil order in Pakistan. Present research is one of attempts to see the beneficial role of Si in wheat under salt stress in *Aridisols*.

Certain crops especially, from Poaceae and Cyperaceae families build up a large amount of Si (Mitani and Ma, 2005) and its application to these crops ensures better growth. Usually graminous plants accumulate and deposit more Si in their tissues than other species (Matichenkov and Kosobrukhov, 2004). Being the member of Poaceae family, wheat is also designated as Si-accumulator. Wheat is the major staple food of Pakistanis (Richmond and Sussman, 2003) and is categorized as salt sensitive glycophyte as salt stress suppresses the vegetative and reproductive growth of wheat (Zhu *et al.*, 2004). Si is the only element that does not damage plants when accumulated in excess due to its properties of un-dissociation at physiological pH and polymerization (Ma *et al.*, 2001). When plants are exposed to various abiotic and biotic stresses the effects of Si against them are generally expressed more evidently (Takahashi *et al.*, 1990; Epstein, 1999b). Growth enhancement in higher plants by Si application is more prominent under biotic and abiotic stresses (Liang *et al.*, 1999). The use of Si in agriculture is cost effective and environmental friendly tool against salt stress. Si is well-known to enhance growth of plants subjected to saline stress, hence is advantageous to ameliorate the salinity stress (Liang *et al.*, 1996).

Different mechanisms by which Si mediates salinity tolerance in plants are described below:

Si maintains the plant water Status under saline conditions: Plants have to face water deficit under salt saline conditions imposed by the low external water potential due to high concentration of salts (Na^+ and Cl^-) in soil solution and their accumulation in extracellular region inside the plant body (Romero *et al.*, 2001). These ions are continuously transported to the aerial parts of plants through transpiration stream and when the saline ions content reach a toxic threshold, cause severe damages to plant tissues. Any factor that enables plants to retard the toxic level of ions is crucial for their salinity tolerance. The plants can survive with situation

if they have ability to retain water in saline medium and in this way they can improve tissue tolerance by mitigating an excessive ion concentration by a dilution effect (Cuartero *et al.*, 1992). Si, due to its hydrophilic nature, helps plants to tolerate salt toxicity by improving the water economy of the plant. Si amendment can improve plant water status by reducing the osmotic effect of salinity on plant water uptake and plant water storage. The increased leaf area due to Si treatment recorded in salinized plants proposed that in addition to benefits of Si to keep/store water and to increase cell turgor, Si could be involved in the expansion of cell wall and consequently enhances cell enlargement. Bradbury and Ahmed (1990) studied in *Prosopis Juliflora* that plants growing in saline soil (260 mM) in the presences of Si had significantly greater Leaf Weight Ratio (LWR) and lesser values of Specific Leaf Area (SLA) compared to salinized plants where Si was not applied. It was suggested that plants treated with Si had lower fraction of dry weight than leaves because the leaves were small and thick as compared to plants grown in the absence of Si. The decreased surface area helped these plants to tolerate salinity by reducing the transpirational loss of water.

Romero *et al.* (2006) noted that the increase in the volume of symplastic water within seedlings of tomato grown under salt stress with Si application in the growth medium and simultaneous promotion in biomass production was a function of increased water influx. Leaf turgor potential and net photosynthesis rates were found 42 and 20% higher respectively in salt-stressed plants treated with Si in comparison to plants grown in Si free solution.

The plant water content was also decreased by 54% in tomato plants due to salt stress. Supply of Si under non-saline conditions did not significantly change the plant water content. However, when salinized plants were supplied with Si, their water content increased upto 40%. Plants treated with NaCl in the presence of Si showed values of turgor potential 42% higher than those plants treated only with NaCl (Romero *et al.*, 2006).

Water Use Efficiency (WUE) estimated as the ratio between net CO_2 assimilation and transpiration rates was decreased under saline conditions in rice plants. However, salt-stressed plants supplied with Si showed values of WUE 17% greater than those of salinized plants which were not supplied with Si by reducing the transpiration.

It can be concluded that Si increases the water storage within plant body, which contributes to salt dilution and allows a higher growth rate by alleviating deleterious effect of salt toxicity.

Si reduces uptake of Na^+ by improving K^+ : Na^+ and also alleviates the toxicity of other heavy metals: Under salt stress conditions, the excessive uptake of certain ions

(Na⁺ and Cl⁻) upto supra-optimal level is the primary cause of growth reduction and is known as specific ion toxicity (Chinnusamy *et al.*, 2005). Lower concentration of Na⁺ in plants reflects their ability to tolerate salt stress. Some mechanisms of salinity tolerance by which Si prevents the accumulation of Na⁺ ion in plant tissues have been reported in various plant species is reviewed below.

