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Review

Harnessing silicon nanoparticles and various forms of silicon for enhanced plant growth performance under salinity stress: application and mechanism

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Abstract
Agricultural production faces significant losses due to salinity, drought, pests, insects, and weeds, particularly in nutrient- and fertilizer-deficient soils. This review focuses on enhancing the productivity of crops grown in dry and saline environments. Silicon nanoparticles (Si NPs) and silicon compounds (SiO_2/SiO_3^{2-}) have shown potential to improve crop yields while mitigating the effects of biotic and abiotic stresses. As an eco-friendly alternative to chemical fertilizers, herbicides, and pesticides, Si NPs stimulate germination, plant growth, biomass accumulation, and nutrient absorption due to their small size, large surface area, and ease of cellular penetration. These nanoparticles reduce salinity stress by modulating gene expression, leading to the activation of antioxidant enzymes such as SOD, CAT, and APX, which help combat reactive oxygen species (ROS). Treatment with low concentrations of nano-silica (100–300 mg/L) significantly enhances plants' tolerance to salinity. Si NPs, when combined with soluble polymeric materials and rhizobacteria, provide a sustainable impact due to their slow-release properties, offering prolonged protection against bacterial and viral infections under saline stress conditions.

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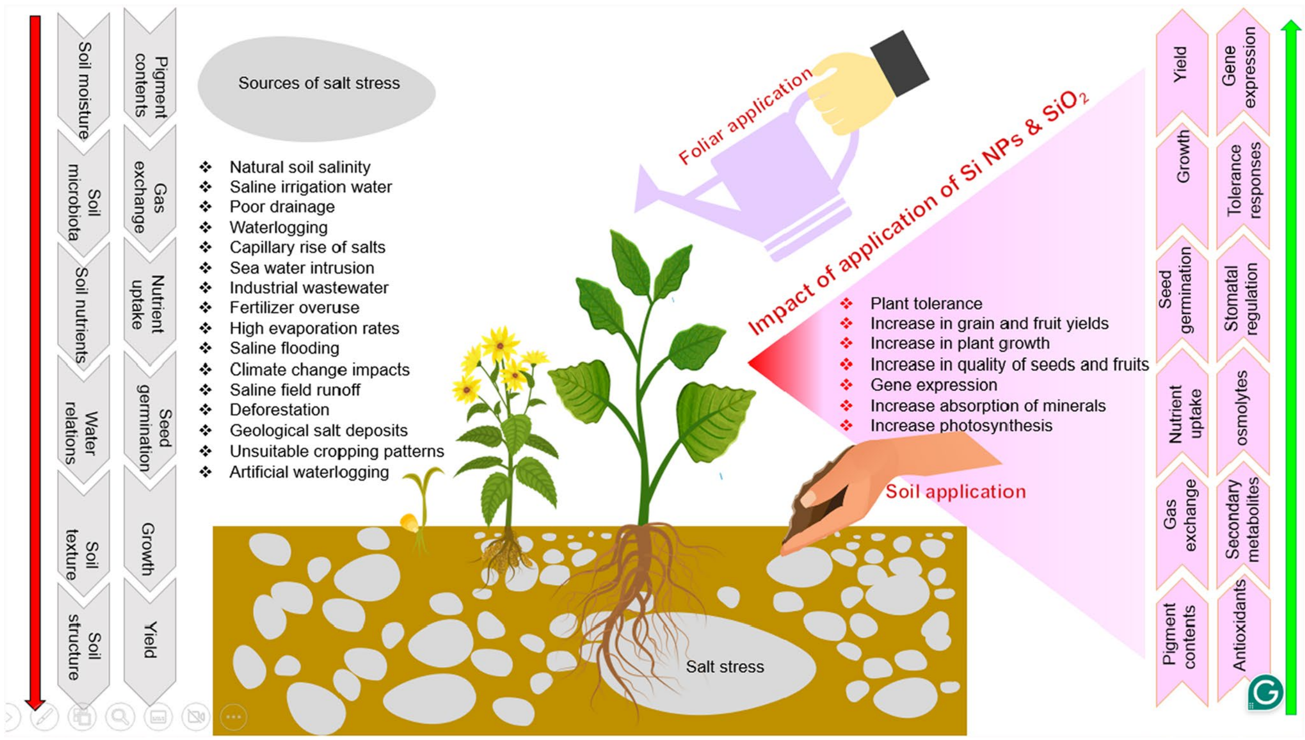
Graphical abstract



Keywords Foliar and soil exposure · Nano fertilizers · Improved salt stress tolerance · Plant growth promoter · Antioxidants · Nutrients carrier

Abbreviations

APX	Ascorbate peroxidase
$CaCl_2$	Calcium chloride
$CaSO_4$	Calcium sulphate
CAT	Catalase
CMSI	Cell membrane stability index
CO_2	Carbon dioxide
DNA	Deoxyribonucleic acid
GPX	Glutahione peroxidase
GSH	Glutathione
H_2O_2	Hydrogen peroxide
K_2SiO_3	Potassium silicate
KCl	Potassium chloride
MDA	Malondialdehyde
$MgCl_2$	Magnesium chloride
$MgSO_4$	Magnesium sulphate
Na_2SiO_3	Sodium silicate
NaCl	Sodium chloride
NH_3	Ammonia
NPs	Nanoparticles
PAL	Phenylalanine ammonia-lyase
POD	Peroxidase
POX	Pyrogallol peroxidase

PPO	Polyphenol oxidase
ROS	Reactive oxygen species
$Si(OH)_4$	Silicic acid or silicon tetrahydroxide
Si-NPs	Silicon nanoparticles
SiO_2	Silicon dioxide
SiO_3^-	Silicon trioxide anion or mesosilicate
SiO_4^-	Silicon tetraoxide anion or orthosilicate anion
SOD	Superoxide dismutase
ZnO	Zinc oxide

