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Silicon as a Stress Alleviator in Horticultural Crops: A Review

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ABSTRACT

The persistence of agricultural systems is facing more complex threats due to environmental discontinuities, which makes the case for targeted approaches to ameliorate the resilience of crops to non-living environmental stressors. Among current practices, which range from mineral addition to conventional farming, silicon (Si) is viewed as an element of lesser importance to the agricultural industry, yet fundamental with regards to explains the adaptation of plants to the environment. The concentration of Si elements in most plants is low but Si elements are usually present, by adding it externally, adverse environmental conditions will easily increase, leading to decreased (osmotically) regulated conditions, stabilizing of cell membranes and oxidative stress. In contrast to other supplements, Si has the unique property of regulating metabolism of phytohormone. Phytohormones, including auxins, cytokinins, ethylene, gibberellins, salicylic acid, abscisic acid, brassinosteroids and jasmonate, are responsible for the communication and control of plant activity in response to external and internal environmental and developmental changes. As Si exists in plant systems, it increases hormone synthesis and receptor activity, antagonize hormone turnover and receptor activity, thereby organizing rationally coordinated defense responses to stress. Smart hormonal changes, in turn, has been positively associated with enhanced physiological integrity and defense responses. Silicon-driven stress resilience versatility includes additional multidimensional remodeling systems, including organizational, transcriptional, biochemical and even metabolic, beyond the aforementioned primary signaling. In Si-treated plants, such systemic stress tolerance modules impact the emerging integrated gene-protein-metabolite networks outlined by multi-omics systems frameworks. In terms of sustainable intensification, the Si integrated hormonal order is a realistic approach to food security and resilient horticultural production. In addition to interfaces of sustainable development, Si provides a new spine to internal control that mitigates abiotic stress. Future work is needed to demarcate threshold application levels, the timing of application and specific pathways toward individual crops. Translational silicates frameworks that draw on delineated system interfaces with advanced biotechnologies offer a critical avenue for the production of engineered stress-resilient crops to sustain agricultural yields amidst growing climate extremes.

INTRODUCTION

For survival and health promotion, it is imperative to ensure that nutritious and secure meals are available. However, the agriculture industry may encounter significant hurdles in the future in satisfying the food production demands of a rapidly growing human population. Over the next 30 years, the global population is predicted to increase by 2 billion people, reaching 9.8 billion by 2050[1]. This population growth poses significant limitations on land availability, particularly in Asian countries[2]. Additionally, human activities, including the release of greenhouse

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gases, contribute to the warming of the environment. This phenomenon adversely affects food security by disrupting resource availability and livelihoods of individuals[3]. As a result, the agriculture industry and scientists are constantly challenged to feed millions of people[4]. Abiotic stressors caused or exacerbated by climatic conditions account for nearly 50% of agricultural losses, making sustainable agricultural output vital to guaranteeing food security[5]. Plant growth rate and output are significantly influenced by temperature, humidity, light, moisture, salt, availability of nutrients and the concentration of industrial and agricultural chemicals in water and soil resources. Osmotic stress is caused by abiotic circumstances, which disturb ion transport and cellular equilibrium in plants. Furthermore, the interplay of abiotic and biotic stressors renders plants more vulnerable to pests[6].

The plant root is home to a rich microbial community that forms complicated relationships with plants, impacting plant growth and production through metabolic characteristics and interactions[7,8]. Plant-associated bacteria display morphological changes within the rhizosphere, reflecting a variety of groups suited to environmental circumstances, aiding adaptation to environmental challenges and maintaining plant health and resilience[9]. Growth-promoting rhizobacteria of plants (PGPRs) are soil bacteria that colonise plant roots (rhizosphere) and contribute to higher plant performance and yields[10]. The PGPRs not only form positive connections with roots, resulting in considerable growth responses but they also play an important function in phytopathogen regulation. They also help to improve soil structure and crop productivity by stimulating the development of soil aggregates and pores[11]. Silicon (Si) use in agriculture has the potential to reduce abiotic stressors in crops[12]. Silicon is the element with the eighth greatest abundance in nature and, after molecular oxygen, the second most widespread constituent in soil[13]. Si is found in soil as monosilicic acid (H_4SiO_4), which is uncharged at pH 9[14]. It may ionize into silicate ions, such as $(OH)_3$ SiO_2, at higher pH values (>9). Weathering of silicate-containing minerals releases Si into the soil[15]. Because most soils are naturally rich in Si, the availability of dissolved Si varies with soil type and conditions in the environment. However, soil types and seasonal fluctuations impact plant absorption. Silicon rapidly interacts with oxygen (O_2) to generate silicon dioxide (SiO_2), which accounts for around 50% of soil mass[16]. Si is found mostly in mineral soils such as SiO_2 and either primary or secondary silicate minerals, which also contain elements like Al (aluminosilicates) and Mg[17]. Recognizing Si's helpful effect in reducing abiotic stress in crops necessitates further research into its physiological and molecular features. This chapter seeks to offer a thorough grasp of Si's vital function in promoting plant growth and production in the face of abiotic stress. Several studies have also been conducted to investigate Si's function in phytohormone synthesis, gene expression regulation and the impacts of environmental stress on metabolism and development. By exploring Si's potential, this chapter hopes to motivate additional study and reveal its critical role in ensuring global food security.