Inhibition of sodium influx, active Na⁺ efflux and compartmentation of Na⁺ into the vacuole has been suggested as mechanism of salt tolerance in plants (Marschner, 1995). In compartmentation, Na⁺ is transported from cytoplasm into the vacuole via different proton pumps to protect cellular components and maintain all metabolic activities in the symplast. Any factor, that makes proton pumps to activate, will definitely favor compartmentation inducing salinity tolerance. The Si-amended stimulation of H⁺-ATPase activity on root plasma membrane and H⁺-PPase activity in tonoplast of barley roots under salt stress enhanced the compartmentation of Na⁺ into the vacuole through Na⁺/H⁺ antiport movement. The stimulated H⁺-ATPase enhanced the uptake and upward transport of K⁺ and retarded the movement of Na⁺ thus, improved the K⁺: Na⁺ selectivity ratio in the shoots of salt-stressed barley (Liang *et al.*, 2005). As Na⁺/H⁺ antiport is operated with input of energy, thus, both the H⁺-ATPase and H⁺-PPase are the chief sources of H⁺ electrochemical potential gradient, which acts as an Electromotive Force (EMF) for such energy dependent antiports (Blumwald, 2000).

It can be concluded that compartmentation is an important mechanism of salt tolerance in plants.

Si can alleviate Na⁺ toxicity not only by decreasing the internal toxicity of Na⁺ in plant leaves and stem but also by reducing the activity of free Na⁺ in solution as well as in roots after it has been taken up by plants, thus reducing its movement to the aerial parts of the plant. It was observed by Ma *et al.* (2001) that the alleviation of Na⁺ toxicity in corn was due to the formation of Na⁺ and Si complexes in the solution as compared to any other physiological impact of Si on the plant. The concentration of toxic Na⁺ was reduced in the presence of Si and the reduction in toxic Na⁺ was paralleled by an increase in root elongation. It is reported that the Na⁺ contents in the rice shoot were nearly 50% of those in the shoots of plants which were not supplemented with soluble silicates in their growth medium (Matoh *et al.*, 1986). Gong *et al.* (2006) suggested that one of the possible mechanisms responsible for the detoxification of Na⁺ ion in Si amended rice plants is co-precipitation of both elements in roots. It is, because, Si deposition (in the form of polymerized silicate) in exodermis and endodermis reduced the translocation of sodium via reduction in apoplastic transport across the root. Yeo *et al.* (1999) described that the probable reason might be the reduction of both Na⁺ transport and the transport of

apoplastic tracer trisodium-8-hydroxy-1, 3, 6-pyrenetrisulphonic acid in salt-stressed rice plants. This means that mode of action of silicate was by partial blockage of transpirational bypass flow, the pathway by which a large fraction of the uptake of total sodium content in rice takes place. Ahmad *et al.* (1992) reported that Si significantly decreased Na⁺ contents in flag leaves of wheat and roots of salt-stressed wheat plants. In case 0.6% NaCl with Si, Na⁺ lowered the amount of Si in the flag leaves as compared to control which indicated the binding of soluble Si with Na in the root and retards its movement to aerial parts of plants

The salinity tolerance due to Si application is also attributed to selective uptake and transport of K⁺ and Na⁺ by plants as they compete with each other at root and shoot level. Liang *et al.* (1999) in two contrasting barley genotypes: Kepin No. 7 (salt sensitive) and Jian 4 (salt tolerant) reported that Si application reduced Na⁺ but increased the K⁺ concentration in shoots and roots of barley when treated with salt. Sodium uptake and its translocation into shoots from roots was greatly suppressed by added Si under saline conditions. However, Si application exhibited a little impact on Ca concentration in shoots of barley when treated with salt. They further reported that major proportion of Na⁺ taken up by plant roots stayed in the apoplast and it seemed as much as 85-90% of the total in some species. In a greenhouse study, Zuccarini (2008) stated that reduction in K⁺ uptake caused by salinity stress was partially overcome by Si, especially in roots. But Cl⁻ content in shoot and root was not altered by Si application significantly. Thus, Si application improved the growth of salt-stressed plants by reducing Na content especially in leaves and suppressing the effect of NaCl on gas exchange.

In addition to Na⁺ and Cl⁻, Si is also reported to ameliorate the toxic effect of many other heavy metals. Ma *et al.* (1999) examined the role of Si as a beneficial element for different crops like rice, wheat, barely, cucumber and tomato, when plants were stressed. They found that that addition of Si had positive effect on crop performance facing mineral stresses (Al, Na⁺, N and Mn⁺² toxicity and P deficiency).

Si can alleviate Al toxicity in soyabean, barley and sorghum, but not in wheat, rice, pea and cotton. Different crop species showed variation in Al and Si-accumulation (Hudson and Evans, 1995). Cocker *et al.* (1998) also reported that Si supply ameliorated the toxic effects of Al in rice grown in nutrient solution. The mechanism of amelioration was indistinguishable. They proposed a model in which root cell walls were the main internal sites for the formation of alluminosilicate and hydroxy alluminosilicate and Al detoxification.

