

AMELIORATION OF HARMFUL EFFECTS OF SOIL SALINITY IN PLANTS THROUGH SILICON APPLICATION: A REVIEW

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Abstract

Improved crop production in salt-affected regions is necessary to counter growing demands for food. Salt stress initiates osmotic and oxidative stress, and specific ion toxicity leading to nutritional imbalance and altered gas exchange characteristics in plants. It is broadly stated that silicon (Si) is the 2nd rich element present in soil used previously to mitigate salt stress. Here we reviewed the salt uptake mechanisms by roots and its integration with different physiological and metabolic processes. The primary focus is to explain mechanisms by which Si uptake in plants contributes to the salt stress amelioration. Numerous studies suggested that Si is effective in improving plant growth and biomass, seed germination, photosynthetic pigment, antioxidant enzymes activity, relative water content and reducing ion toxicity and oxidative damage under salt stress. However, it is a prerequisite to determine Si-mediated salinity tolerance mechanisms under different edaphic and climatic conditions with varying species types and field practices systems which are considered here in detail.

Key words: Salt stress, Osmotic stress, Nutritional imbalance, Photosynthesis, Si uptake, Salinity tolerance.

Introduction

Abiotic stress in plants, including drought, salinity, heavy metals, and other environmental extremes negatively affect crop plants (Adil *et al.*, 2022; Altaf *et al.*, 2021; Kamran *et al.*, 2020). Among these, salt stress is a primary stress factor that limits growth and yield of plants particularly in the arid and semi-arid environments where irrigation with saline water causes accumulation of salts in the arable soils (Welfare *et al.*, 2002). As a result, water uptake by plants is decreased in saline environments, and Na⁺ and Cl⁻ are up taken by plants in greater amounts which adversely affect the metabolic processes and photosynthetic activity (Mäser *et al.*, 2002, Naveed *et al.*, 2020). Plants responses to salt stress can occur in two stages including osmotic stress and accumulation of Na⁺ ions (Munns *et al.*, 2008). A rise in salt stress inside a plant affects metabolism and synthesis of proteins. Salt stress has affected about 1/3 area of the world's cultivated land (Perez-Alfocea *et al.*, 1996). According to Poss *et al.*, (1999), a multidisciplinary team of scientists is required to understand the connection between mineral nutrition of plants and salinity. Romero-Aranda *et al.*, (2001) described that under saline conditions, low external water potential results in water stress within the plant, so the survival of the plant becomes difficult.

In salt stress conditions, salts are present in higher concentrations. The soil solution surpasses the osmotic pressure made in plant cells, leading to decreased plant roots capacity to absorb the minerals like K⁺, Ca⁺ and water. High salt concentrations restrict the seed from absorbing water from the soil and hinder seed germination

(Gupta and Huang 2014). One of the salts tolerance indicators is the presence of K⁺ in plant body parts, which designates the lower level of Na⁺ uptake (Ali *et al.*, 2021).

Earth crust contains silicon (Si) as a second most rich component after oxygen. About 0.1 to 0.6 mM concentration of silicic acid is present in soil solution (Epstien, 1994, 1999) Application of Si has proved to lessen the fatal effects of salinity on plants, for instance, Tuna *et al.*, (2008) stated that small amounts of soluble Si could significantly enhance the salt tolerance in wheat (*Triticum aestivum*) crop. Ashraf *et al.*, (2010) revealed that the application of silicon might reduce the detrimental effects of salt stress. Silicon application decreased the uptake of Na⁺, prohibited its transport into the shoots and enhanced the K⁺ concentration in the shoots, ultimately causing a better K⁺/Na⁺ ratio. According to Liang *et al.*, (2003) barley (*Hordeum vulgare*) treated with silicon improved the structure of leaf cells and photosynthetic activity and improved the plant growth under high saline environment and decreased the electrolyte leakage from leaves. Tuna *et al.*, (2008) described that barley grown in hydroponics increased salt tolerance when treated with Si. Moreover, studies have revealed that the application of silicon improved K⁺/Na⁺ proportion/ratio which decreased the toxic effects of Na (Liang *et al.*, 2003).