The importance of silicon for sustainable agricultural growth: The growing population has put enormous strain on the agricultural sector to solve food insecurity. While technological interventions have enhanced crop yields, industrialization has also resulted in increasing environmental pressures, which have harmed crop output and hampered long-term agricultural progress. Plants respond by modifying their metabolic networks and producing physiological changes[18]. Numerous studies have shown that Si has an important function in improving agricultural productivity and yield under adverse environmental circumstances[19]. Si buildup in plant organs improves both monocot and dicot crop growth and metabolism[20]. Because of increased Na^+ competition with K^+ and Ca^{2+} transport in cell plasma membranes, for example, affects reproductive activities[20]. According to recent studies, Si reduces Na^+ buildup, Osmotic pressure and oxidative damage[21,22]. To counteract abiotic stressors, Si stimulates defense pathways linked with phytohormone production and compatible solutes[23,24]. Exogenous Si treatment improves salt tolerance in salt-sensitive okra genotypes by increasing proline accumulation[25]. Si also increases the synthesis of the total number of free amino acids, proline and glycine betaine, for example, are found in *Capsicum annuum* cultivars, improving salt stress resistance[26]. Furthermore, Si buildup in crops such as tomato, okra, rice and wheat leads to a decrease in proline concentration, suggesting Si's efficiency in activating its own salt-resistance mechanisms[27]. Silicon (Si) treatment improves crop growth, production and fruit quality in a variety of fruit crops[28,29]. Si promotes water and energy conservation, improves fruit quality and boosts production. On the other hand, plants accumulate Si in distinct ways, resulting in diverse Si-mediated responses to abiotic stresses[30]. Major crop plants, such as cotton, soybean, cucurbits and tomato as well as monocots like rice, maize and wheat, collect Si via specialized transporters to ameliorate diverse stress effects[12].

Si treatment increases the expression and activity of defense-related genes while also boosting the accumulation of defensive chemicals such as phenol compounds, phytoalexins and momi-lactones[31]. Supplementation of Si, for example, lowers Reactive Oxygen species (ROS) scavenging capabilities in vegetable cultivars such as Cucumis sativus under stressful circumstances[32]. Exogenous Si supplementation alleviates sulphur and osmotic stress in tomatoes by increasing root sucrose levels[33]. Si can also alleviate heavy metal stress by activating several pathways and scavenging ROS[33]. Si enrichment increases plant growth and development by increasing fruit Nutrient Usage Efficiency (NUE)[34].

Silicon (Si) further mitigates the toxicity of metal ions in plants by either reducing their solubility or catalytically detoxifying them in the apoplastic space. Evidence indicates that Si enhances the tolerance of crops to UV-B stress by subsequent stimulation of defensive metabolites and mechanical thickening of the cell wall[35]. Collectively, the data imply that Si exerts a constitutive and adaptive influence over the physiological and metabolic responses of crops exposed to prolonged water deficits. The preceding analysis focused on the modulatory role of Si in optimizing phytohormonal signaling pathways that regulate abiotic stress. Taken in aggregate, these observations underscore Si's pivotal contribution to elevating plant tolerance to chronic abiotic shock, thereby constituting a promising agronomic intervention to sustain productivity in environments afflicted by recurring, pronounced drought.

Differential synthesis of phytohormones in response to silicon and abiotic stress: The plant hormones Gibberellins, Cytokinins, Ethylene, Brassinosteroids, Jasmonic acid, Salicylic acid and Abscisic acid, along with signaling molecules such as Calcium and Nitric oxide, exert pronounced influence on physiological processes, even when present in minor concentrations[36]. Within horticultural science, these phytohormones have been implicated in the growth and morphogenesis of economically important vegetable crops, including tomato (*Solanum lycopersicum*), cucumber (*Cucumis sativus*) and pepper (*Capsicum annuum*)[37]. Concurrently, silicon exhibits decisive interaction with reactive oxygen species to restore and preserve cellular symmetry at the structural, molecular and biochemical scales, thereby mitigating a wide spectrum of abiotic and biotic stresses. By modulating multiple pathways-nutrient assimilation, the regulation of source and sink dynamics and the reinforcement of cellular antioxidant and signaling networks-silicon measurably enhances the plant’s resilience to severe environmental perturbations[38]. Furthermore, combining critical metabolites with silicon to ameliorate abiotic stressors has shown complex and interrelated mechanisms that can improve crop development and production, as seen in pepper (*Capsicum annuum*)[39]. The complex link between silicon-mediated plant growth and stress tolerance, which involves cross-talk with phytohormones, ROS and signaling molecules, has received much attention. Gibberellins (GA) are phytohormones that contribute considerably to many developmental phases in plants and act as effective mechanisms to counteract abiotic stressors[40]. Higher dosages of silicon supplementation resulted in increased endogenous levels of GA_1 and GA_4 in *Crocus sativus* plants subjected to salt and drought stress, showing a major metabolic reshuffling inside stressed plants following silicon therapy[41].

Si treatment has been reported to promote the production and accumulation of Gibberellins in salt-stressed *Glycine max* and Oryza sativa plants while lowering the levels of Jasmonic Acid (JA) and Ethylene (ET)[42]. Apart from its importance in a variety of plant processes involved in development and growth, cytokinin also shows a significant role in effectively reducing abiotic stressors. Si-mediated intervention increases cytokinin production, which improves their stress-resistance function[41]. Cadmium (Cd) poisoning harms pea plants, producing changes in root and stem development, architecture and biochemistry. Plants exposed to Cd toxicity develop more slowly with Cd buildup, decreased chlorophyll content and changes in primary metabolites such as carbohydrates and proteins. Cadmium exposure induces oxidative stress in plant systems, evidenced by elevated malondialdehyde (MDA) and hydrogen peroxide (H_2O_2) levels, subsequently triggering an up-regulation of antioxidant enzymes, specifically catalase and peroxidase, in an adaptive response to cellular perturbation. Structural alterations noted under increasing cadmium concentrations include the development of aberrant vascular patterns, irregular lignification in the pith parenchyma and hypertrophy of cortical parenchyma, corroborating the morphological instability observed by El-Okkiah et al.[43]. Conversely, pre-application of silicon ions effectively abrogates the oxidative burst associated with cadmium stress, thereby sustaining cellular homeostasis. The concomitant use of silicon and 24-epibrassinolide has been demonstrated to bolster Brassica juncea's resilience to sodium chloride lethality by sustaining maximal photochemical efficiency, enhancing the activities of catalase, peroxidase and superoxide dismutase and by promoting the accumulation of proline, as reported by Siddiqui et al.[44]. Moreover, silicon treatment positively modulates membrane integrity, an effect partly ascribed to an augmented biosynthesis of jasmonic acid, a lipid-derived phytohormone consistently elevated in stressed tissues, thereby reinforcing osmotic adjustment and stress signaling pathways, as elaborated by Bhardwaj et al.[24].