Linjuan *et al.* (1999) investigated the effects of Si on cadmium toxicity and showed that it affects the cellular and intra-cellular accumulation of cadmium and its

distribution. The Si-depleted rice plants varied significantly in Cd distribution in the cell walls and vacuoles of the leaves and roots as compared to Si-repleted treatments. It was detected through energy dispersive X-ray microanalysis that the remarkable amount of cadmium was present in the cytoplasm, vacuole or cellular organelles in Si-deprived rice plants in comparison to Si-amended ones.

Nable *et al.* (1992) reported from long term experiments carried out in barley crop that uptake of Si differed significantly amongst varieties and also reflected the relative susceptibility to boron (B) toxicity. Non-competitive interaction was noticed in the uptake of B and Si.

Chen *et al.* (1999) conducted experiment on ornamental plants and concluded that K-silicate has its beneficial effects on the growth of ornamental plants by tolerating Mn toxicity. He grew thirty-seven cultivars from thirty-five genera of ornamental plants in a soil-less medium supplied with K_2SiO_3 . Added Si significantly increased the dry weight of 16 cultivars and ameliorated the Mn toxicity.

Stimulation of antioxidants and detoxification of ROS by Si application under salt stress:

Any stressful environment enhances the accumulation of ROS, such as superoxide radicals (O_2^-), hydroxyl radicals (OH \cdot) and hydrogen peroxide (H_2O_2). These strong oxidizing species cause oxidative damage to biomolecules such as proteins, lipids and eventually lead to cell death (Mittler, 2002). It is well known that lipid peroxidation of membranes lipids induced by free radicals is an indicator of stress-induced damage at the cellular level. Literature shows that plasma membrane injury induced by salt stress is associated with increased production of highly toxic free radicals. When stress appears plant defensive power becomes weak due to reduced activity of antioxidants. Similarly under salt stress, activities of both superoxide dismutase and catalase are declined in plants (Halliwell and Gutteridge, 1999), whereas the Malondialdehyde (MDA) content (the product of peroxidation of membrane lipids) accumulated rapidly resulting in an increased permeability of plasma membranes. It is therefore used as an indicator of oxidative damage.

Defensive system of plants enables them to ameliorate salt stress via production of enzymatic antioxidants such as Superoxide Dismutase (SOD), Catalase (CAT) and Ascorbate Peroxidase (APX) and second non-enzymatic antioxidants such as ascorbate, glutathione and α -tocopherol. Different scientists studied in different plant species that the activity of defense system affected by salinity stress may be enhanced by Si application. Al-Aghabary *et al.* (2004) reported that Si moderately offsets the negative effects of NaCl stress by increasing tolerance of tomato plants through enhancement in

activities of SOD and CAT and soluble proteins contents in leaves. In contrast, salt stress slightly promoted APX activity. Si addition slightly decreased APX activity but, significantly decreased H_2O_2 and MDA concentrations in the leaves of plants when compared with plants treated with salt alone.

Liang *et al.* (1996) conducted his experiments on two contrasting barley cultivars: Kepin No.7 (salt sensitive) and Jian 4 (salt tolerant) and reported that exogenous application of Si significantly stimulated the activities of antioxidant enzymes, CAT (catalase), SOD (superoxide dismutase) and POD (peroxidase) in roots of barley plants subjected to salinity stress in comparison to Si-depleted salt treatment. Si effect was time dependent and became more prominent as the experiments continued. Plant roots were harvested 2, 4 and 6 days after treatment applied. The activities of CAT (catalase), SOD (superoxide dismutase) and POD (peroxidase) in roots of salt-stressed plants were significantly depressed from day four onward. Again in 1999, he examined the defense system of barley plants induced by Si under saline conditions. Barley plants were grown in hydroponics containing 120 mol m^{-3} NaCl only and 120 mol m^{-3} NaCl with 1.0 mol m^{-3} Si (as potassium silicate). They further, reported that the activities of Superoxide Dismutase (SOD) and H^+ ATPase in leaves and roots were significantly increased, whereas the concentration of Malondialdehyde (MDA) in plant leaves was found to be significantly decreased for both varieties Kepin No.7 (salt sensitive) and Jian 4 (salt tolerant) when treated with salt and Si as compared with the plants treated with salt alone.

It can be concluded that higher activities of SOD, CAT, POD, H^+ ATPase and lower concentration of MDA in salt-stressed plants induced by Si addition may protect plant tissues from membrane oxidative damage under salt stress, thus mitigating salt toxicity and improving the growth of barley plants.

Zhu *et al.* (2004) in cucumber plants reported that application of one mM Si under 50 mM NaCl toxicity significantly decreased ELP (electrolytic leakage percentage) due to limited production of LPO (lipid peroxidation), H_2O_2 (hydrogen peroxide) and TBARS (thiobarbituric acid reactive substances) content. On the other hand, it enhanced the activities of SOD (superoxide dismutase), GPX (guaiacol peroxidase), APX (ascorbate peroxidase), DHAR (dehydroascorbate reductase) and GR (glutathione reductase) in salt stressed leaves. It was concluded that increased activities of SOD, GPX, APX, DHAR and GR in salt stressed leaves induced by Si addition helped plants to withstand oxidative damage under salt stress, thus alleviated salt toxicity and improved the growth of cucumber plants.