1 Introduction

The world population is increasing and food crop production is decreasing due to various anthropogenic activities, global climate change, and abiotic stresses like salinity, drought, cold, pollution, toxic metals, and heat [1–3]. Among these, soil salinization is a major environmental threat to food safety, impacting 7% of the world's land area and 33% of irrigated land, leading to harmful abiotic stress [1]. Salinity alone causes a reduction in the vegetative growth of plants, grain size, germination, ionic imbalance, osmotic stress, photosynthesis, chlorophyll pigments, respiration, and activity of enzymes [4–6]. Looking at the decreasing food crop production, with shrinking soil and increasing population, it has become essential to raise the production of food grains, fruits, and vegetables. Agriculturists, ecologists, biologists, and environmental professionals are making all possible efforts to grow more eatables with bare minimum resources. The use of nanotechnology has become prevalent almost in every field because it is simple, economical, and timesaving. It has been found that the use of nano fertilizers and Si NPs [3, 7–10] increase the yield of food grains and tolerance against salinity [11–14]. Reactive oxygen species (ROS) are derived from oxygen, including free radicals like superoxide (O_2^-) and non-radicals such as hydrogen peroxide (H_2O_2), which can cause cellular damage through oxidative stress, especially build-up in higher amounts under stresses. Translocation of food and respiration are slowed down and ROS are produced in their cells [15–17] which damage the proteins, lipids, genes, and DNA [18] under salt stress. The dynamic balance between sodium (Na^+) and potassium (K^+) ions across plant cell membranes, is regulated by ion transporters and pumps. This equilibrium of Na/K is essential for maintaining cellular osmoregulation, ion homeostasis, and proper functioning of physiological processes. Salinity stress can be overcome by maintaining Na/K equilibrium, closing stomata, reducing transpiration, ROS, MDA [19] and increase in the activity of antioxidants [20] with the application of Si NPs on crop plants [21, 22]. NPs penetrate the plant cells, go to the plantlets, accumulate in tissues, and boost crop yield. They are absorbed immediately after they come in contact with plasmodesmata [20]. All NPs are not equally beneficial to all crop plants [23]. The concentration and size of NPs are crucial to having the maximum impact on crop production. These NPs can be synthesized by different methods such as top-down, bottom-up, chemical reaction, sol–gel, precipitation, and green approach. Among these, the green route is the most popular because it does not use hazardous chemicals and also does not leave toxic residues [24].

To make the land fertile, the salinity of the soil should be reduced and irrigation from water polluted with NaCl, and toxic metals should be discontinued. Na_2SiO_3, K_2SiO_3, and Si NPs should be applied to the soil/plants to increase their growth. Silicon protects plants from abiotic stress and increases the production and quality of seeds, fruits, vegetables, and grains [25]. Si-NPs have unique properties that make them more effective than bulk Si because they are extremely small and have a larger surface area than bulk Si. Exogenous application of Si NPs on *Elymus sibiricus* under saline conditions showed remarkable improvement in protein by 96%. The Na + ion concentration, ROS, and oxidative damage were decreased with a consequent increase in nutrient uptake and activity of CAT, POD, SOD, and APX by 42 to 215% [26]. Similar results have also been reported in the case of beans [27] but it was observed that SiO_2 gave better results than SiO_3^{2-}. However, a combination of SiO_2 and beneficial microbes gave the best result. Interaction between plants and microbes further helps in sustaining normal function. Si NPs can enter the plasma membrane while bulk SiO_2 or SiO_3^{2-} fail to reach them owing to their large size. It has been reported that priming of wheat grain with SiO_2 NPs increased the rate of germination and decreased salinity stress [28]. Foliar application of SiO_2 at a concentration of 200 mg L^{-1} has been found to reduce salt stress in tomatoes [29].

Some plants like rice, wheat and barley accumulate silicon [30–32] in their tissues as silicic acid, $Si(OH)_4$, which improves cell wall strength and provides elasticity to them. Silicon is absorbed from the soil through roots and protects plants from insects and microbes. SiO_2 and Si NPs of 10- 100 nm are easily absorbed and act as carriers for fertilizers and metal nutrients [33, 34]. The mechanism of action of silicon is not yet clear but it is thought that it increases the efficiency of nutrients thereby increasing the growth, photosynthesis, and activity of antioxidants. It is not known if silicon is an essential nutrient but it is useful to many plants. It protects the plants from harsh environmental conditions [35–37]. Some plants require silicon as an essential component for their growth [38] but it acts as a stress buster for all plants regardless of their source [39]. Even though wheat, rice, maize, and millet contain large quantities of silicon [40, 41] their additional application during stress further increases the growth of plants and grain yield. It is absorbed by plants through silicon transporters and increases the absorption of N, P, K, and Mg which enhance the growth of grains in many crops [42].

Despite the well-established role of silicon in mitigating salinity stress, existing research predominantly focuses on the effect of silicon in alleviating salinity stress but limited comparative studies are present on the different forms of silicon. The precise mechanisms through which these silicon forms enhance plant growth and salinity tolerance remain unclear. This review aims to fill this gap by critically evaluating the differential effects of various silicon forms, exploring their unique applications and underlying mechanisms in stress mitigation, and providing insights into their comparative effectiveness for improving agricultural productivity under saline conditions.

2 Structure and formula of silicates

Silicates have been classified into three groups depending on their structure and pore size (a) Mesosilicates (b) Sorosilicates and (c) Cyclosilicates. Besides $Si(OH)_4$, Na_2SiO_3 is also soluble in water giving large polymeric anions in alkaline medium.

$$Na_2SiO_3 + 3H_2O \rightarrow Si(OH)_4 + 2NaOH$$

The silicic acid is easily absorbed but dehydrated to SiO_2 if left in the open, as shown below:

$$Si(OH)_4 \rightarrow SiO_2 + 2H_2O$$

Since SiO_2 can re-absorb water, it is used as a dehydrant. Mesoporous silica is in between macro- and micro-silica films of 20–100 nm pore size which have been found to carry biomolecules to the target [43].

3 Plant Studied

Several studies have highlighted the effects of Si-NPs on growth, nutrient uptake, ROS concentration and improved salt stress tolerance in plants. They have been summarized and a comparative analysis is presented (Table 1). Further, explanation of some selected crop plant species are given in the following subheadings.

3.1 Banana

Mahmoud et al. [44] have shown that spraying 150 mg L^{-1} and 300 mg L^{-1} of nano-silica in different seasons on saline and fresh water irrigated Williams's banana plants increased the salt tolerance and fruit yield by 30–45%. Continuous spraying of nano silica reduced the sodium ion concentration in different parts of the plants. However, in subsequent years the effect was diminished because the absorption of other essential elements was reduced although chlorophyll a and b were enhanced in silica-treated plants. Salinity increased the activity of antioxidant enzymes (CAT, PPO, and POX) in Williams banana which was further increased when sprayed with green nano-silica. It also decreases the size of fruits and total yield, relative to plants grown in fresh water. The taste of banana and mango (*Mangifera indica*) under salinity stress also changes due to reduced sugar in fruits [7]. The release of antioxidants increases in response to increasing salinity due to irrigation by saline water. Foliar application of green nano silica on Williams banana [7] increases the sugar contents and weight of the fruit by about 40–50% which has also been found in mango and sugar beet [45]. Perhaps silica eases the absorption of nutrients required for the growth of fruits and reduces the stress caused by the sodium ions. However, no mechanism has been proposed as to why foliar spray with a very small quantity of silica (150–300 mg L^{-1}) enhances photosynthetic pigments, rate of photosynthesis, weight and size of fruits and sugar contents in the plants. It is known that sodium ion causing salinity is a metal of large ionic radius (0.95 nm) while silicon is a metalloid of very small radius (0.04 nm) having properties of both metal and non-metal. Since silicon is about 24 times smaller than sodium it is easily