Categorization of physiological responses indicates that exogenous silicon mitigates saline stress by conferring cellular protective modalities. Such treatment preferentially lowers ion efflux and membrane lipid peroxidation, while concurrently depressing Jasmonic Acid (JA) concentrations relative to untreated cohorts; by contrast, levels of Indole-3-acetic Acid (IAA) and Salicylic Acid (SA) exhibit elevation[45]. Profiling of defense signaling reveals that silicon augments transcripts participating in JA biosynthetic cascades in mechanically wounded tissues, thereby attenuating injury-induced stress. Nonetheless, a more granular elucidation linking silicon-mediated modulation of JA-associated mRNA abundance to stress relief remains to be consummated[46]. Concurrent work shows that conjoint application of Si and external salicylic acid confers acid stress tolerance to tomato seedlings by elevating endogenous sodium and potassium reservoirs; this osmotic adjustment in turn curtails Reactive Oxygen Species (ROS) accumulation through reinforcement of antioxidant pathways and by transcriptionally up-regulating transporters and enzymes of Si acquisition and SA biosynthesis[46]. Salicylic Acid (SA), a phenolic phytohormone, is essential for dealing with abiotic stressors and sustaining optimum plant development[47]. SA promotes the antioxidative defense mechanism in plants to reduce heavy metal toxicity, although its levels have decreased when Si is used on the surface[48].

Abscisic Acid (ABA), also known as the stress hormone, accumulates in plants subjected to salt stress, causing stomatal closure and consequent water conservation[49]. ABA modulates a wide range of physiological reactions in vegetable plants, involving stomatal closure and seed dormancy, assisting in adaptation to abiotic conditions such as drought or excessive salt[50]. For example, ABA stimulates stomatal closure in tomato plants (*Solanum lycopersicum*) under water stress[51] and modulates seed dormancy in lettuce plants (*Lactuca sativa*) under unfavorable environmental circumstances[52]. An increased supply of Si to salt-stressed vegetable plants results in a beneficial relationship between Si activity and ABA. Exogenous Si supplementation improves salt tolerance by increasing Si absorption and ABA synthesis[53]. In Si-mediated stress tolerance, ABA has an antagonistic connection with SA/JA biosynthesis, demonstrating ABA's dynamic involvement in response to Si treatment. Plant ABA content reduces when Si concentration increases during heavy metal, salt and drought stress conditions[54]. Hormones that cause stress, such as ABA, JA and SA, are testified to rise in cold-stressed maize (*Zea mays*) seedlings, whereas the production of other plant growth regulators, such as auxins, gibberellins (GA) and cytokinins, is inhibited[55].

Polyamines, a group of nitrogen-rich, aliphatic cationic molecules that includes putrescine, spermidine and spermine, are known to accumulate in elevated amounts within plant tissues as a cellular strategy to mitigate oxidative and salinity stress[56]. Empirical evidence supporting their protective role continues to mount, notably evidenced by enhanced synthesis when plants are treated with exogenous silicon (Si), a response thoroughly documented in S. bicolor[57]. Following Si supplementation, transcriptional data show that the S-adenosyl-L-methionine decarboxylase (SAMDC) gene-coding for the rate-limiting enzyme in polyamine biosynthesis-exhibits elevated expression. The resultant increase in polyamine biosynthetic activity, driven by Si-mediated signal transduction, in turn orchestrates a cascade of cytoprotective and metabolic buffering effects that collectively attenuate stress injury and promote the sustainment of vegetative and reproductive processes[31].

Silicon's mechanism for reducing abiotic stress: Silicon exerts its influence on plants by modulating multiple developmental processes, thereby serving as a crucial element in mitigating diverse abiotic stresses. One of its primary mechanisms involves promoting the upregulation of antioxidants[53].

Silicon's role in enhancing salt tolerance in plants: Salinity stress has a detrimental influence on the development and visual appeal of ornamental plants and it continues to be a key limiting factor for agricultural output globally[58,59]. Morphological features such as leaf number and leaf area can be harmed by salt stress[60]. Furthermore, lower chlorophyll levels, relative amount of water, important nutrient intake and higher leakage of electrolytes are seen[61]. Silicon can boost production in salt-stressed plants[62]. Although ,silicon is not a required nutrient, it does engage in processes of metabolism that increase resistance in plants to environmental circumstances such as drought and salt[63-65]. Silicon application is a low-impact method for improving plant reactions to salt stress[66]. It improves plant resistance to salinity and drought stress[26,67], minimizes the detrimental effects of salt stress on chlorophyll content and the generation of biomass[68] and promotes adaptive responses like phenolic compound manufacture, mineral uptake and antioxidant activity[69,70].

Under both salt stress and normal circumstances, halo-priming with silicon nanoparticles (Si NPs) encourages the development of seedlings and germination[64,71]. Silicon nanoparticles (Si NPs) have received a lot of interest in agriculture, horticulture and biotechnology because of their ability to withstand environmental challenges and post-harvest losses[72]. Nanotechnology has had a revolutionary influence on horticulture, notably in fruit crops, due to its efficacy against environmental challenges and post-harvest losses[73].

The incorporation of nano-silica ($nSiO_2$) has been demonstrated to mitigate salt-induced plant damage while simultaneously facilitating faster vegetative growth in strawberry cultivars[62]. Halo-priming applications employing silicon or silicon nanoparticles (Si NPs) conferred enhanced salt tolerance in *Lathyrus* seedlings, according to findings by El-Serafy et al[58]. In sweet pepper, an aerial silicon application significantly elevated the concentrations of both chlorophyll a and b, ameliorated the translocation of mineral nutrients, improved the hydration of the leaf tissue and ultimately increased fruit yield. Concurrent physiological advantages included decreased lipid peroxidation, reduced electrolyte leakage and lowered levels of superoxide and hydrogen peroxide[74]. In a wider context, silicon supplementation has been correlated with improved germination rates, faster germination percentages and lengthier shoot growth-benefits that registered in both unstressed and saline or drought-stressed scenarios[75,76]. By contrast, the influence of silicon on saline-stressed root systems has yielded mixed or negative results. At the same time, shoot growth recovery has been recorded in wheat and cucumber, the root systems in those same trays exhibited negligible enhancement[77]. In a complementary study of tomato, the employment of SiO_2 nanoparticles elicited appreciable physiological improvements, signifying a source of consistent positive responses from this class of novel silica amendments[78]. Tantawy et al.[79] discovered that nano silicon is more effective and efficient at mitigating salt stress in sweet pepper plants. Spraying Si NPs on "Ewais" mango plants increased overall yield (number and weight of fruits per tree) and fruit physiochemical properties[80]. To counteract salt stress in watermelon agriculture, a combination of mycorrhiza and silicon might be used[81].