Studies revealed that Si produced a significant rise in growth of various higher plants in biotic and abiotic stressed environments (Ali *et al.*, 2021a, b). Various mechanisms and procedures are suggested in Table 1 through which Si could rise the tolerance against salt stress in plants which is among the major factors responsible for

limiting the yield in semi-arid and arid areas. A rise in dry matter was significantly prominent in salt stress demonstrating the positive effects of use of Si in lessening salt stress (Al-ghabary *et al.*, 2005). According to (Romero-Aranda *et al.*, 2006) application of silicon on Kikar (*Prosopis juliflora*) under saline conditions significantly increased the dry matter production with increased uptake of K^+ (Liang *et al.*, 2007). Moreover, salt stress caused a significant decline in K^+ concentration when silicon was not applied to the root medium, however, endodermis and exodermis deposits of silicon in roots decrease Na^+ uptake in plants (Guntzer *et al.*, 2012).

Si application improved the germination percentage of wheat (*Triticum aestivum*) grown in salt stressed environment (Bybordi 2014). Moreover, Haghghi *et al.*, (2012) compared the results of tomato (*Solanum lycopersicum*) grown under salt stress and stated that silicon-nano (1 mM) improved the percentage of germination and rate of germination significantly as compared to tomato (*Solanum lycopersicum*) grown in salt stressed environment without the application of silicon. Si application (1-5 mM) improved vitality index, germination index and rate of germination of balsam-pear plant (*Momordica charantia*) grown in salt stressed conditions (50 and 100mM) (Wang *et al.*, 2010). Gong *et al.*, (2003) revealed that the application of Si resulted in leaf thickness of wheat (*Triticum aestivum*) under drought environments, moreover, drought tolerance might be improved by applying silicon ultimately reduces the transpirational loss of water. Water uptake by roots is also adjusted by plants to maintain water balance in all parts of a plant. Yin *et al.*, (2013) recommended that the presence of silicon in culture solution is able to increase water uptake by root in water stress through vigorous addition of soluble sugars and amino acids.

Mateos-Naranjo *et al.*, (2013) found that harmful effects of salinity on photosynthetic efficiency and leaf gas exchange are recovered by the application of (Si) on cordgrass (*Spartina densiflora*), a halophytic grass. Moreover, water use efficiency, net transpiration and stomatal conductance are significantly lowered in salinity stress in rice (*Oryza sativa*). At the same time, by the

application of silicon these attributes are enhanced considerably (Ming *et al.*, 2012). Salt stress reduces the activities in the cell as well as photosynthesis and results in nutritional imbalance (Rios *et al.*, 2017).

Chen *et al.*, (2012) revealed that the addition of (Si) also improves the quality of photosynthetic pigments b, and enhances the basal important yield (Fv/F0). The addition of silicon is helpful in improving the activities of certain photosynthetic enzymes. Zhu (2014) observed the activity of ribulose-bisphosphate and carboxylation was enhanced by Si in cucumber. According to Gong & Chen (2012) under drought conditions, Si application boosted the activities of carboxylase and phosphoenolpyruvate, and the inorganic phosphorus concentration in wheat (*Triticum aestivum* L.) leaves. These studies revealed that Si is involved in both photochemical reactions and stomatal conductance, hence regulates photosynthesis. In conclusion, added Si has positive effects on water status of plant and photosynthesis in drought conditions. According to the above studies, Si might improve seed germination in saline conditions however, it is still required to explore the detailed procedures and mechanisms behind this for better and comprehensive understanding of Si role and its application in crops in saline environments at all periods, especially in field experiments.