Table 1 A comparative analysis table summarizing the effects of Si-NPs across different crop plants with dose and their impact under salt stress condition

Studied plants	Salinity levels	Size of silica nanoparticles	Concentration of Si NPs used	Mode of application	Impact	Key references
Banana (*Musa acuminata*)	50 mM NaCl	–	200, 400 and 600 mgL^{-1}	Nutrients solution and foliar spray	Enhanced photosynthesis and uptake of K^+, as well as modulated Na^+ levels	[44]
	Saline groundwater (EC = 4.12 $dS\ m^{-1}$)	–	150–300 mgL^{-1}	Spray	Increase salinity stress tolerance and fruit yield by 30–45%	[7]
Orange (*Citrus x sinensis* L. Osbeck)	60 and 120 mM NaCl	10–20 nm	200, 400 and 600 mM	Foliar application	Enhanced chlorophyll content, and Na^+ cotransporter ((*CsSOS1*, *CsSOS2*, *CsSOS3* and *CsNHX1*) and aquaporin (*CsPIP1;1*, *CsPIP2;3*, and *CsTIP4;1*) transcript expression in root tissues	[48]
Strawberry (Fragaria × *ananassa*)	25 or 50 mM NaCl	10–20 nm	50 and 100 $mg\ L^{-1}$	Amendment in nutrient solution	Increased plant growth rate, productivity, the epicuticular wax layer, chlorophyll content, and carotenoid content	[65]
	50 mM NaCl	Not specified	1 and 2 mM	Amendment in nutrient solution	Silica nanoparticles mitigated salt stress and improved the vegetative growth and reproduction	[59]
	2.5 $g\ Kg^{-1}$ NaCl	20–30 nm	0.75 and 1.5 $g\ Kg^{-1}$ soil	Soil supplementation	Increased plant growth, but reduced the inhibitory effects of salinity	[60]

Table 1 (continued)

Studied plants	Salinity levels	Size of silica nanoparticles	Concentration of Si NPs used	Mode of application	Impact	Key references
Tomato (*Solanum lycopersicum* L.)	50 mM NaCl	10–20 nm	250 and 500 mg L^{-1}	Soil drenching	Increased chlorophyll, GSH, PAL, and Vitamin C levels. In addition, the treatment helped to maintain fruit size and quality	[95]
	250 mM NaCl	Not specified	100 mg L^{-1}	Root dipping and foliar applications	Foliar application of Si-NPs seems to be more effective than root dipping in reducing salt stress	[95]
	4000 and 8000 mg L^{-1} NaCl	4.75–6.95 nm	0.5 mg L^{-1}	Foliar application	Foliar applications of nano-silicon on grafted tomato showed higher levels of plant growth, fruit yield, and fruit quality	[208]
	Different combinations	–	200 mg L^{-1}	Hoagland solution	Increased photosynthesis, chlorophyll content, antioxidants	[29]
Mango (*Mangifera indica* L.)	Salinized drainage water (Na^+ = 75 mg L^{-1}; Cl^- = 147 mg L^{-1})	5–15 nm	150 and 300 mgL^{-1}	Foliar application	SiNPs improve plant growth, nutrient uptake, carbon assimilation, enhancing mango fruit quality, and positively affecting nutrient uptake	[114]
	Saline water (1750 and 3500 ppm)	Not specified	1 g L^{-1}	Foliar application	Nano-silicon increased leaf pigment, soluble carbohydrate, total phenol content, Mg, N, P, and K levels	[125, 126, 209]
	–	–	150 mg L^{-1}	Spray	Fruit yield, flowering, absorption of nutrients, amino acids	

Table 1 (continued)

Studied plants	Salinity levels	Size of silica nanoparticles	Concentration of Si NPs used	Mode of application	Impact	Key references
Barley (*Hordeum Vulgare* L.)	Saline water (Na^+ = 16.45–16.75 mq L^{-1}; Cl^- = 11.33–11.75 mqL^{-1})	10–20 nm	500 mg L^{-1}	Foliar application	The combination of PGPR and SiNPs significantly enhanced physiological properties, enzyme activity, yield, and nutrient uptake, reducing Na^+, hydrogen peroxide, MDA, electrolyte likage, and proline content	[45]
	–	–	500 mg L^{-1} Foliar spray + bacteria 0.5 kg^{-1} soil	–	Enzymes SOD, CAT, POX, NPK, better result, conductivity, prevent toxic effect, and also increase yield	[45, 127, 128, 131, 132]
Maize (*Zea mays* L.)	50 and 150 mM NaCl	55–75 nm	10 mg mL^{-1}	Seed priming	Nano-silica priming improved the metabolic state of maize seeds subjected to salinity stress	[150]
	Salinity stress (Na^+ = 190–192 meqL^{-1}; Cl^{-1} = 3.32–3.41 meq L^{-1})	10–20 nm	500 mg L^{-1}	Foliar and soil applications	The use of SiNP with PGPR showed significant improvements in soil health, and plant development	[133]
	100 mM NaCl	10–20 nm	90 mg L^{-1}	Soil application	Si-NPs regulates osmotic potential, limits Na^+ accumulation, and increases Zn and Si accumulation in maize plants, aiding them in overcoming salt stress	[210]
	–	–	55–75 nm Si NPs, 100 mg L^{-1}, 10 g L^{-1}	-	Increased germination by 55%, Increased grain yield, plant growth, CO2, chlorophyll, photosynthesis, nutrients, proline gene decreased, absorption of nutrient increased	[45, 134, 138, 145]

Table 1 (continued)

Studied plants	Salinity levels	Size of silica nanoparticles	Concentration of Si NPs used	Mode of application	Impact	Key references
Wheat (*Triticum aestivum* L.)	Tape water (Na^+ = 1.67 meq L^{-1}; Cl^{-1} = 1.53 meq L^{-1}), and saline water (Na^+ = 44.05; Cl^{-1} = 60.04 meq L^{-1})	16.6–24.1 nm	80 mg Kg^{-1} and 600 mg L^{-1}	Soil addition and foliar application	The application of nano-silica improved nutritional absorption of N, P, K, and Si contents	[168]
	–	–	330–1200 mg L^{-1} Spray/900 mh Kg^{-1}	Spray	Growth yield, plant growth, photosynthesis up to 96%, increased enzyme activity	[156, 211, 212]
	–	–	Soil chitosan + Si NPs (Si + NPK)	-	More effective than SiNP alone, increased amino acid biosynthesis	[159]
	100 mM NaCl	10–20 nm	0.1% (w/v)	Foliar application	Enhanced antioxidant systems, redox homeostasis, and increased proline, free amino acids, glycine betaine, and sugars, protecting cells from salinity stress	[157]
	200 mM NaCl	Not specified	Si-NP based biochar (1 to 2.5%)	Soil amendments	Regulated antioxidants, N, K, gas exchange characteristics, and decreased Na, Cl, and electrolyte leakage	[21]
Rice (*Oryza sativa* L.)	100 mM NaCl	14.98–23.74 nm	20 mgL^{-1}	Foliar application	SiNPs significantly increased the growth of both N-22 and Super-Bas, chlorophyll content, carotenoids, total soluble protein content, and antioxidant enzyme activity	[169]