Si uses various methods to protect plants against salt stress. These strategies include minimizing ion toxicity while maintaining plant water balance, improving inorganic absorption and incorporation, controlling the production of suitable solutes and phytohormones, mitigating oxidative stress, changing gas exchange characteristics and manipulating gene expression. The reduction in Na^+ uptake and accumulation, which has been widely observed with Si supply under salt stress, results in a boosted K^+/Na^+ ratio[12]. However, the molecular basis of Si absorption in fruit trees is unclear[82].

Silicon amendment mitigates oxidative damage in a variety of plant species facing saline stress by augmenting the activity of key antioxidant enzymes, including superoxide dismutase (SOD), catalase (CAT), peroxidase (POD), glutathione S-transferase (GSH) and ascorbate peroxidase (APX), while stabilizing membrane fluidity and sustaining plasma membrane H+-ATPase function, all of which culminates in the suppression of Reactive Oxygen Species (ROS) accumulation[83,84]. In addition to preventing oxidative injury, Si application enhances salt tolerance by reprogramming osmotic adjustment mechanisms in the shoots and roots of okra, as evidenced by modifications in the concentrations of proline, glycine betaine and the pool of free amino acids[25]. Salt-stressed soybean seeds, in turn, exhibit altered phytohormonal profiles, notably a rise in gibberellin (GA) titers concomitant with reduced abscisic acid (ABA) levels, following Si supplementation[85]. The fabrication and administration of nano-silicon dioxide in strawberry plants positively impacted the stability of the epicuticular wax layer, preserved chlorophyll and carotenoid concentrations and restrained proline accumulation[62]. Such effects, in concert, enabled the amelioration of morphological and metabolic derangements customary to saline environments[61]. Furthermore, the accumulation of silica in plant tissues has been observed to correlate with the surveillance of epicuticular wax biosynthesis; for example, the exposure to Si treatments modified the morphology of fruit trichomes in cucumber (*Cucumis sativus* L., cv. Corona) such that a significant fraction of silica deposit was sequestered within the wax of trichome cells[86].

Silicon's contribution to drought resistance in plants: Drought is a key environmental restriction that limits the development and production of field and horticultural crops[87,88]. It is distinguished by limited water availability, both physically and physiologically, which has a negative worldwide influence on the evolution of plants and output[89]. Drought-induced stressors have a detrimental influence on agricultural yield and quality[90], particularly in arid and semiarid locations where water shortage stress is a major factor impacting crop productivity[91]. Water deficit stress response varies depending on plant species, development stage, interval and strength of the stress[92]. Globally, significant efforts have been undertaken to increase irrigation water efficiency in diverse fruit crop species[93].

Drought-induced osmotic stress, on the other hand, increase the formation of Reactive Oxygen Species (ROS)[94], which can cause oxidative damage to proteins, DNA and lipids[95]. Prolonged water shortages can impair stomatal sensitivity to low water potential, resulting in lower water content, turgor and total water potential, as well as partial or full stomatal closure. Cell enlargement, growth rate and total plant growth are all lowered under these circumstances[96]. Plants contain both enzymatic and non-enzymatic antioxidant systems that help them endure stress caused by water and avoid photooxidative harm[97].

Agriculture researchers have long explored strategies to reduce the detrimental effects of drought on crops. Exogenous protectants, which include trace elements such as silicon (Si), are a regularly used approach. Plants that store silicon can endure water stress by using efficient compounds. Silicon has been shown to be beneficial in reducing biotic pressures such as plant disease and insect pests, drought, salt, metal toxicity, temperature stress, nutritional imbalance and waterlogging are among abiotic difficulties. Its significance has been recognized in the development of horticultural crops such as vegetables, fruits and floricultural crops. Plants treated with silicon have higher stomatal conductance, transpiration rate, Leaf Relative Water Content (LRWC) and hydraulic conductivity in the roots and throughout the plant. When used in areas with limited water supply, silicon increases LRWC, improves water potential through osmotic adjustment, decreases electrolyte leakage and impacts proline levels. Furthermore, silicon boosts the antioxidant defense system in drought-stressed plants. The key mechanism behind silicon's protective role in plants is the buildup of polycyclic acids in cells[98].

Research demonstrates that the promotion of silicon in water-stressed crops and cultivars can exhibit cultivar-specific and cultivation-condition labile morphological and physiological alterations[99]; for instance, Si supplementation has been associated with enhanced radicular architecture in melon[100]. Such effects extend beyond structural adaptation: the element intervenes in a constellation of biochemical, physiological and photosynthetic pathways, synergistically fortifying the plant against the rigours of hydric deficit[101]. During episodes of water shortage, Si has been shown to sustain germination rates, permit greater biomass accumulation and elevate the photosynthetic carbon-assimilation rate, mechanisms that are correlated with osmotic adjustment, modulation of stomatal conductance, improved mineral translocation and a robust redox balance governed by modulated reactive oxygen species scavenging[67]. Notwithstanding its earth-abundant and insoluble bulk, silicon, constituting circa 32% of the crust's mass, enters the plant through the mineralised reaction mediated by the mono-silicic acid monomer[102,103].

Accumulating evidence supports a beneficial role for silicon as an exogenous stress-relief agent across diverse horticultural species, encompassing tomatoes (*Solanum lycopersicum* L.), carrots (*Daucus carota* L.) and melon[104-107]. When applied as a soil or foliar amendment, silicon markedly alleviates imposed drought stress, as observed in cantaloupe (*Cucumis melo* L.) and strawberry (Fragaria ananassa Duch.)[108]. Notably, the Se/SiO_2 composite has been highlighted as an effective formulation in field trials, ameliorating soil moisture deficits in strawberry and additional agronomic species[109].