Hazardous effects of salt stress: Excessive amounts of salts result in water and soil salinity, commonly Na^+ is the sources of salinity. The ultimate results of salinity include reduction in water potential, initiation of ionic imbalance, disruption in ion-homeostasis and specific ion poisonousness in plants. This changed water position results in initial growth reduction and lessens the plant productivity. Growth suppression is directly linked to soluble salts concentration or soil water osmotic potential (Azevedo Neto *et al.*, 2004, Zulfiqar *et al.*, 2021). The salinity causes detrimental effects on plant parts and results in decreased productivity. Hazardous effects of salt stress on plant metabolic processes are described in (Fig. 1). While possible mechanisms for reduction in hazardous impacts of salinity by the application of Si are described in (Fig. 2).

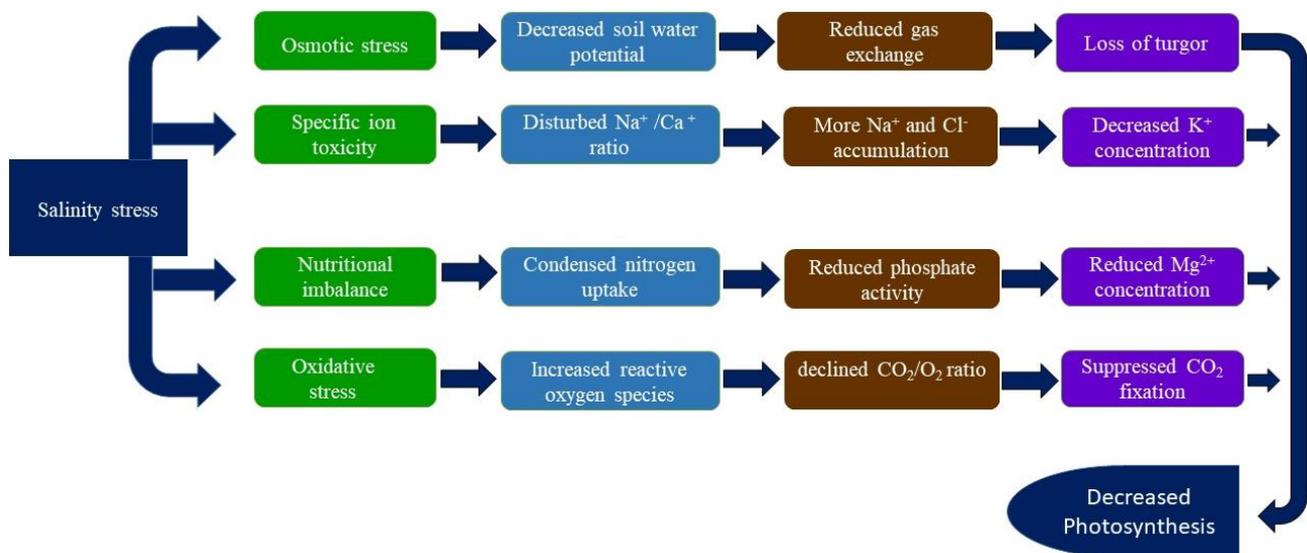


Fig. 1. Hazardous effects of salinity stress on plant metabolic processes eventually affecting photosynthesis.

Table 1. Effects of silicon application on antioxidant enzyme activity, ion accumulation, transpiration detected in varying growth media in different plant species under salt stress conditions.