Table 1 (continued)

Studied plants	Salinity levels	Size of silica nanoparticles	Concentration of Si NPs used	Mode of application	Impact	Key references
Pea (*Pisum sativum* L.)	100, 150, 200 and 250 mM NaCl	-	3 mM	Soil amendments	Nano-silicon increased pea crop productivity, with the greatest response observed at 100 and 150 mM NaCl concentrations	[190]
	Different concentration	-	Si NPs 50 mlL^{-1} (S iNP + melatonin)	-	Increased plant growth, and yield, reduced metal toxicity, and maintain metabolic function	[177, 180]
	Different concentration	-	3 mM Si NPs of 5.9 nm	Spray	Increased root and shoot, grain yield, reduce ROS	[190–192]
	50 and 100 mM NaCl	-	50 mL L^{-1}	Foliar Application	Decreases the negative effects of salt stress on pea plants and improves production characteristics under salt conditions	[177]
Fenugreek (*Trigonella foenum- graceum* L.)	50, 100 and 150 mM NaCl	10–15 nm	SiNPs, Na_2SiO_3 SiNPs + Na_2SiO_3 Na_2SiO_3	Seed drenching	Both showed similar effect, increased silicon in shoot was more (75%) than root (25%) Combined effect was much greater than the individual effect Increased plant growth, putative silicon transporter gene was expressed at higher level then Si-NPs	[198, 213]

Table 1 (continued)

Studied plants	Salinity levels	Size of silica nanoparticles	Concentration of Si NPs used	Mode of application	Impact	Key references
Basil (*Ocimum basilicum* L.)	1, 3 and 6 ds/m NaCl	–	10 mL L^{-1}	Foliar application	Silicon nanoparticles application minimised the polluting effects caused by salinity in Basil	[121]
	50 and 100 mM NaCl	3–5 nm	25, 50 and 100 mg L^{-1}	Foliar application	Octa-aminopropyl polyhedral oligomeric silsequioxanes (OA-POSS) nanoparticles increased photosynthetic pigment, and activated all antioxidants	[202]
Bermuda grass (*Cynodon dactylon* L.)	5, 7 and 9 ds/m NaCl	Not specified	1, 2 and 3 mm/l	Soil amendments	Nano-silica proved beneficial in helping Bermuda grass tolerate salinity, increased chlorophyll and photosynthesis	[141, 203]
Faba Beans (*Vicia faba* L.)	Sea water (2000 and 4000 ppm)	Not specified	A mixture of ascorbic acid 200–300 mg L^{-1}; Si NP 2–3 mM and Rhizobium	Foliar application	Improved plant growth, physiological characteristics, and yield, while affecting gene expression of POX and PPO, increased germination, yield of seeds and gene expression	[204, 206, 207]

absorbed and induces the absorption of other elements. Consequently, large fruits of better quality are produced. The saline-stressed banana plant showed a reduction in chlorophyll pigments [44] which was restored by the application of SiO_2–NPs. Although saline-stressed plants (50 mM NaCl) were treated with three concentrations of SiO_2 (200, 400, 600 mg L^{-1}) they had the same impact on the improvement of chlorophyll pigments and rate of photosynthesis [46]. Accumulation of NaCl in apoplast causes dehydration of cells [47] which reduces chlorophyll pigments under abiotic stress.

3.2 Orange

The impact of the application of Si-NPs varies from plant to plant. In some plant species, it affects superficially vegetative growth but, in most cases, it enhances fruit yield, activates metabolic function, and increases tolerance against salinity. In a very recent work on the sweet orange plant, the effect of nano-silica under NaCl stress has been thoroughly investigated [48]. Structural changes, increase in photosynthesis, decrease in malonaldehyde, improvement in water retention, antioxidant, and reduction in NaCl have been observed [49, 50]. Each crop of citrus fruits, grapes, and strawberries is protected from damage by salinity by treating them with Si-NPs [51, 52]. Treatment of sweet orange plants with 60 and 120 mM of NaCl showed a reduction in chlorophyll, photosynthesis and root growth, water retaining capacity by leaf, membrane damage, and overall metabolism. NaCl dissociates the plant cells preventing their proper functioning to absorb CO_2 and produce carbohydrates. Foliar spray of Si-NPs on orange plant alleviated salt stress, increased the rate of photosynthesis, water retaining capacity of leaves and overall growth and yield of fruits [53, 54]. Silicon NPs control the metabolic activity and production of antioxidants in plants [55, 56]. It has been suggested that silicon and lignin react together to give a solid complex which inhibits the passage of absorption of other nutrients [57]. Larger silicates adsorb a larger number of water molecules/ions and transport them to various parts of the plant. Since Si NPs are extremely small they can be transported more efficiently than SiO_3^{2-} and alleviate the stressful condition caused by salinity. Sodium ion concentration may also fall by increasing fresh water supply and mineral nutrients [58] (Fig. 1).

3.3 Strawberry

Saltwater-irrigated plants showed a decrease in growth, shoot length, and delayed flowering. Treatment of strawberry plants with SiO_2 NPs or K_2SiO_3 reduced the toxic effect of Na and increased plant growth [59, 60. 61]. SiO_2 is, however,