Gunes *et al.* (2007) studied in spinach and tomato plants grown on sodic-B toxic soil that Si addition into the growth medium suppressed the salt-induced

production of H₂O₂ and increased the chlorophyll content, ribulose biphosphate carboxylase activity and photosynthetic activity of leaf cell organelles under salt stress. Si-applied improved the stability of lipids in cell membranes and prevented the structural and functional weakening of cell membranes under salt stress. Thus it was concluded that Si is involved in the metabolic or physiological changes occurring in plants under environmental stress.

Moussa (2006) conducted his experiments on maize plants and reported that the concentration of MDA and H₂O₂ in the leaves and free proline content were decreased in salt-stressed maize plants.

Gong *et al.* (2005) studied the influence of Si for the improvement of plant defense affected by water stress. He found that Si supplementation in wheat under water stress conditions enhanced the activities of some antioxidant enzymes: SOD, CAT and Glutathione Reductase (GR), the unsaturation of fatty acids whereas that of H₂O₂, acid phospholipase were reduced and the oxidative damage was ameliorated.

Morphological and physiological improvements in plants due to Si deposition within plant body under salt stress conditions:

In addition to the maintenance of water status, improvement in K: Na and alleviation of oxidative stress, Si amendment also plays a pivotal role to enhance chlorophyll content, stomatal conductance, photosynthesis and rigidity of plants under stressful conditions. Vorm (1980) observed a gradual shift from metabolic absorption to metabolic exclusion, depending on the Si concentration in the solution culture. Absorption of Si increased in the order of soybean < sunflower and wheat < sugarcane and rice.

Chlorophyll fractions and their ratios indicate the efficiency of photosystem, which in turn enables the plants to produce dry matter via continual supply of photosynthates. Any treatment that can increase or maintain chlorophyll contents is important for better crop growth. It is reported that Si can also enhance the photochemical efficiency of plant even under different stresses including Si. Al-Aghabary *et al.* (2004) reported that salinity stress significantly decreased both *Chl a* and *Chl b* contents in tomato plants, however, Si supplementation increased both *Chl a* and *Chl b* under salt stress after 10 days of application and enhanced the photochemical efficiency of PS-II. Salt stress also significantly decreased both *Chl a* and *Chl b* in maize plants, however, added Si increased them under salt stress after two months of treatments. This increase in the photosynthetic efficiency was 22.2% greater than the control plants (Moussa, 2006). Foliar spray of potassium silicate in straw berry not only increased chlorophyll content in leaves, but also caused metabolic changes such as increase in citric acid and malic acid levels and reduction in fructose, glucose, sucrose and *myo-inositol* contents. The Si-treated tissues also had higher

proportions of fatty acid unsaturation in glycolipids and phospholipids and prominent amounts of membrane lipids (Wang and Galletta, 1998). The degree of unsaturation of lipids and their contents are a sign of salinity tolerance adopted by straw berry that helped to keep intact the leaf chloroplast and protected from salinity damage.

Si application reduces the transpiration rate to restrict the Na uptake as a result CO₂ intake is enhanced showing higher stomatal conductance. Yeo *et al.* (1999) reported that Si amendment enhanced the stomatal conductance of rice plants subjected to salt stress showing that silicate can reduce Na uptake via decline in the transpiration rate, which ultimately results into the reduction in growth and net photosynthesis induced by salinity stress.

Increased water content in plants favors higher stomatal conductance and photosynthesis. Si treated sorghum plants can take out larger amount of water from drier soil under water deficit conditions and maintain an elevated stomatal conductance and photosynthesis which in turn increases the relative growth rate (dry matter production per unit dry weight), which occurs due to higher Net Assimilation Rate (NAR) or photosynthetic rate and increases Water Use Efficiency (WUE) (Hattori *et al.*, 2005). Si pretreatment in rice plants subjected to salinity stress in a greenhouse study enhanced the stomatal conductance from 138 mmol m⁻²s⁻¹ to 50 mmol m⁻² s⁻¹. This increase was 20% more as compared with control. It resulted in an increase in assimilation rate (NAR) (Gong *et al.*, 2006).

In addition to these physiological changes, Si application also gives mechanical strength to plants and facilitates them to resist lodging. It occurred due to thickening of cell walls of sclerenchyma tissue in the culm and led to the shortening and thickening of internodes (Takahashi, 1995). Linjuan *et al.* (1999) investigated the effects of Si on the seedling growth of creeping bent grass and zoysia grass grown in nutrient solution in a green house chamber. Si significantly enhanced the grass quality including rigidity, elasticity and traffic resistance. It also enabled the creeping bentgrass to tolerate heat stress beyond 45°C during the day time and 35°C at night.