S. No.	Crop	Growth medium	Parameters	Observed Effects of Silicon in salinity	References
1.	Tomato	Solution culture	Antioxidant enzyme activity	Decrease or no effect depending on stress duration	(Al-aghaby <i>et al.</i> , 2005)
2.	Grapevine	Potting soil	Ascorbate peroxidase	Increase or no effect subject to cultivars	(Soylemezoglu <i>et al.</i> , 2009)
3.	Cucumber	Solution culture	Catalase	No effect	(Zhu <i>et al.</i> , 2004)
4.	Grapevine	Potting soil	Catalase	Decrease	(Soylemezoglu <i>et al.</i> , 2009)
5.	Tomato	Solution culture	Catalase	Increase	(Al-aghaby <i>et al.</i> , 2005)
6.	Maize	Solution culture	Catalase	Increase	(Moussa 2006)
7.	Canola	Solution culture	Catalase	Increase	(Hashemi <i>et al.</i> , 2010)
8.	Barley	Solution culture	Catalase	Increase or no effect subject to stress duration	(Liang <i>et al.</i> , 2003)
9.	Grapevine	Potting soil	Superoxide dismutase	No effect	(Soylemezoglu <i>et al.</i> , 2009)
10.	Barley	Solution culture	Superoxide dismutase	Increase	(Liang <i>et al.</i> , 2003)
11.	Cucumber	Solution culture	Superoxide dismutase	Increase	(Zhu <i>et al.</i> , 2004)
12.	Tomato	Solution culture	Superoxide dismutase	Increase	(Al-aghaby <i>et al.</i> , 2004)
13.	Maize	Solution culture	Superoxide dismutase	Increase	(Moussa, 2006)
14.	Wheat	Potting soil	Na ⁺ /Cl ⁻ accumulation	Decreases Na concentrations in both shoot and root	(Tuna <i>et al.</i> , 2008)
15.	Barley	Solution culture	Na ⁺ /Cl ⁻ accumulation	Decreases shoot and root Na ⁺ concentrations	(Liang, 1999)
16.	Alfalfa,	Solution culture	Na ⁺ /Cl ⁻ accumulation	Decreases Na ⁺ Concentration in roots	(Wang & Han, 2007)
17.	Barely	Solution culture	Na ⁺ /Cl ⁻ accumulation	Decreases root Na ⁺ concentration	(Liang & Ding, 2002)
18.	Tomato	Solution culture	Na ⁺ /Cl ⁻ accumulation	No effect on shoot Na ⁺	(Romero- Arand <i>et al.</i> , or Cl ⁻ concentration, 2006)
19.	Sugarcane	Potting soil	Na ⁺ /Cl ⁻ accumulation	Reduction in shoot Na ⁺ and/or Cl ⁻ concentrations	(Ashraf <i>et al.</i> , 2010b)
20.	Barley	Potting soil	Na ⁺ /Cl ⁻ accumulation	Cl ⁻ concentrations	(Gunes <i>et al.</i> , 2007b)
21.	Tomato	Potting soil	Na ⁺ /Cl ⁻ accumulation	Cl ⁻ concentrations	(Gunes <i>et al.</i> , 2007a)

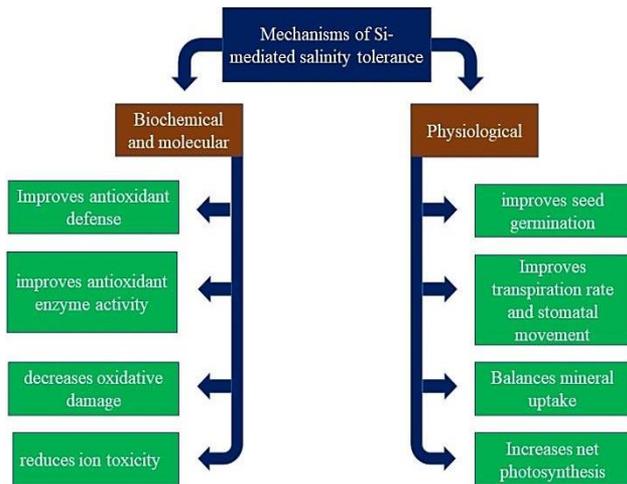


Fig. 2. Mechanism for reduction in hazardous impacts of salinity in plants by the application of silicon.

Influence of salinity on Plant morpho-biochemical traits

Plant growth: Excess salts results in distinct stunting of plants (Parveen *et al.*, 2021), whereas, reduction in leaf surface area is an instant reaction to increased salt concentration (Zribi *et al.*, 2009). Significant decline in the dry and fresh weights of stems, roots and leaves was observed by the increased concentrations of the salts (Chartzoulakis and Klapaki, 2000). A reduction in stomatal conductance was the 20% remaining effect of salinity on growth. Yousif *et al.*, (2010) described that at low salinity levels (50mM NaCl), an increase in total plant weight was observed while at increased salinity levels (100 and 200 mM NaCl), decreased total plant biomass in camel thorn (*Alhagi pseudoalhagi*), a leguminous plant.