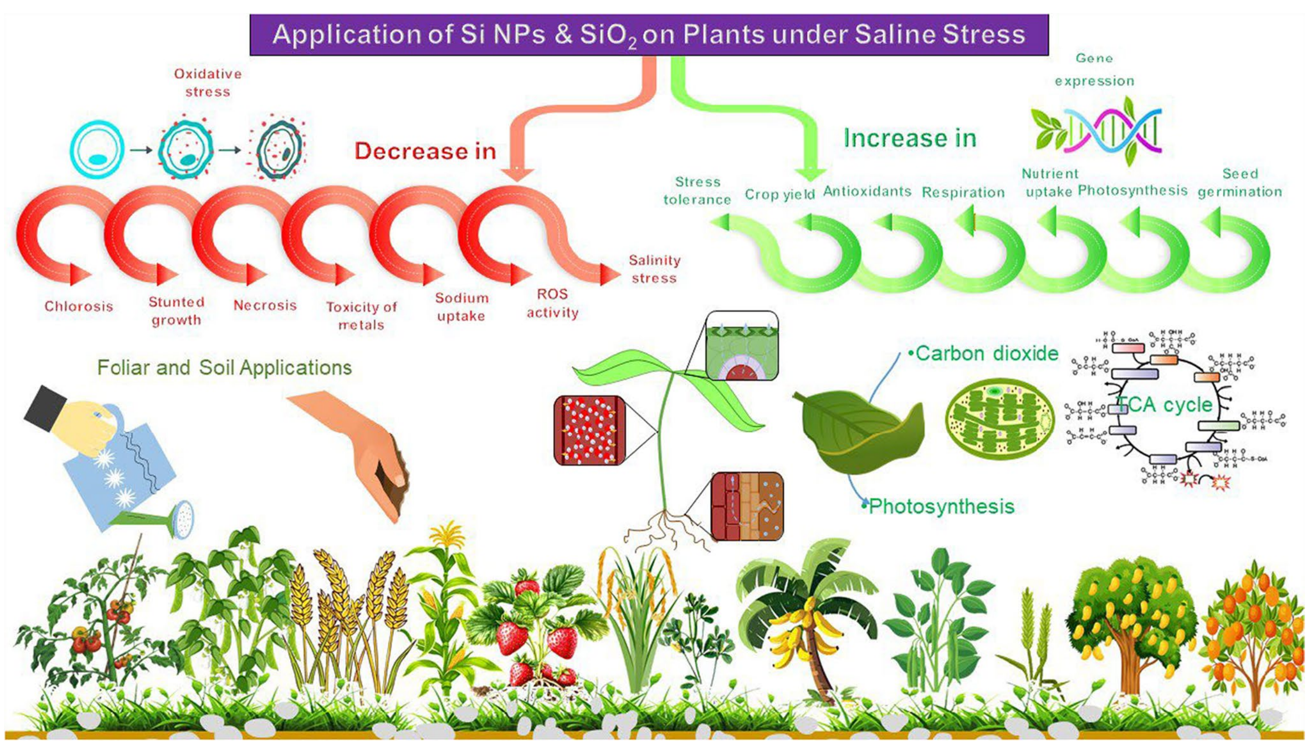


Fig. 1 Overall effect of application of SiO_2/Si-NPs in plant system under salinity stress situations

non-toxic even if applied in excess. Its application in cotton plants showed a decrease in the biomass of root and shoot [62] and also influenced the uptake of copper, magnesium, and sodium. It also depends on the presence of toxic elements in the soil. Marmiroli M, Pigoni V, Savo-Sardaro ML and Marmiroli N [63] have found that SiO_2 treatment of tomato plants affected the arsenic accumulation. Application of K_2SiO_3 or SiO_2-NPs in the soil increased potassium, calcium, coumaric acid, and a nine-fold increase in quercetin concentration. The antioxidant enzymes are produced in defense to reduce H_2O_2 and Na accumulation in root and leaves [64]. The adverse effect of NaCl was reduced in strawberries when the soil was fortified either with Si NPs or K_2SiO_3. The quantity used was very high (0.75–1.5 g Kg^{-1} of soil) even though the growth of the plant and physical parameters remarkably improved. However, such protocols are not economical and may be limited to laboratory experiments only.

Strawberry and tomato crops are very sensitive to minor stresses [65] which are reflected in their slow development [66] and low production of fruits. Avestan S, Ghasemnezhad M, Esfahani M and Byrt CS [65] have reported that the strawberry plants treated with SiO_2 NPs (50 and 100 mg L^{-1}) showed an increase in root and shoot development similar to that found in cucurbits [67] and wheat [68]. SiO_{2}-NPs increase photosynthesis, and water absorbing capacity and reduce transpiration in strawberry [69]. It has also been observed that a thin wax film is formed on the cuticle to prevent evaporation of water [65]. Proline accumulation increases due to NaCl which declines with SiO_2 treatment [70, 71]. It has been noticed that plant growth and productivity increases with increasing concentration of Si NPs. Treatment with Si-NPs increases more productivity than either with sodium-or potassium silicate.

3.4 Tomato

Tomato crop is negatively impacted by soil composition and salinity. Since it is used globally as a vegetable and a good source of vitamins and minerals, its yield and productivity must be enhanced to meet the demand [72]. Salinity and erosion are associated with excess of sodium chloride, irrigation by polluted water [73, 74] and excessive use of herbicides and pesticides [75, 76].

Alam P, Arshad M, Al-Kheraif AA, Azzam MA and Al Balawi T [77] have reported the impact of Si NPs on the structural, biochemical, and physiological features of tomato plants under salinity stress. Root, shoot, and biomass were reduced under stress, but all parameters were restored after the application of Si-NPs. Rate of photosynthesis, concentration of mineral nutrients, and activity of antioxidants enzymes [78, 79] were increased up to an appreciable extent.

The tomato and other plants, under salt stress, show reduced yield [80] because excess of Na dehydrates the plants. Since silicates are sparingly soluble [81] they are hardly available to plants. The dissolved Si/Si-NPs are transported to different parts of the plant via transporter proteins. Salt-stressed *Capsicum annuum* [82] treated with Si NPs showed significant improvement in growth [83, 84]. Also, the activity of SOD, CAT, glutathione (GSH), ascorbate peroxidase (APX), and proline was enhanced due to a decline in sodium concentration and lipid peroxidation. The oxidative damage may thus be prevented and the plant may be relieved from stress [85, 86. 87].

The effect of Si NPs (0.5 ppm) on grafted and non-grafted tomato plants under saline stress (4000- 8000 ppm NaCl) has also been investigated. The plants showed improvement in growth and mineral contents [88, 89]. Application of Si NPs showed a much better impact on grafted tomatoes than those grown under normal conditions [88–90]. They showed a large number of leaves and fruits of large size [69, 91]. These positive effects of Si-NPs have been attributed to an increase in RNA polymerase expression and ribosomal protein activity which in turn, decrease the rate of transpiration and oxidative stress and increase crop yield [92, 93]. However, similar treatment of self-grafted tomato plants under saline stress showed an overall decrease in growth and yield of fruits due to nonavailability of nutrients. Excess sodium accumulated in a leaf vacuole interferes with osmotic pressure [94] and disturbs the Na/K ionic gradient. Increasing salinity causes a decrease in the concentration of N, P, K, Mg, Fe, Zn and water in both, grafted and naturally grown tomato plants. The rate of photosynthesis is slowed down as a consequence of which the yield and quality of fruit is negatively affected.

Application of spherical SiO_2 NPs of 10–20 nm and K_2SiO_3 (250–500 mg L^{-1}) on tomato plant under NaCl stress (50 mM) showed increase in root, shoot and fresh weight with the production of large fruit and increased yield of 18%. Chlorophyll a and b, flavonoids, phenol, ascorbic acid, proteins and glutathione increased. Salinity increased vitamin C in tomato by 72.6%, which did not change even after the application of Si-NPs. However, K_2SiO_3 application decreased vitamin C in the leaves of the tomato plants with or without salt stress which may be due to potassium ions released from K_2SiO_3. Catalase activity significantly decreased by the application of both SiO_2-NPs and K_2SiO_3 while those of glutathione (60%), SOD (80%), PAL (80%), and APX (60%) increased [95].