Silicon improves growth and dry matter production under salt stress conditions:

It is evident from the above discussed literature that Si promotes the morphological, physiological and metabolic performance of plants both under saline and non-saline conditions. This improved performance of plants due to Si amendment ensures their better growth resulting in an increased yield and yield contributing factors in many plant species growing in lab, greenhouse and field conditions. It is mostly reported that as Si content with in plant body increases, yield increases as described by different plant scientists in the following.

Linjuan *et al.* (1999) observed that the Si-amended plants produced more fresh matter over the Si deprived plant. Addition of Si into the culture solution @ 5.0 mM increased the root length, root fresh weight and leaf fresh weight of creeping bent grass and zoysia grass, because, the Si-treated seedlings showed the higher uptake of P and Si deposition in shoots as compared to the non-treated seedlings. It might be due to the positive effect of Si nutrition on Nitrogen (N) and Carbon (C) assimilation as suggested by Watanabe *et al.* (2001) in rice plants who examined the effect of Si-addition on metabolism and translocation of nutrients in rice plants. Matichenkov and Calvert (2002) conducted a number of field and greenhouse experiments on sugarcane (*Saccharum officinarum* L.) crop. They found that Si concentration in cultivated plants ranged from 0.3 to 8.4%. A range of 210-224 million tons of Si or 70-8000 kg/ha of plant available Si is harvested with the sugarcane crop every year. Removal of Si by sugarcane crop exceeds those of the macronutrients N, P and K and usually the Si content in sugarcane leaves ranged from 0.1-3.2%. They concluded that sugarcane yield is associated with Si concentration in the leaves. They also stated that added Si had a positive effect on the disease, pest and front resistance of sugarcane. The sugarcane productivity ranged from 17-30% whereas production of sugar increased from 23-58% with increasing levels of fertilizer.

Jiang *et al.* (2003) selected 274 standard barley cultivars from the barley germplasm center of the Research Institute for Bio-resources located in Okayama University and 135 varieties were taken from the barley core collection of Americans. They were sown in the same field and then plants were for Si content. The Si concentration of barley grain indicated more variation from 0 to 3600 mg/kg in standard varieties and from 0 to 3800 mg/kg in barley core as compared to hulled barley. The Si content was observed lower in hull-less barley in comparison to the hulled barley. The Si content of two-row barley was found equivalent to that of six-row barley. Greater than 80% of the Si was deposited in the hull. The Si concentration of the hull ranged between 15343 and 27089 mg/kg. They concluded that the change in Si concentration of barley grain is controlled genetically and it provides fundamental basis for breeding Si-rich barley cultivars.

Necrotic spots in rice leaves were noticed in Si deficient plants, which might be called as deficiency symptoms. Si lacking rice plants showed retarded growth and the proportion of sterility increased in them significantly. Application of Si greatly increased yield (Mitsui and Takatoh, 1963).

Si fertilization benefits rice plants in the field after transplanting in field experiments. Various rates of Cassilicate slag supplied to nursery plants increased the number of leaves and dry matter production per plant (Lee *et al.*, 1985).

Bradbury and Ahmed (1990) conducted their research work on *Prosopis juliflora* by growing in the saline soil and treated with saline irrigation (260 mM) water for 24 days. Si (SiO_2 @ 0.46 mM) application increased the dry weight (34%) and leaf area of plants as compared to control plants.

Marschner *et al.* (1990) concluded that the exclusion of Si from growth medium causes Si deficiency. Subsequently the positive effect of added Si on the growth of rice plants occurred due to its rectifying effects on an imbalance between Zn and P supply. Agurie *et al.* (1992) investigated that the Si-fertilization maintains the photosynthetic activity. It could be one of the reasons for increased dry matter production in rice.

Increasing concentration of NaCl reduced the germination percentage and growth of wheat in Si free medium. Increase in dry weight of the shoot was significant in wheat after Si addition at 0.6% salinity, whereas dry weight of the root remained unaffected. Concentration of Si in roots increased with increasing Si levels under salt stress. A gradual reduction in tiller initiation and dry matter production of shoot was observed due to increase in salinity. It was noticed that the inclusion of 20 mg/L Si increased the number of tillers both under saline and control conditions (Ahmad *et al.*, 1992).

Friesen *et al.* (1994) carried out field trial in Colombia to study the effect of Si deficiency on upland rice. They concluded that Si deficiency proved to be a major soil nutrient constraint, restraining yield of upland rice upto 40% (600-900 kg/ha). When Si was supplemented, it increased the rice yield up to a significant extent.