Experiments revealed that under hydroponic culture, the growth of plant was ideal at 100mM NaCl in a salt non-secretor mangrove swamp boronia (*Bruguiera parviflora*), whereas a gradual rise in NaCl absorption confines plant growth and 500 mM NaCl has proved fatal in this type of plants (Parida *et al.*, 2004). Mishra & Das, (2003) described that up to 250mM NaCl levels were tolerated by a salt secretor black mangrove (*Aegiceras corniculatum*) and 300mM NaCl levels were proved to be fatal. High salinity causes major decrease in plant height, root surface area, root length, quantity of leaves per plant and shoot weight in tomato (*Solanum lycopersicum*) plant (Mohammad *et al.*, 1998).

Leaf anatomy: Salinity has many harmful effects on plant structure, especially on leaves. Its harmful effects result in thickness of epidermal tissues, the thickness of mesophyll tissues, palisade diameter, palisade cell length in cotton and bean (Longstreth & Nobel, 1979). When swamp boronia (*Bruguiera parviflora*) treated with NaCl, there was a significant decline in the width of mesophyll and leaf epidermal intercellular spaces (Parida *et al.*, 2004a). Parida *et al.*, (2004) also suggested that salt stress caused decline in leaf intercellular spaces.

The injurious effects of salt stress include: Reduction in the size of mitochondrial cristae and inflammation of mitochondria. Vacuolation progress and partial swelling of endoplasmic reticulum.

Fragmentation and vesiculation of tonoplast membrane. Leaves of sweet potato undergo degradation of cytoplasm with combination of cytoplasmic and vacuolar matrix (Mitsuya *et al.*, 2000).

Salinity stress results in turning of cells, reduced intercellular spaces and decrease in amount of chloroplast (Salah *et al.*, 2017).

Salinity causes a visual decrease in stomatal thickness and leaf area of tomato (*Solanum lycopersicum*) crop (Romeroaranda *et al.*, 2001).

Salinity effects on plant water relations: With a rise in salinity, osmotic and water potential of plants becomes more negative, while a gradual rise in salt stress increases turgor (Khan, 2001; Meloni *et al.*, 2001; Romeroaranda *et al.*, 2001). When a mangrove plant (*Rhizophora mucronate*) was grown in saline media, there was an increase in osmotic potential, xylem tension, and leaf water (Aziz & Khan, 2001). According to (Geissler *et al.*, 2009) reduction in leaf osmotic potential was noted with the rise in NaCl in sea aster and Chrysanthemum. When jute (*Corchorus capsularis* L.) was treated with short-term NaCl stress, a major decrease in rate of transpiration, leaf water potential, retention of water, relative water content, water use efficiency and uptake of water was recorded (Karlberg *et al.*, 2004). Zehra *et al.*, (2012) observed that with a rise in salinity, a decrease was recorded in pressure potential and the development of negative water potential and stomatal conductance were observed in the perennial halophytic grass (*Urochondra setulose*). Similarly (Lu *et al.*, (2002) confirmed that there was a significant decline in leaf water potential and rate of evaporation but there was no considerable effect on leaf relative water content with an increasing salt concentration in Seepweed (*Suaeda salsa*) depending on the mode of imposed stress and rooting medium osmotic potential, however, there was a drop in leaf water potential, while under prolonged NaCl presence, a substantial drop in osmotic potential was detected (Rajasekaran *et al.*, 2001).