Antioxidants reduced the ROS and H_2O_2 before they damaged the plant [96–98]. Ascorbic acid also reduces the ROS in the presence of the enzyme ascorbate peroxidase. It has been reported that Si NPs also induce stress [99] unlike the ionic SiO_3^{2-}.

O* as a free radical is highly reactive which can cross the cell membrane and damage it [95, 100]. Antioxidants are produced in defense to diffuse the free radicals into an innocuous species. They reduce sodium concentration and their accumulation [101] in plants. Si NPs enhance the activity of SOD, GPX, and APX in plants under salinity and decrease the ROS and increase the growth and yield of fruits/grains [84, 102, 103]. It has been reported [104] that plants treated with abnormally large quantities of silicon produce damaging effects. In response to it, photosynthesis is decreased with a consequent increase in the activity of antioxidants [62, 105]. In some cases decreased root and shoot growth has also been reported [106]. It should be noted that any essential nutrient or even fertilizers in large excess will damage the plants and alter the growth parameters.

It is misleading that silicon is absorbed in amounts greater than the essential nutrients like K and Mg [25]. The requirement of silicon varies in a wide range (0.1- 10%) [107], depending on plant size and their life span. It is generally absorbed as $Si(OH)_4$ in the basic pH range [36] via transporter genes [108–110].

Mesoporous silica with a pore size of 2–50 nm is capable of transporting nutrients N, P, K, Mg, and urea [111–113].

3.5 Mango

The use of Si-NPs to increase fruit yield in large plants is not common even though its effect is highly encouraging [114]. Plants grown in dry and highly saline soil always give a low fruit yield. They require adequate nutrition and protection from pathogens before flowering. Mango is a popular fruit grown mainly in normal and temperate climates. Its fruit yield is affected by soil composition, fertilizer [115], and availability of water. High concentrations of NaCl, KCl, $CaCl_2$, $CaSO_4$, $MgCl_2$, and $MgSO_4$ decrease plant growth, yield, and quality of fruits [116, 117]. Absorption of soluble silicates in excess is always slightly harmful to plants while nano silicon in moderation is useful. The meso-silicates, (SiO_3^{2-}) and their derivatives are very large which get accumulate in roots and leaves while nano-silicon is easily absorbed and transported to various parts of the plant [118]. The effect of ZnO and Si NPs on mango trees irrigated with polluted water containing large amounts of salt has been investigated. A foliar spray of ZnO alone (100 mg L^{-1}) on a mango tree showed similar results in all parameters. Further, increase in a concentration above 100 mg L^{-1} did not show any improvement. A combination of 100 mg L^{-1} ZnO + 150 mg L^{-1} Si NPs showed the best result. All concentrations above 150 mg L^{-1} restrict the absorption of other nutrients, decrease leaf size [119] and deactivate the enzymes. Since zinc is an essential constituent of several enzymes it activates them but its excess is harmful. Application of Si NPs + ZnO increases the uptake of N, P, K, Ca, Mg, and Fe which has been verified from the analysis of leaf [120, 121]. In many cases, the application of Si-NPs/Si on plants under salinity showed an increase in proline, amino acids, photosynthesis, and the activity of SOD, POX, AA, and GSH [122–124]. It has been reported that a spray of ZnO NPs prevents the mango flowers from falling [125]. It reduces ethylene formation [126] and protects the flowers from infection by pathogens. Spraying a mixture of ZnO and Si-NPs before flowering decreases the malformation of flowers and increases mango size and yield. The number of mangoes increased from 99 to 224/tree and weight from 29 to 59 kg/tree [125, 126]. It is a substantial increase in weight of about 40%.

3.6 Barley

It has been reported that the treatment of barley grown in saline soil [127] with a mixture of growth-promoting *Azotobacter chroococcum* and *Pseudomonas koreensis* bacteria together with Si NPs (500 mg L^{-1}) showed an increase in the activity of SOD, CAT, POX; and uptake of minerals (N P K). Na ion, H_2O_2, MDA and proline were reduced. It was also observed [127] that K^+, Ca^{2+}, and Mg^{2+} concentration increased after foliar application of bacteria/Si-NPs but the conductance remained unaltered. Conductance must increase in the presence of the above ions but when they form a complex with the biomolecules present in the plant the free ions are not available and hence the electrical conductivity remains unchanged. It is, therefore, proposed that crops can be cultivated even in saline soil or irrigated with hard water after applying Si NPs coupled with rhizobacteria. The growth-promoting bacterial colony also decreases in highly saline soil or saline water. Usually, water shortage occurs due to the accumulation of sodium ions in the leaves compared to freshwater irrigation [128]. Silica/SiO_2 from different sources (Si-NPs, Na_2SiO_3, micro-silica, silicic acid) applied on the crop at a concentration of 0.5 g Kg^{-1} of soil also increased microbes in the soil [129]. Nano silica is more effective than other silicates which are further synergized by the uptake of phosphorus [130]. Si NPs increase he activity of urease which breaks down the urea into CO_2 and ammonia NH_3 and increases the availability of essential nutrients to plants [131, 132].

$$(NH_2)_2CO + H_2O \xrightarrow{\text{urease}} CO_2 + 2NH_3$$

It also prevents the formation of toxins like ethylene and phenols. Bacteria fix the free nitrogen into nitrogenous compounds. However, hormones are also produced by these bacteria (auxins, cytokinins, gibberellins) which are helpful in the growth of plants. Si NPs decrease ROS and increase the growth and yield of barley [133, 134].

3.7 Maize

Food crops sown in dry-arid zones produce poor quality grains in low yield. There is always a competitive absorption of nutrients by plants depending on their ionic size and solubility in water. Application of different quantities of Si NPs or silicates on maize crops [127, 135] showed increased yield of grain. SiO_2 NPs containing controlled release fertilizer in the form of globules are capable to withhold water twice as much as their mass. They are released very slowly for up to 180 days. Since the fertilizer contains water too it can provide both water and nutrients to the crop for longer duration of time. The plants can therefore grow even under salinity and drought. The application of SiO_2 NPs decreases the Na ion and increases K ion uptake. It increases tolerance against stresses and microbial (bacteria and virus) infection [9].

Application of 50 mg L^{-1} of SiO_2 showed complete recovery of potato plant suffering from salt stress. An increase in the concentration of NPs up to 100 mg L^{-1} did not show further improvement which suggests that the impact is dose-dependent. Large silicon derivatives such as $ZnAl_2Si_{10}O_{24}$ can withhold water, nutrients, and fertilizer and release them slowly to have a sustainable effect on plant growth, grain yield, and tolerance against stresses. The water molecules and nutrients embedded in the cavity provided by the large silicate molecules work as storage tanks for fertilizers and nutrients needed for the growth of plants under adverse environmental conditions [75].