Daren *et al.* (1994) studied the changeability and relation of Si concentration depositing in rice plant tissue with yield components of ten rice varieties grown at two different sites in Florida on Si-deficient organic histosol. The plots were replicated five times with two treatments i.e. Si-amended soil and non-amended (control). Plots were sampled for determination of Si concentration in plant tissue. Si application increased yield as a result of increase in number of grains per panicle, whereas weight per 100 seeds and panicles per square meter exhibited less change. Liang *et al.* (1994) studied the effect of Si on rice crop in calcareous soils and reported significant increase in its yield due to Si application.

Shengyi *et al.* (1998) studied the effect of Si fertilization on cotton growth in a field trial in china. They experienced improved early growth of cotton due to Si application. Si significantly increased total number of sympodia plant⁻¹, number of bolls plant⁻¹, boll size and lint percentage. Lint yield was enhanced by an average of 11.7% due to Si addition.

Alvarez and Datnoff (1999) carried out field experiments on rice-sugar cane rotation in Florida and worked out an economic analysis of rice and sugarcane upon Si application. The exercise of Si containing fertilizer application significantly increased the yield of both the crops.

The increasing rate of Si nutrition in the field promoted the dry matter yield, amount of N/leaf area and chlorophyll of rice plants. Moisture content of leaf blade/light transmission was higher in Si-treated plots as compared to control. Si supplementation also increased number of grains per unit area, %age of mature grains and ultimately the yield of rice (Ando *et al.*, 1999).

Muir *et al.* (1999) carried out experiments by growing cucumber and paper daisies in an organic and sand based control mix (CON), + Si mix (SIM = CON + Si) and Rice Hull Ash Mix (RAM)". Molybdate reactive Si ranged between 2.25 to 2.55 mg/L for CON, 14.1 to 15.0 mg/L for SAM and 11.4 to 13.6 mg/L for RAM. Growth of cucumber and paper daisies in RAM and SIM was observed significantly higher than those sown in CON. Plants sown in RAM accumulated more Si than from CON. The effect of Si on various plants growing in yellow River alluvial plains of China was studied. The results showed that Si fertilizer application enhanced the grain production by 10-26% for peanut (Cai, 1999).

Korndorfer *et al.* (1999) observed the influence of Si containing fertilizer on grain discoloration and growth of rice crop at four different Savanna soils in Brazil. Five Si levels were applied to each soil. Si supplementation increased total grain weight and significantly reduced grain discoloration independent of soil type. Increasing amount of Si fertilizer increased Si concentration in the leaves.

The influence of Si, Zn and Mn was studied on high yielding maize plants grown under field conditions. The increase in average length of cob by 0.3, 0.8 and 0.5 cm and the reduction in the length of sterile ear tip by 0, 0.3 and 0.2 cm due to Si, Zn and Mn treatments, respectively. The number of seeds per ear and 1000 grain weight was increased by treatments with Si, Zn and Mn and ultimately increased the maize yield. The optimized dose sodium silicate applied was of 90 kg/ha (Hua *et al.*, 1999).

Wang and Galletta (1998) studied the influence of Si fertilizer on rice grown in fields. Si fertilization into the field increased Si and Phosphorus uptake, number of productive panicles and grain per panicle. They concluded that yield increased upto 5% with silicate application.

The influence of different doses of SiO₂ on three rice cultivars (Carajas, Caiapo and Confianca) under green house condition was studied in Brazil. The linear and significant relationship between SiO₂ and grain yield was observed. The maximum grain yield increase of 23% was seen as compared to control by using 3 g/pot of SiO₂ which corresponds to one ton/ha. The cultivar Confianca showed the highest tissue concentration of Si followed by Carajas and caiapo. The application of SiO₂ increased the pH and soluble Si in soil solution (Filho *et al.*, 1999).

Fujii *et al.* (1999) studied the effect of Si on rooting ability and early growth of rice plants by using silica gel. The results demonstrated that seedlings treated with Silica gel had a higher dry weight, higher dry weight to plant height ratio. Supplementation of silica gel also increased Si deposition, photosynthetic rate, number of roots and root dry weight.

Field experiments using treatments comprising sugar mill ash alone and a sugar mill filter mold/ash mixture with supply of nutrients were conducted. Data were obtained from first and second ratoon crops for 2 years. A good yield response to both sugar mill wastes in first and second ratoon crops was observed. Yield benefits were attributed to better N and Si nutrition and decreased bulk density. Sugar mill wastes resulted in higher concentration Si in soil and leaf than other treatment. It appears as if Si in ash has improved N use efficiency (Kingston, 1999).

Talashilkar *et al.* (1999) conducted two field experiments on a Vertisol and on an Inceptisol to study the influence of Calcium Silicate Slag (CSS) on plant growth, nutrient uptake, yield and juice quality of two sugarcane varieties (Co-86032 and Co-92013). The CSS (45% SiO₂) was applied as a basal dose at six rates (0, 2, 4, 6, 8 and 10 t/ha) and compared with recommended levels of Farmyard Manure (FYM) and NPK fertilizers were used. In both the experiments, the application of different levels of CSS resulted in significant increase nutrient uptake, plant growth, cane yield and sugar recovery.