Silicon uptake mechanisms: Si concentrations in aerial parts of the plants vary greatly, from 0.1 to 10.0% of plant dry weight. Liang (2007) revealed that the reason behind the extensive difference in Si concentrations in plant materials is the differences in the mechanisms of uptake along with transport of Si. Generally, uptake of Si is much more in *graminaceous* plants than other species, while Si is absorbed by most dicotyledonous plants passively and is excluded after uptake such as in some dicote legumes (Liang *et al.*, 2005). According to Ma *et al.*, (2006) rice (*Oryza sativa*) is a typical accumulator of Si, moreover, the uptake and transportation of Si is an active process in rice (*Oryza sativa*), whereas, dicots like cucumber (*Cucumis sativus*), melon (*Citrullus lanatus*), tomato (*Solanum lycopersicum*), soybean (*Glycine max*), strawberry (*Fragaria ananassa*) and bean passively uptake the Si and eliminate it after the uptake (Ma, 2005; Mitani & Ma, 2005; Liang *et al.*, 2005b). Rice (*Oryza sativa*) mutants has been progressively used in characterizing (Si) uptake and transport (Tamai and Ma, 2003). According to Ma and his colleagues, the lateral roots of rice (*Oryza sativa*) are very important in silicon uptake, while there was no contribution of root hairs in the uptake of

(Si) (Ma *et al.*, 2001). Mitani & Ma (2005) have described that in the xylem sap of cucumber, the (Si) concentration was lower than in external solution, proposing that a passive diffusion mechanism facilitated xylem filling of (Si) in cucumber (*Cucumis sativus* L.). According to Liang and his co-workers, Si uptake along with transport are dynamic procedures in cucumber (*Cucumis sativus* L.) (Liang *et al.*, 2005). In addition, (Si) application significantly improves antioxidants and enzymes activity in plants which helps plants to resist stress tolerance.

Salt stress amelioration by Si application

Reduction in ion toxicity: Under salt stress, keeping low concentration of Na^+ and high concentration of cytosolic K^+ is essential, whereas, plants have to spend extracellular resources to maintain this concentration, likewise, increased accumulation of Na^+ and Cl^- concentrations results from increased salt treatments and, at the same time, decreased cations, e.g. K^+ and Ca^{2+} (Wang & Han 2007). Silicon could reduce Na^+ gathering in or shoots and roots. When salt-stress was applied to barley (*Hordeum vulgare*) roots, (Si) addition decreased the absorption of Na^+ and Cl^- and increased K^+ levels, with more uniform distribution of K^+ and Na^+ in the root segment; which has been recommended to be among key procedures and mechanisms of silicon-mediated salt tolerance in this specific species (Mali *et al.*, 2008).

Gong *et al.*, (2006) revealed that the Si application on rice (*Oryza sativa*) declined the Na^+ concentration in shoots, but there was no effect on roots of salt-stressed plants, which relates to positive effect of silicon with improved shoot growth. According to Gunes *et al.*, (2007) the movement of Na^+ and Cl^- beginning from roots towards shoots in tomato (*Solanum lycopersicum*) plants grown up in sodic (type B) contaminated soil are attained by the application of silicon. Shahzad *et al.*, (2013) describes that salt stress results in increased Na^+ amount in leaf apoplast of dicot bean (*Vicia faba* L.) while the application of silicon decreased it significantly. When wheat (*Triticum aestivum*) was grown in saline conditions, concentration of Na^+ was significantly decreased both in roots and shoots by the application of silicon (Tuna *et al.*, 2008). The concentration of Na^+ was decreased and K^+ concentration increased in shoots of the sugarcane (*Saccharum officinarum*) (Ashraf *et al.*, 2010). The silicon addition decreased the Cl^- concentration in the shoots in saline environments (Shi *et al.*, 2013). These readings described that (Si) might be supportive in diminishing the damaging effects of salt stress through avoiding Na^+ uptake via roots and its transportation in plants.

Positively regulation of mineral uptake: The water deficiency decreases nutrient uptake via roots and follows transportation to shoots, hence decreasing metabolism and availability of nutrients (Farooq *et al.*, 2009, Rahman *et al.*, 2021). Transport of sodium with the added silicon was determined by (Yeo *et al.*, 1999) and they revealed that Si significantly decreased the quantities of Na^+ in the shoots. Moreover, it indicates that the transportation of water and sodium was blocked on apoplastic leakages.