Subsequent phytochemical analyses reveal that, in response to drought stress, the foliar tissues of all tested mango cultivars exhibit a consistent enhancement in the activity of key antioxidative enzymes, specifically peroxidase (POX), catalase (CAT) and superoxide dismutase (SOD), across a full three-season trial[110]. Silicon has an effective mechanism for scavenging reactive oxygen species, which protects plants from oxidative damage and improves their capacity to endure environmental stress in dry environments, including mango trees[110]. The administration of Na_2SiO_3 has been demonstrated to be an effective therapy for severe water shortage stress, notably in the '*Gavioita*' strawberry cultivar[111]. However, silicon inhibited the generation of activated oxygen species and oxidative damage in potato plants subjected to water stress[112]. Water scarcity is a severe abiotic stress that can reduce tomato output by up to 50%[113]. Exogenous silicon treatment reduces the antagonistic effects of drought stress in tomatoes[114] and greatly enhances tomato crop water usage efficiency[115]. Cantaloupe production, like other horticultural crops, needs adequate management practices to obtain a good yield and high-quality fruit[116]. Low-quality fruit development in cantaloupes is frequently attributed to insufficient pollination, prevailing high temperatures and water-deficit stress conditions[117]. Application of Si-based fertilizers, when applied at appropriate rates in conjunction with regulated soil moisture, has been shown to enhance yield and irrigation water productivity, thus suggesting agronomic advantages for cantaloupe cultivation when subjected to mild drought stress[108]. Further corroborative evidence indicates that exogenous applications of magnesium carbonate, enriched with silicon, in banana cultivation can function effectively as an anti-transpirant agent, thereby augmenting fruit weight and improving overall fruit quality[117].

Silicon's influence on heavy metal stress mitigation: Toxic metalloids such as copper, lead, nickel, chromium, mercury, zinc, arsenic and cadmium are contaminating a substantial agricultural land area due to urban or peri-urban cities[118]. Pollution from the environment or human activity can both introduce heavy metals into the food chain[119]. Heavy metal contamination of agricultural land can occur because of the use of sewage, sludge or industrial effluents[120]. Consuming a variety of fruits and vegetables is critical for receiving key micronutrients and dietary fibre for overall wellness. According to American standards for 2015-2020, fruits and vegetables should account for around half of every single meal[121]. In research, toxic metal exposure in fruits and vegetables has been documented due to fertilization, irrigation and air deposition[122]. Consuming contaminated veggies can expose you to heavy metals and offer a serious health risk[123]. Heavy metals in the soil can be taken up by plants and delivered to pollinators during pollination, thereby changing their behaviour and plant fitness[124]. Heavy metal contamination has also harmed the quality and safety of medicinal plants[125]. Consuming medicinal plants polluted with lead (Pb), mercury (Hg) and copper (Cu) are examples of heavy metals endangers consumer health. To solve this issue, it is critical to manage heavy metal levels in medicinal plants[125]. Certain hazardous non-essential heavy metals, such as Pb, Hg, Cd and As, can be harmful to human health even at low levels, particularly in susceptible populations such as pregnant women and young children[125-127]. Increased Cd intake can harm the liver, respiration, kidneys and bones[128]. Elevated Pb levels in the circulation can cause hypertension, compromised skeletal, immunological and endocrine systems, decreased cognitive ability in children and changes in renal and cardiac functions in adults[130]. As a result, it is critical to analyse the human health concerns associated with heavy metals in widely consumed fruits and vegetables[128]. In addition, extended exposure of grown crops to metal-contaminated growth medium reduces production sustainability. Toxic metal-induced soil fertility loss and nutrient imbalances lead to reduced agricultural yields[130,131].

Heavy metals including chromium, nickel, copper, arsenic, cadmium and lead were detected in potato (*Solanum tuberosum*), red onion (*Allium cepa*) and wild carrot (*Daucus carota*) in a study conducted by Islam et al.[132]. Heavy metal pollution reduced the chlorophyll content and biomass of vegetables, according to Li et al.[133]. Peroxidase activity, on the other hand, rose at low concentrations and decreased at high concentrations of heavy metals. They advocated for the development of salt-tolerant crops such as tomato (*Solanum lycopersicum*) in heavy metal-contaminated regions. Green pepper (*Capsicum annuum*) and lettuce (*Lactuca sativa*) collected high levels of copper and zinc, whereas green pepper, tomato and onion acquired considerable quantities of lead[134]. These heavy metal deposits were linked to the development of tannery enterprises in the region. Another research conducted by Lacatusu and Lacatusu[135] found significant levels of Cd and Pb in carrots (*Daucus carota subsp. sativus*), radish (*Raphanus raphanistrum subsp. sativus*) and potatoes (*Solanum tuberosum*). Cd and Pb levels in lettuce, parsley, dill and orach were up to 17 times higher than the allowable limits.

Silicon has been found to reduce the negative impacts of heavy metal pollution as well as long-term dangers in agriculture[136,137]. Heavy metal removal by silicon may be divided into two categories: external and internal[35,138]. External approaches include metalloid absorption or inactivation by silicon, as well as changing their present form by the addition of silicate minerals. Internal techniques, on the other hand, include processes such as increasing antioxidant enzyme activity, complex formation and compartmentalization, all of which assist lessen the negative consequences of heavy metal toxicity[138].