The influence of Calcium Silicate Slag (CSS) on nutrient uptake, plant growth and yield of irrigated transplanted rice (Cv. RTN-24) was observed on an Inceptisol in India. The CSS used enhanced the, nutrient (N, P, K, Ca, Mg, Si) uptake, growth and yield in comparison to the split application of prilled urea and basal SSP (Talashilkar and Savant, 1999).

Correa-Victoria *et al.* (1999) carried out field trials in Colombia collected the data over two years. They determined the level of Si at which deficiency symptoms appear and the rice yield is restricted. Si application increased rice yield approximately upto 40%. A residual effect was also observed on the yield. Kumbhar and Savant (1999) studied the effect of rice hull ash (RHA) (as a source of Si) in combination with Rice Straw (RS) (as a source of K and Si) on, plant growth, yield and incidence of blast disease in transplanted rice field in India. The combined use of ash and straw @ 2.0 kg/m and 2 t/ha respectively increased grain yield @ 405 Quintal/ha in comparison to the control (Non-treated).

Liang *et al.* (2000) conducted study to investigate the impact of Si on plant growth and its role in nutrient uptake in barley plants grown hydroponically under toxic levels of Aluminum (Al). Plants exhibited more dry weight, root length and shoot length with Si at 50 µmol/L in comparison with 75 µmol/L and beyond. Gong *et al.* (2003) studied the effect of Si on the growth of wheat

under drought. They reported an increase in wheat production in arid or semi-arid areas due to application of silicate fertilizer. Inclusion of Si in nutrient solution alleviated the negative impact on growth induced by Na⁺ and augmented dry matter accumulation in all parts of tomato leaf, stem and root (Al-Aghabary *et al.*, 2004).

The influence of Si application on plant size of sorghum became clear as the plant continued to grow. Added Si increased the Si concentration in the shoot and led to higher dry matter production under water stress conditions (Hattori *et al.*, 2005).

Supplemental application of Si increased dry matter accumulation in all parts of maize under saline conditions and the raise in leaf and total plant was significant. Added Si had no effect on dry matter accumulation under no salt stress, signifying that added Si in nutrient solution alleviated the growth inhibition induced by added NaCl (Moussa, 2006).

Gong *et al.* (2006) determined that salinity (50 mM NaCl) reduced the growth of shoots and roots in rice. Exogenously applied silicate (3mM) to the saline culture solution increased the growth of shoots but not roots. Supplemental application of Si significantly enhanced shoot dry weight, fresh weight and height of plants growing in solution culture alone by an average of 26% and spectacularly reduced the negative impact of salinity to an average of 8%. The increase in shoot growth due to silicate was correlated with reduced sodium concentrations in shoots.

Si application also enhances the crop performance against biotic stress: Si application is not only crucial for crops growing under abiotic stresses, but also shows significant improvement in crop growth growing under biotic stress like insect pest and diseases as described below.

Datnoff *et al.* (1991) studied the impact of supplied Si on blast and brown spot diseases in rice. Application of Si resulted in decrease in blast ranging from 17 to 30% and in brown spot from 15 to 32% in rice grown on histosol in the subtropical climate in Florida. The effects of Si on disease tolerance of rice were studied. The genotypes used were IR 36 and IR 50. They concluded that Si addition (1.4 mol/m) into nutrient solution significantly suppressed the incidence of blast in rice. Si application increased shoot dry matter and total biomass production. However the difference in Si uptake among genotypes was not significant (Osuna-Canizales *et al.*, 1991).

The role of Si against fungal attack in cucumber plants was marvelous. Supply of soluble Si to cucumber plants caused a marked stimulation of chitinase activity and rapid activation of peroxidases and poly phenol oxidases after infection with pythium spp (Cherif *et al.*, 1994). Belanger *et al.* (1999) reviewed different mechanisms through which Si acts as disease preventing agent in

cucumber. They suggested that Si also played dynamic role in strengthening plants against diseases by stimulating the expression of its natural defense reactions.

Bollich *et al.* (1999) conducted field experiments to verify the effects of Si-soil- amendments in checking the attack of sheath blight; blast disease and increasing grain yield of rice on two different location. The use of calcium silicate slag resulted in an increase in rice yield and accumulation of Si in leaves, whole plant and mature rice straw. The importance of Si for rice plants was studied in Canada. They concluded that Si-amendment significantly controlled plant diseases and insect attack and increased the yield of rice crop (Menziez *et al.*, 1999).

Park (1999) conducted field trials to see the effect of Si on rice crop in Korea. Added Si not only increased the growth and yield of rice but also reduced incidence of leaf blast leaf scald disease. Datnoff and Nagata (1999) studied the influence of Si on gray leaf spot disease in augustine grass. Si application obviously reduced the area (44-78%) for gray leaf spot among all 4 cultivars. Si content in rice plants for all cultivars under Si- amended treatment increased 2.2 to 3.5 folds as compared to the non-amended control.