Moreover, the uptake, distribution and transport of minerals may be balanced by Si in salt-stressed plants. Ca^{2+} is more closely associated with the exhibition of osmotic stress-responsible genes (MAPKs genes) (Mahajan and Tuteja 2005), while plant osmotic regulation depends on K^+ levels (Ashraf *et al.*, 2001). According to Kaya *et al.*, (2006), Si improved Ca^+ and K^+ levels in maize leaves grown in salt stress. According to (Detmann *et al.*, 2012) Si is responsible for increasing the both rice (*Oryza sativa*) nitrogen use efficiency and grain yield, while Xie *et al.*, (2008) observed that the added Si decreased concentration of P in xylem sap of maize.

Antioxidant capacity: Si addition improved the activity of superoxide dismutase, glutathione reductase, guaiacol peroxidase, ascorbate peroxidase and dehydroascorbate reductase in the salt-stressed leaves, which ultimately decreased the percentage of lipid peroxidation level, electrolyte leakage and H_2O_2 content proposing that the addition of Si can diminish oxidative damage brought by salt (Tripathi *et al.*, 2020). Liang (2003) reported the result of added silicon on antioxidant enzymes in salt stress and he observed a rise in superoxide dismutase activity in high salinity barley leaves and enhancement in glutathione reductase, guaiacol peroxidase and catalase activity in barley roots under salt stress (Zhang *et al.*, 2004). Experimental results revealed that Si addition significantly improved activities of ascorbate peroxidase, superoxide dismutase, guaiacol peroxidase and dehydro ascorbate reductase under salt-stressed cucumber leaves, however, no increase in catalase activity was observed (Feng *et al.*, 2009). Protection systems are very helpful against oxidative stress and can contribute a very important role in preventing the plants from salt damage (Ahmed *et al.*, 2019).

Improvement in seed germination: Salt accumulation in soil inhibits seed germination and hampers water uptake by seeds (Gupta & Huang 2014). According to Bybordi (2014) wheat (*Triticum aestivum*) seed germination was improved with the silicon application in salt stress. Similarly, (Haghighi *et al.*, 2012) stated that the nano-silicon (1 mM) improved tomato (*Solanum lycopersicum*) germination percentage under 50 mM NaCl compared to no Si application. When 50 and 100 mM salt stress was applied to balsam pear (*Momordica charantia*) with silicon application of 1 to 5mM, Si improved the vitality index, germination index and germination rate (Wang *et al.*, 2010). Moreover, the hazardous effects of salt stress on wheat (*Triticum aestivum*) seeds was reduced by the addition of 20 ppm Si. Pooled estimates of variance revealed that the variation among treatments and days resulted in significant differences; however their interactions remained non-significant (Gong *et al.*, 2006). Above discussed studies suggested that Si might be responsible for improved seed germination in saline conditions but there is still a need to explore the procedures behind these studies.

Remedial effects on photosynthesis, plant growth and biomass: Application of Si increased the photosynthetic pigments, plant growth and plant biomass in many plants (Rizwan *et al.*, 2015, Ali *et al.*, 2021b). Abdalla (2011)

described that application of Si in diatomite form under saline conditions improved the photosynthetic pigments and fresh and dry weights in Egyptian clover (*Trifolium alexandrinum* L.). According to Amirossadat *et al.*, (2012) application of silicon enhanced chlorophyll contents, dry and fresh weights and plant height of cucumber under saline environment. Si application resulted in increased chlorophyll contents, number of seeds/plant and faba bean (*Vicia faba* L.) plant yield in salt stressed environments (Qados *et al.*, 2015). Mainly (Si) application in tomato plants studies and revealed improved photosynthesis by over expression of photosynthesis related genes.