Heightened transcription of metal ion transporters such as OsLsi and OsHMA3 has been implicated in the mechanisms whereby Si amendment ameliorates Cu and Cd toxicity. Evidence further reinforces this proposition, with recent studies linking Si application to the induction of pathways that collectively scavenge reactive oxygen species[139]. These pathways decrease the bioavailability of toxic metals either through the precipitative immobilization of cations within the cell wall matrix, or via biochelation and detoxification processes that effectively sequester metal ions and alter their cellular trafficking bioavailability[140,141]. In peanut and rice seedlings, Si has been shown to lower the root, stem and foliar uptake of aluminum and chromium, further corroborating its protective action against the deleterious impacts of heavy metals[142]. Moreover, Barley exposed to osmotic and sulphur imbalances exhibited and enhanced root system biomass, accompanied by stratospheric sucrose concentrations consequent to Si foliar amendment, mitigating the detrimental stresses attributed to abnormal osmotic conditions and sulphur deficiency[143]. The attenuation of metal ion activity by Si proceeds via a combinatorial suppression of soil acidity, K, Ca, or Al fluctuation, selective precipitate formation and cellular reservoir routing[144]. Quantitative expression assays demonstrate that exogenous Si significantly elevates PsbY transcription (Os08g02530), a polyprotein contributor to the antenna complex of Photosystem II, whilst zinc elicitation exhibits the converse expression profile in comparable rice conditions. Plants primarily absorb available soil Si as monosilicic acid through their roots[145,146].

Silicon is plentiful in practically all soil types, accounting for roughly 28% of soil composition[147]. However, a large amount of silicon occurs as insoluble silicon dioxide, which is inaccessible to plants. Furthermore, some soils may be lacking in monosilicic acid, which is required by plants to satisfy their silicon requirements[148]. Silicon fertiliser has been proven to boost total plant biomass by improving morphological and physiological parameters, as well as fibre quality[120]. Furthermore, silicon fertilisation has been shown to reduce acid rain's negative effects on rice plants[120]. The removal of heavy metals by silicon may be divided into two categories: internal and exterior. External approaches include metalloid absorption or inactivation, enhancing metal activity, or changing their present form by adding silicate elements. Internal techniques, on the other hand, include processes such as increasing antioxidant enzyme activity, complex formation and compartmentalization, all of which assist lessen the negative consequences of heavy metal toxicity[139].

Promoting wound stress tolerance with silicon: Environmental stress involves any external factor capable of perturbing living systems[149]. The disruption of tissue integrity in cut fruits and vegetables accelerates both respiration and ethylene synthesis, outcomes intensified by the greater surface area-to-volume ratio and concomitant water efflux[150]. Plant wound stress arises from abiotic and biotic agents, including mechanical lesions induced by wind or herbivory[151]. The compromised parenchyma, vasculature and epidermis become susceptible to secondary colonization by bacteria and fungi[31]. In both C3 and C4 crop species, lodging events represent a common wounding factor[152]. The molecular patterns elicited by mechanical injury, similar to salt stress, promote a heightened oxidative burst, damaging the polyunsaturated acyl moieties of the membrane lipids and resulting in membrane destabilization.

Upon mechanical injury, tissue-derived lipoxygenase catalysis escalates membrane lipid peroxidation, thereby intensifying Jasmonic Acid (JA) synthesis via α-linolenic acid-derived signals[153]. Notably, mechanical wounding amplifies both lipid peroxidation and JA biosynthesis[154]. A rigorous comprehension of JA-mediated pathways that underpin stress tolerance during wound events is, therefore, imperative. Several lines of inquiry have recently targeted silicon supplements, demonstrating lodging mitigation in both rice and wheat[155,156]. Site-specific disruption triggers oxidative bursts in affected cellular masses. Subsequent measurements indicate that catalase (CAT), peroxidase (PO) and polyphenol oxidase (PPO) activities in rice subjected to silicon amendment and mechanical injury exhibit significantly elevated levels relative to untreated controls[140]. Corresponding increases in antioxidant enzyme activities have likewise been documented in wounded wheat[157], maize[158] and barley[158]. The hydrogen peroxide (H_2O_2) generated is phytotoxic; however, silicon-acclimated tissues demonstrate elevated pools of CAT and PO that catalyse the conversion of H_2O_2 to innocuous water under wounding. Consequently, the augmented synthesis of antioxidative enzymes under silicon treatment serves as an effective defensive stratagem against the secondary oxidative stress that accompanies mechanical injury.

Research indicates that silicon applications mitigate lipid peroxidation during wounding events while simultaneously modulating oxidative stress[159]. It is already established that plant cultivars exhibit variable physiological and metabolic responses to both biotic and abiotic stressors and such divergences extend to the composition and quantity of bioactive metabolites[160]. Notably, Si-amended rice cultivars exhibit significantly reduced levels of lipid peroxidation markers following mechanical stress, in contrast to untreated controls[140]. Elevated leaf silicon concentrations lead to a distinctive development of silicified cells, which exhibit a reduced degree of lipid saturation; this is corroborated by the noted decrease in malondialdehyde, a recognized end-product of lipid peroxidation[161]. The deposition of Si within cellular structures yields a hardened wall that serves as a mechanical barrier, thereby physically obstructing the ingress of potential pathogens through wound sites and thereby curtailing subsequent infection pathways[162]. In the context of interaction with herbivores, the high silicon concentration in the leaf tissue of rescue grass has been established to lead to substantial mandibular wear in grasshoppers, thus indicating an additional mechanical deterrent[163]. Consequently, such findings collectively position silicon as a key mediator of physical resistance toward mechanical and subsequent biotic stress[159]. Notably, the precise biochemical pathways that underlie the observed protective effects in both metabolic and structural contexts have yet to be elucidated, warranting further mechanistic investigation.

Enhancing high temperature stress tolerance with silicon: Anthropogenic climate change is raising heat stress, among the most severe abiotic pressures on terrestrial flora[164]. Projections indicate mean global temperatures may increase by 1.5°C by the mid-century and 3.5°C by the close of the century[165]. Phenological adjustments, including altered timing of budburst and leaf senescence, have been observed across numerous plant species subjected to rising mean temperatures[166]. Crop taxa sensitive to thermal extremes, such as Prunus and Vitis, as well as economically important overlaps of Citrus and various berries, remain particularly exposed[167]. Elevated thermal regimes have been shown to perturb the maturation and colour development of Citrus, resulting in quality-limiting disorders, including insolation necrosis[168]. Extreme thermal stress compromises cellular homeostasis by perturbing osmotic and ionic balances, thus inhibiting critical metabolic and physiological functions and by extension, curtailing biomass accumulation, developmental milestones and commercial viability[169]. Episodes of excessive heat during anthesis and the establishment of the seed set stage have been associated with severe yield reductions, representing a major barrier to the improvement of global food security[170,171]. Heat stress is known to depress vegetative growth, impair chlorophyll biosynthesis and diminish enzymatic activities vital to metabolic integrity[172]. Elevated leaf temperatures stimulate the excessive generation of Reactive Oxygen Species (ROS), resulting in oxidative cellular damage and the subsequent disruption of antioxidant and repair systems[173].