SiO_2 NPs decrease the rate of transpiration by reducing the pressure on stomata [136]. Similar results have been reported on wheat [137] and soybean [138]. Si NPs however, showed no impact on root weight in plants grown under normal conditions. It suggests that SiO_2 adjusts water uptake [139, 140] and photosynthesis. Water deficiency causes crystallization of silicon as grains in the cell wall of the leaves [141]. The efficacy of the SiO_2 NPs application on crops depends on various factors such as size of NPs, time or duration of spray, number of treatments or concentration, duration of stress and so on.

Plants under abiotic stress may protect themselves by enhancing the activity of antioxidants [142]. The mechanism of action of SiO_2 on the ROS scavenging has been explained in the following scheme:

$$SiO_2 \xrightarrow{\text{increases antioxidants}} \text{SOD catalyses the conversion of } O* \text{ to } O_2$$

$$2H_2O_2 \xrightarrow{\text{breakdown}} 2H_2O + O_2$$

CAT in combination with SOD is more effective in removing the ROS through the above mechanism [143]. APX helps in providing hydrogen for the reduction [144, 145].

Maize seeds grown under salinity (50 and 150 mM NaCl) showed a decrease in germination up to 55%. When they were soaked in Si NPs, they showed 100% germination which was 20% greater than those germinated under normal situations. The NPs stimulate germination by reducing NaCl concentration which has also been observed in soybean, chickpea, barley, wheat, and sugar beet [146–148]. Rapid cell multiplication, availability of water, DNA, and RNA synthesis facilitate the rate of germination [148]. ROS is increased in large amounts in untreated plants and damages biomolecules in seedlings and proteins [149] whereas a decrease in H_2O_2 in Si-treated seeds has been noted with a consequent increase in enzymes [150, 151].

The treatment of maize crops with Si NPs coupled with growth-promoting rhizobacteria further enhances the productivity and total grain yield. Rhizobacteria increase the availability of nitrogen by converting the atmospheric nitrogen into nitrogen compounds which can be taken up easily by plants. Besides total yield, the grain size and their quality are also influenced [151].

The decreasing concentration of sodium ions has been ascribed to their binding with exopolysaccharide [152]. They are not selective to Na ion binding but all alkali and alkaline earth metal ions (Na, K, Ca, Mg) have the same affinity for sugars. Rather, it is due to enzymes and bacteria that activate the absorption and transport of nutrients to shoot and scavenge ROS [153]. Similar roles of Si NPs in stress mitigation and photosynthetic attributes has also been reported in other crops [154, 155].

3.8 Wheat

Foliar application of Si NPs in different doses (330, 600, 900, 1200 mg L^{-1} and soil application (900 mg Kg^{-1} of soil) showed remarkable plant growth and grain yield [156]. It is worth noting that foliar application showed a massive grain production (96%) than that in silicon amended soil. Silicon applied to the soil will require water for solubilisation which may also contain toxic elements as pollutant. Availability of silicon to plants is thus reduced as a result of which the growth and yield of wheat grain is reduced. Chlorophyll pigments, carotenoids, photosynthesis, and transpiration rate showed a tremendous increase (60–130%) in silicon-treated plants compared to the control. However, rapid transpiration causes rapid loss of water.

Slow release of nano silicon/nano fertilizer over an extended period leaves a lasting effect on plants. The impact of encapsulated nano silicon with chitosan tripolyphosphate on wheat plants under saline conditions (100 mM) was compared with those treated with nano silicon and nano chitosan separately. It was observed [157] that the combined effect of chitosan encapsulated nano silicon was greater than those treated with only chitosan or nano silicon.

Chemical analysis of the plant at this stage showed an increase in SOD, CAT, and APX which diminish the formation of H_2O_2 [157, 158]. However, it was noticed that chitosan mixed with silicon nanoparticles was more effective in reducing the toxic effect of NaCl than only chitosan or nano silicon [157]. Among the non-enzymatic antioxidants, phenol and its derivatives (flavonoids, anthocyanins, proline and carotenoids) play a crucial role in scavenging free radicals and H_2O_2. As a result of oxidation of phenols, their concentration is reduced by the reactions of phenol with oxygen.

Reduction in the quantity of phenol is due to an increase in POD and PPO which also act as scavengers of ROS [157, 159]. The biosynthesis of proline, amino acids, and alpha-tocopherol is also increased. Photo-degradation decreases with Si NPs application. Also, soluble carbohydrates have been shown to increase in rice and wheat plants after Si NP application [8, 160]. Protein reduction due to its bio-degradation and decreased biosynthesis in the wheat plant is an indication of stress. Martino et al. [160] have also shown an increase in free amino acids in spinach leaves grown under saline conditions.

Sometimes soil contains non-essential elements that are toxic to both the plants and human subjects. Toxic metals are also absorbed by the plants/vegetables along with the essential nutrients and reach animals and man through the food chain [161]. For instance, cadmium is a highly toxic metal that should be prevented from reaching living beings by cutting its source and by reducing its quantity in plants. Cadmium causes oxidative damage in wheat plants and reduces the activity of enzymes. Its accumulation decreases the photosynthesis, biomass and yield of grain/fruit [162, 163]. Alkali and alkaline earth metals (Na, K, Mg) generally form silicates but their solubility is very low and therefore, they are available to plants in very minute quantity. Silicon also decreases the accumulation of toxic metals by inhibiting their absorption [161–164].

As the silicon concentration increases the absorption of N, P, K, Mg and other nutrients is also enhanced [165, 166]. Silicon protects the cell membrane and increases photosynthesis leading to increased biomass of plants [167].

Treatment of wheat plants with Si/SiO_2 mixed with N, P, and K gives better grain yield [168]. However, the concentration of nano silica (600 mg L^{-1}) and frequency of spray (five times) was too high which is not economical on large scale.

3.9 Rice

Ijaz et al. [169] have studied the effect of Si-NPs on the yield and quality of two varieties of rice cultivated under salinity (100 mM of NaCl). Spherical SiO_2 NPs of 14.9–23.7 nm, extracted from paddy [170] were sprayed (20 mg L^{-1}) which increased overall growth and biomass [171]. Similar results have also been reported by other workers in their study of wheat crop [168] and mungbean [172].

Si-NPs increased water retention, photosynthesis, stomatal conductance [173, 174] and prevented lipid peroxidation. Slow photosynthesis in salt-stressed plants leads to their stunted growth.

Salt stress also caused a reduction in carotenoid and chlorophyll pigments as a result of ROS production in thylakoid membrane [175] but Si NPs increased their concentration up to 18–20% and reduced Na ion concentration up to 185%. An equilibrium is thus, maintained between Na–K and Na-Ca ions.