Adding 20 ppm silicon showed significant results overall in saline and non-saline environments as the addition of silicon enhanced the quantity of tillers significantly and recorded a significant rise in shoot dry weight at 0 and 0.6% NaCl (Gong *et al.*, 2006). According to Kafi & Rahimi (2011) Si application (1 mM) to purslane (*Portulaca oleracea* L.) in salt stressed environment enhanced shoot biomass and root growth parameters (diameter, volume, length, area and root dry weight). Parande *et al.*, (2013) suggested that added Si under salinity enhanced seed mass and overall yield of bean (*Phaseolus vulgaris* L.) plant. Li *et al.*, (2015) discovered that Si addition in sand culture enhanced root morphological characters like surface area and volume, root length and overall diameter of salt-stressed tomato (*Solanum lycopersicum*). Under saline conditions, added silicon (in the form of Ca-silicate) enhanced number of grains per spike and wheat (*Triticum aestivum*) grain yield (Ali *et al.*, 2012). It is reported in many studies that the addition of Si in salt-stressed wheat (*Triticum aestivum*) improved plant biomass, plant growth and development and photosynthetic pigments in various growth environments (Zhu *et al.*, 2014). Possible mechanisms for reduction in hazardous impacts of salinity in plants by the application of silicon are presented (Fig. 2).

Improvement in relative water contents: Salt tolerance in plants may possibly be contributed through Si-mediated improvement in relative water content and decline in osmotic potential in plant leaves in saline environments. Main response of plants towards osmotic stress is the decrease in relative water content of leaf under saline conditions (Fahad *et al.*, 2015). Si application resulted in the improvement of relative water content of wheat (*Triticum aestivum*) leaf (Bybordi, 2014), maize (Rohanipoor *et al.* 2013), tomato (*Solanum lycopersicum*) (Li *et al.*, 2015), turfgrass (*Cynodon dactylon* L.) (Esmacili *et al.*, 2015) and sorghum (Yin *et al.*, 2013) grown in salt stressed environments.

Regulation of oxidative stress: In saline environments, plants typically undergo water scarcity that results in more reactive oxygen species production (Liang *et al.*, 2005) mainly superoxide anion, hydrogen peroxide and hydroxyl radical which are considered to disturb the normal metabolism of plant cell (Zushi *et al.*, 2009) moreover, harm the endomembrane systems and plasma membrane (Gill & Tuteja 2010). There are various complex antioxidant protection systems in plants including enzymatic or non-enzymatic ingredients which

search the reactive oxygen species, while antioxidant enzymes comprise of superoxide dismutase, ascorbate peroxidases, guaiacol peroxidase, glutathione reductase, catalase and dehydroascorbate reductase, amongst them, superoxide dismutase is a main searcher which changes the superoxide into hydrogen peroxide. The most detrimental procedure in living organisms is the lipid peroxidation mediated through reactive oxygen species (Gill & Tuteja, 2010).

It is reported that Si reduces the amount of malondialdehyde (lipid peroxidation end-product) in barley (*Hordeum vulgare*) plant (Liang *et al.*, 2003), grapevine rootstocks (Soylemezoglu *et al.*, 2009) and maize (*Zea mays*) (Moussa, 2006) in saline environments, proposing that Si application can reduce the peroxidation of lipids. Moreover, antioxidant enzymes activities are affected by the silicon addition while this effect depends on time and plant species such as Liang *et al.*, (2003) observed that the activity of catalase improved under salt stress on 2nd day as related to control (with no silicon and NaCl addition) irrespective of whether Si was added or not. However, on day 4 and 6 of salt application, catalase activity declined under salt stress, but this decrease significantly lessened by silicon addition in salt stress (Liang *et al.*, 2003).

Conclusions and prospects

Silicon-mediated salinity alleviation and recovery in growth and biomass of plant in salt stress can be linked to various mechanisms working together. These included improvements in antioxidant defense, improvement in antioxidant enzyme activity, reduction in oxidative damage, reduction in ion toxicity and nutrient homeostasis. In contrast, at physiological level, the mechanisms include improvement in seed germination, improvement in transpiration rate and stomatal movement; balanced mineral uptake and increase in net photosynthetic rate. Si-mediated salinity mitigation and increased plant growth and biomass can be linked with enhanced uptake and translocation of K⁺ and decline in free Na⁺ in plants. Moreover, the alleviation of salt stress with Si could be one of the possible ways to increase seed germination and growth and crop yield. Above all, this review can help better understand the mechanisms of Si-mediated salinity tolerance enhancement in plants and increase crop productivity in salt stressed environments.

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