Improving horticultural plant microclimates is critical for guaranteeing year-round production[174]. Foliar applications of silicon (Si) to mitigate heat stress within agricultural systems are widely adopted, with documented enhancements to yield quantity and quality[175]. Bakhat et al.[175] endorse Si spraying as a sustained intervention for augmenting productivity in vegetable cropping systems. The physiochemical interactions triggered by Si deposition reduce heat-related metabolic perturbations, effectively buffering plants from exigent heat waves and as a consequence, safeguarding economic yield[176]. In addition, Si behaves as a modulatory agent across critical physiological domains, influencing seed germination, stomatal dynamics, ionic translocation, membrane conductivity, photosynthetic efficiency and cumulative growth rates[177]. Cucumber (*Cucumis sativus* L.), acknowledged as among the most extensively cultivated greenhouse vegetables, experiences protracted biotic and abiotic stress in controlled environments[178]. Exceeding recommended mineral nutrient applications, the progressive sodification of root substrates and recurrent peak-season thermal accumulation constitute substantial yield-limiting factors, particularly in arid greenhouse systems[179]. The employment of Si foliar applications has been corroborated as an effective amelioration, dampening both salinity and thermal stress symptoms in cucumber, thereby sustaining plant metabolism and productivity[180].

The combination application of Si and salicylic acid has beneficial benefits on cucumber plants in minimising the negative effects of high temperatures[181]. Under salt and heat stress circumstances, Si supplementation improves photosynthetic metrics and chlorophyll content in cucumber leaves[180]. Under heat stress circumstances, the combined use of rice straw as a soil cover and potassium silicate treatment improves soil fertility, nutrient absorption and crop output[182]. Unfavorable weather conditions, climate change and nutrient imbalances can all have a detrimental impact on tomato growth and output[183]. High summer temperatures can stymie tomato growth and reduce output[165]. Tomato seedlings, in contrast, may withstand severe temperature stress in greenhouses by receiving foliar applications of plant probiotics, sucrose and silicon[184]. Shading has been proven to boost plant development and production by minimising the negative effects of high summer air temperatures on tomato plants[185]. The foliar spray of potassium silicate has a considerable effect on celery yield during heat stress[177].

High temperatures during the blooming stage of monocotyledonous and dicotyledonous plants such as Brassica napus, Solanum lycopersicum and Triticum aestivum can diminish seed output[172]. Furthermore, spraying magnesium carbonate (silicon) as an anti-transpiration treatment has been proven to increase growth parameters, yield weight and fruit qualities in bananas[117].

By reducing sunburn, calcium silicate has been found to improve the value and worth of Valencia orange fruits[168]. Exogenous silicon (Si) administration improves the physiological growth of *Salvia splendens* at high temperatures by boosting the antioxidant system[186]. The date palm is well-known for its capacity to survive adverse environmental conditions such as salt, drought and heat stress. Heat and drought, on the other hand, can have a detrimental influence on fruit yield, quality and a variety of physiological and metabolic processes in date palm seedlings[187,188]. GA_3 and Si coupled have been found to boost plant development and rescue date palm growth under heat stress conditions[189].

As a cool-season food legume, garden pea is quite sensitive to temperature changes[190]. Even a one-degree temperature increase can be termed heat stress for cool-season food legumes, with serious consequences for their development and metabolic functioning[134].

Understanding the impact of silicon on cold stress: Cold and freezing stress has been shown to depress crop yields by as much as 70%[191], primarily owing to the simultaneous decline of temperature and irradiance[192]. In certain species, suboptimal chill conditions induce large-scale physiological cascades, manifesting as abnormal leaf expansion, stunted growth and extensive necrosis[193]. These conditions likewise accelerate the generation of Reactive Oxygen Species (ROS), including superoxide radical (O2.-) and hydrogen peroxide (H_2O_2), the accumulation of which evolves as a secondary stress[192]. Elevated ROS concentrations compromise cellular integrity by peroxidising membrane lipids and inducing programmed cell death[194]. In mitigation, plants synthesize an array of enzymatic antioxidants, including superoxide dismutase (SOD), catalase (CAT), guaiacol peroxidase (GPX), glutathione peroxidase (GSH-Px), ascorbate peroxidase (APX), glutathione reductase (GR), dehydroascorbate reductase (DHAR) and monodehydroascorbate reductase (MDHAR), all of which operate in an integrated defense network against ROS[195]. Non-enzymatic antioxidants, namely reduced glutathione (GSH) and ascorbate (AsA), further reinforce this defense array, collectively maintaining the cellular redox homeostasis requisite for survival in chilling environments. Plant tolerance to cold stress is increased by supplementing with silicon (Si), which maintains photochemical processes, photosynthetic gas exchange and activates antioxidant defence capability[196-198]. Exogenous Si treatment raises silicon concentrations in plants[199] and increased endogenous silicon deposition lowers lipid peroxidation[200]. The quantity of malondialdehyde (MDA), which represents membrane damage, can be used to detect lipid peroxidation[201]. Low temperature, for example, can increase MDA content[32,202], indicating membrane degradation under cooling temperatures and low light circumstances[192]. Silicon supplementation, applied via seed soaking, foliar spray, or root drench, alleviates chilling injuries and frost incidence in species regardless of their Si-accumulators capacity[203]. Its protective capacity extends across numerous abiotic stressors, including lodging, drought, excessive radiation, thermal extremes and biochemical stressors such as salinity, metallic toxicity and nutrient imbalance[204].