3.10 Pea

It is a universal truth that plants and animals [176] respond to all kinds of stresses and physical injury. Even though, the effect of nano silica has been investigated in several cases, the impact of silica fortified with melatonin has rarely been investigated. Al-Shammari WB, Altamimi HR and Abdelaal K [177] have studied the combined effect of Si-NPs and melatonin on the growth and yield of pea crop under salt stress (50 mM, 100 mM NaCl). High sodium ion concentration decreases the water content and absorption of nutrients [178] as has been reported in the case of wheat [179], pea [180], and rice [181]. Foliar application of Si-NPs mixed with melatonin further promoted the growth and yield of the pea crop. It is believed that melatonin interacts with elements present in the plant, increases water contents, improves cell division and photosynthesis by reducing Na/Cl concentration [182–185]. This mixture allows regulated transport of nutrition and water because melatonin acts as a growth regulator [186, 187]. The plants produce CAT, POX, SOD, proline, and phenols to protect themselves against the stress [188, 189].

Every crop grown in saline soil gives poor yield due to stress and nonavailability of nutrients [190]. The quality and yield further deteriorate if the crop is irrigated with saline water [191]. Silicon stimulates the activity of defensive mechanisms [192]. Ismail LM, Soliman MI, Abd El-Aziz MH, and Abdel-Aziz HM [190] have investigated the effect of exogenous application of three mM Si and Si-NPs on the growth and yield of pea plants under NaCl stress (100, 150,200, and 250 mM). Plants showed increased root/shoot growth and grain yield [193, 194].

The plants under stress activate the enzymes (SOD, POD, CAT) to prevent macromolecules from damage by ROS [195, 196]. Silicon is generally absorbed through roots as silicic acid, Si $(OH)_4$ and distributed to different parts of the plant. It adsorbs water in its lattice but after losing water it crystallizes as tiny SiO_2 crystals in the leaf just like a small pearl [197].

$$Si(OH)_4 \rightarrow SiO_2 + 2H_2O$$

Many authors [197, 198] have termed it precipitation which is crystallization. Precipitation is an ionic reaction between two molecules while crystallization is simply the deposition of molecules as solute from a solution as shown below:

$$AgNO_3 + HCl \rightarrow AgCl_{(solid)} + HNO_3 \text{ Precipitation}$$
$$NaCl_{(solution)} \rightarrow NaCl_{(solid)} \text{ Crystallization}$$

Silicon NPs work better than silicates due to their small size [199].

3.11 Fenugreek

A comparative study of Na_2SiO_3 and Si-NPs application on fenugreek plants at different stages of development has been reported [200]. They both showed similar impact on the vegetative growth of the plant. It was found that presence of silicon in shoot was greater (75%) than in root (25%). However, a combined effect of Na_2SiO_3 and Si-NPs was greater than their individual effect. Its concentration is actually doubled as shown below due to common ion effect (Si-NP and SiO_3^{2-}) relative to sodium ions.

$$Na_2SiO_3 \rightarrow 2Na^+ + SiO_3^{2-}$$
$$SiNP \rightarrow SiNP$$

The activity of antioxidants in fenugreek was estimated after treatment with Na_2SiO_3 and Si-NPs separately. SOD activity was decreased and POD activity increased with Na_2SiO_3 but no change was observed with Si-NPs. However, no significant difference in the activity of enzymes was recorded with Si or Si-NPs. Putative silicon transporter gene (PST) was expressed at a higher level with Na_2SiO_3 treatment than Si NPs and facilitates transport of silicon to shoot and root. PST controls the uptake of silicon regardless of their source [201]. It has been proposed that Si NPs would have been converted to silicate before its absorption by plants.

It is a wild guess and highly improbable because the conversion of Si to SiO_3^{2-}/SiO_2 is not a reversible process. If it happens at all, there will be no difference between Na_2SiO_3 and Si-NPs application, on the growth and activity of enzymes of fenugreek.

Absorption of Si NPs is always fast due to their high solubility and tiny size which increases plant growth [73]. This work is highly controversial concerning the impact of Na_2SiO_3/Si-NPs on the growth parameters of the fenugreek plant and needs verification [74].

3.12 Basil

Sweet basil under saline stress treated with a very large silicate molecule reduced sodium ion, ROS generation, and H_2O_2 production and enhanced the activity of antioxidants [202]. Silicon protects and provides strength to the cell wall and gives stability.

However, the authors failed to explain the size effect of the silicon derivative. Results are positive but the reasons are vague. In practice the extremely large silicon derivative can accommodate large number of NaCl molecules and remove them. Thus, a small quantity of the large silicon derivative will be required comparative to small silicate molecule.

3.13 Bermuda grass

Bermuda grass grown under saline stress has shown a consistent decrease in chlorophyll pigments [203] photosynthesis and magnesium which is an essential ingredient [204]. The increase in proline, MDA, CAT, SOD, and electrolyte leakage (EL) is proportional to the increase in salinity. The following reasons have been given for the decrease in chlorophyll due to salinity.

- Deficiency of Mg
- Extent of salinity
- Modification in metabolic steps and
- Decreasing availability of CO_2 due to aggregation of abscisic acid in leaves.

Treatment of the grass with Si NPs and humic acid separately increased chlorophyll and photosynthesis [205]. A very small quantity of the Si NPs is needed compared to humic acid to produce the same positive effect on Bermuda grass [206].

3.14 Faba beans

Vegetables are another class of food for human consumption which is cultivated worldwide in all types of soil. Faba beans cultivated under salinity gave a reduced production of pods, decreased plant growth [207] photosynthesis, absorption of nutrition, and delayed flowering [29]. As a result of high Na concentration, cell division is slowed down, Na/K ratio is disturbed which alters osmotic pressure [1]. It was noticed that chlorophyll, water availability, yield of seeds, germination rate, and gene expression were increased after a single application of a mixture of ascorbic acid (200, 300 mg L^{-1}), Si NPs (2–3 mM), and rhizobium.

4 Conclusion

Silicon, positioned between metals and non-metals, exhibits both conductive and semiconductive properties. Silicon significantly enhances growth, productivity, and resistance to biotic and abiotic stresses. It improves soil fertility, aids in water retention, and acts as a carrier for fertilizers and nutrients. Silicon in the form of SiO_2 or SiO_3^{2-} strengthens plants against saline stress and microbial attacks. Nano-silicon, even in minute quantities, has shown to be more effective than bulk SiO_2 in promoting plant health and resilience. Due to its low cost and widespread availability, silicon nanoparticles (Si-NPs) hold considerable promise in mitigating environmental stresses and boosting crop productivity. The novel combination of Si-NPs with soluble polymers and rhizobacteria for slow nutrient release offers an exciting avenue for enhancing agricultural sustainability. Future research should explore innovative silicon applications to further improve crop quality and yield, particularly under other stress conditions.

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