The added calcium metasilicate in cucumber plants reduced the infestation of powdery mildew and the number of mildew colonies by 30.0% and 36%, respectively over the control (Oliveira *et al.*, 1999). Prabhu *et al.* (1999) conducted a field experiment and studied the effect of Si on rice crop and its grain discoloration. They presented results that the supplementation of Si fertilizer at different levels significantly increased paddy yield. Applied Si also enhanced the resistance in rice plants against rice blast and grain discoloration.

Sherazi and Miller (1999) studied the influence of different levels of potassium silicate in suppressing the attack of adult Japanese beetle (*Popilla japonica*) causing damage to leaf tissues of sergeant crab apple. After three days of post treatment, detached leaves were placed in three Petri dishes in combination with one adult female (*Popilla japonica*) for the period of seven days. K-silicate applied at 100 mg/L concentration significantly decreased percentage of leaf tissue eaten by beetle. When plant tissues were assayed, the results obtained indicated that Si and Ca concentrations were significantly higher in root tissues of Si treated plants in comparison to stem and leaves. The K and Mg concentrations were recorded higher in root tissues in comparison to stems and leaves of Si-deprived plants.

The rice plants infested with blast disease tended to have lower level of Si in comparison to the healthy plants. It was also found that addition of Si into the soils increased the concentration Si in rice plants and induced an enhanced blast resistance. Si was mainly deposited leaf surface tissues and acted as a physical

barrier against penetration of infection thread by blast fungus (Ishiguro, 1999).

Voogt and Sonneveld (1999) conducted his experiments on different horticultural crops and presented their results showing that strawberry, cucumber and rose were benefited from increased Si concentration in the growth medium around the root. Addition of Si increased the yield due its control over powdery mildew and also affected the Mn distribution in lettuce and bean.

The influence of different levels of Si sand (99.64%) on blast control in the rice cultivar Cimason was studied. The experiment was conducted on two different sites located in the state of Portuguesa. Leaf blast control ranged from 46.9-83.7% over the control treatment. The decrease in blast incidence on the panicle was ranging from 36.5-65.7% as compared to control treatment (Zambrano *et al.*, 1999).

Rodrigues *et al.* (1999) evaluated the effect of calcium-meta silicate on incidence of sheath blight in rice. Six rice cultivars were sown on a Typic Acrustox soil. They found that higher relative lesion height was suppressed due to Si application in comparison to the control.

Anderson and Sosa (2001) conducted the field trials through broadcast application of calcium silicate slag (0 and 6.7 Mg/ha) and studied the impact of calcium silicate supplementation on the development of resistance in sugarcane against borer attacks. Five cultivars CP70-1133, CP72-1210, CP72-2086 and CP74-2005 and CP80-1827 were examined for yield response and borer resistance. Across all cultivars, Si-amended fields showed increased cane yield and borer resistance by 16.7 and 19.5%, respectively.

Epilogue: The above review leads to the following generalizations/conclusions.

1. Soil salinity is a huge problem negatively affecting physiological and metabolic processes in plant life, ultimately diminishing growth and yield.
2. Salts taken up by the plants influence the plant growth by inducing adverse effects on different physiological and biochemical processes, including turgor, photosynthesis and enzymatic activities.
3. Mechanisms responsible for reduction in plant growth under salt stress are: (1) Osmotic stress, (2) Specific ion toxicity, (3) Nutritional imbalance and (4) Oxidative stress.
4. Different approaches such as introduction of new genes into genotypes responsible for salt tolerance, screening of large international collections and conduct of field trials on selected genotypes, conventional and non-conventional breeding methods and adequate regulation of mineral nutrients have been employed to enhance salinity tolerance in plants.
5. Saline agriculture and exogenous application of mineral elements including Si has been professed as cost effective approach to ameliorate the salt stress in cereal crops like wheat.

6. Si is categorized as a beneficial element in plant biology. It is unquestionably an important requirement for the normal growth of many plants and must be called as "Quasi essential".
7. Si amendment also plays a pivotal role to enhance chlorophyll content, stomatal conductance, photosynthesis and rigidity of plants under stressful conditions.
8. There are different mechanisms by which Si mediates salinity tolerance in plants. It maintains the plant water status under saline conditions. It reduces uptake of Na⁺ by improving K⁺: Na⁺ and also alleviates the toxicity of other heavy metals.
9. Its application helps to improve the defensive system of the plants by producing anti-oxidants which in turn detoxify reactive oxygen species. Morphological and physiological improvements in plants were observed due to Si deposition within plant body under salt stress conditions.
10. Silicon improves growth and dry matter production under salt stress conditions. Its application also enhances the crop performance against biotic stress.

Conclusion: It is, therefore, concluded that supplemental application of Si must be included in salt stress alleviation management techniques.

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