Controlled exposure to sodic-boric sodic layers and chilling conditions confirms that exogenous Si attenuates malondialdehyde (MDA) accumulation, an indicator of lipid peroxidation[32,205]. Further, Liang et al.[196] reported that Si supplementation ameliorates freezing injury in overwinter wheat by remodeling the biophysical and biochemical attributes of the leaf apoplast, effectively substituting for the natural cold-acclimation response. Mechanistically, Si may fortify the antioxidative apparatus and stabilize the plasma membrane architecture, thereby diminishing cellular injury under diverse abiotic stress conditions[137]. Support for agronomic applicability is evident; Datnoff et al.[206] documented enhancement in growth metrics, biomass allocation, yield components and successful fertilization as a consequence of foliar and root Si feeding.

In many grape-growing locations, grape (*Vitis vinifera* L.) is vulnerable to cold temperatures[207]. Foliar Si treatment can successfully mitigate freezing damage in grapes by preserving membrane integrity and reducing photoinhibition during recovery[208]. Colder temperatures may lead to harm in pistachio growing areas, although foliar-applied Si mitigates the negative impacts of cold by raising Relative Water Content (RWC) and soluble sugar content in pistachio[209]. Cucumber is a vegetable crop that is vulnerable to chilling[192]. Exogenous Si treatment boosts endogenous silicon deposition, boosts antioxidant activity and lowers lipid peroxidation caused by chilling stress in cucumber[32]. Cucumber cold resistance is improved by grafting and Si addition[210]. Treatments such as salicylic acid or potassium silicate dipping keep cucumber fruits' freshness, flavour and appearance while also preventing decay and chilling damage symptoms[211]. Chitosan/nano-silica coating improves chilling resistance and increases loquat fruit storage life[212]. The addition of chitosan and nano-silica enhances the quality of longan fruit during storage at room temperature[213]. Cold stress is a harmful abiotic stress that lowers medicinal plant output[214]. Silicon has been shown to aid Sorghum bicolor growth under salt stress[215]. Some wheat varieties thrive under cold conditions[196].

Silicon's role in improving oxidative stress tolerance: Exposure to abiotic stress markedly elevates the production of reactive oxygen species (ROS)-chiefly hydrogen peroxide (H_2O_2), superoxide ($O_2•^−$) and hydroxyl radicals (•OH)-within plant tissues, thereby threatening cellular integrity through oxidative damage to membranes and membranes and organelles[216]. The plant antioxidant apparatus comprises both enzymatic and nonenzymatic components, the former including catalase (CAT), peroxidase (POD), superoxide dismutase (SOD) and ascorbate peroxidase (APX), while the latter is represented by vitamin E, ascorbic acid and Glutathione Reductase (GR)[217]. Published studies underscore that the protective efficacy of these antioxidants is, to varying extents, modulated by silicon (Si) amendment. For instance, Si supplementation augmented the activities of CAT, SOD and GR in watermelon tissues, whereas APX activity remained constant[81]. Conversely, in cucumber-another model species-application of Si raised the activities of APX, SOD, glutathione peroxidase (GPX) and GR, while CAT activity showed no measurable variation[218]. In tomato, exogenous Si not only curtailed the accumulation of H_2O_2 but also enhanced aquaporin-mediated water flux, thereby facilitating increased water uptake[112]. These divergent biochemical modulations suggest the selective responsiveness of antioxidant mechanisms to Si, a noteworthy property that might be tailored to ameliorate oxidative and osmotic stress in species-specific contexts. Okra, grapes, wheat, rice and other plant species have shown similar outcomes[219,220]. Depending on the plant species and Si content, the regulation scheme may vary. POD activity rose and MDA concentrations reduced with Si addition in Glycyrrhiza uralensis, whereas SOD activity increased only at a certain Si concentration[221].

Silicon influences plant antioxidant systems in a manner that is contingent upon species-specific responses, exposure duration, concentration and agronomic conditions, arguably succeeding in decreasing Reactive Oxygen Species (ROS) accumulation chiefly through the simultaneous regulation of both enzymatic and non-enzymatic antioxidant mechanisms[222]. Nevertheless, extensive agronomic trials remain imperative to ascertain the practical utility of silicon in commercial systems, since in vitro conditions generally fail to replicate the protracted and fluctuating abiotic stressors that characterize natural cropping environments. Interest in this regard has focused on the application of silicon compounds via foliar spray; evidence confirms that this method consistently enhances vegetative growth, elevates yield metrics and ameliorates stress symptoms across a broad taxonomic array of cultivated plant species[223]. Given that the silicon is made directly available to aboveground tissues, foliar application is postulated to confer a comparative advantage over traditional soil incorporation. Additionally, the direct supply of silicon to leaves may positively influence root morphology and length, consequently widening the effective root fringe and promoting improved nitrogen uptake, as observed in the recent comparative investigations by Kovács et al.[224]. Nonetheless, the extant literature does not provide a comprehensive, comparative evaluation of the relative efficiencies of soil- versus foliar-applied silicon; focused agronomic trials that systematically vary both application modes, concentrations and frequencies in parallel are prudent for fully characterizing the effective dosage and mode of delivery in differing cropping systems.

CONCLUSION

Silicon has been widely researched for its effect on plant developmental processes and physiological activities. It is necessary for maintaining ionic equilibrium, controlling water status, enabling photosynthesis, altering phytohormone levels and performing other important tasks. Furthermore, Si has been reported to promote antioxidative responses, raise osmolyte levels and stimulate stress-related signaling pathways in plants under stressful circumstances. Si is also effective in mitigating both biotic and abiotic stress. It increases the release of antimicrobial compounds within plants, assisting in pathogen defense and lowering infection rates. Furthermore, modern molecular approaches such as metabolomics, proteomics and transcriptomics have revealed on Si's exceptional significance in plants. Furthermore, research has shown that phytohormones crosstalk is involved, in which distinct hormones from plants and their signaling pathways interact in response to Si. However, more study is needed to comprehend the regulatory processes governing Si responses in plants, both in regular and stressful situations. Emphasizing genetic engineering methods can aid in the discovery of metabolic pathways responsible for various plant characteristics connected to Si. We can acquire a more thorough grasp of Si's impacts on plant physiology and its potential for stress management by going deeper into these areas.

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