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The Role of Silicon in Enhancing Crop Yield and Quality Under Abiotic Stress

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Silicon is regarded as an essential element that enhances crop productivity under multiple abiotic stresses. Due to changing weather patterns, cereal crops are exposed to various climatic adversities such as drought, salinity, heavy metal toxicity, and temperature stress, which adversely affect soil health, plant growth, photosynthesis, nutrient uptake, and ultimately crop productivity. This review highlights the importance of silicon in mitigating these stresses through its beneficial effects on both soil and plant systems. Si application enhances soil aggregation, nutrient availability, microbial activity, and the immobilization of toxic metals thereby, improving physical, chemical, and biological properties of the soil. Therefore, integration of silicon based agronomic practices provides a resilient and sustainable cereal based cropping systems under challenging environmental conditions.

Keywords: Silicon; abiotic stress; drought; salinity; heavy metal toxicity; oxidative stress; antioxidant defence; cereal crops; sustainable agriculture; climate resilience

Introduction

Environmental stresses are one of the major constraints affecting plant growth, development and agricultural productivity worldwide. Additionally, rapid climate change, environmental degradation, and the growing demand for food due to population expansion have further aggravated the situation. Consequently, ensuring sustainable agricultural production under challenging environmental condition has emerged as a major concern for researchers, policymakers and farmers across the globe. Excessive use of agrochemicals, inappropriate land management practices and degradation of natural resources have intensified environmental problems and have significantly reduced agricultural sustainability. Changing rainfall patterns and rising temperature, disrupts soil structure and functions. In this context, Silicon (Si) has emerged as a promising yet underutilised alternative in climate resilient agriculture. At plant level, it helps in regulating photosynthesis, antioxidant enzyme activities, nutrient uptake and endogenous hormone synthesis. It also fortifies structural integrity and causes an increase in the production of reactive oxygen species (ROS) through various metabolic processes such as respiration, NADPH oxidase, lipid peroxidation, and purine catabolism. Moreover, it is also used as fertilizers due to its property of mitigating stress and enhancing quality and production. Si enhances soil stability, fosters nutrient cycling mediated by microbes and contributes to long term C-sequestration through phytolith-occluded carbon (PhytOC) formation. In addition, its application also reduces greenhouse gas emissions by reducing N_2O release and enhancing oxidation of CH_4.

Silicon Uptake and Translocation in Plants

Si is taken up by plants as silicic acid [$Si(OH)_4$], whose uptake and translocation are regulated by specific transporters. In rice, Lsi1, a passive transporter, facilitate silicic acid movement into the root cells along the concentration gradient while Lsi2 actively transports Si across the plasma membrane through proton-coupled transport. Together, they mediate the uptake of Si from the soil and its transfer into the stele. Lsi6, a homologue of Lsi1, is involved in xylem unloading and the distribution of Si to leaf cells. During reproductive stage, several transporters, such as, Lsi6, Lsi2 and Lsi3 facilitate the transfer of Si from enlarged vascular bundles to diffuse vascular bundles, resulting in its high accumulation in the husk. During silicification, transpiration and transporter-mediated Si accumulation increase the local concentration of silicic acid, leading to its auto-condensation and deposition as insoluble biogenic silica. Cell-wall components, particularly hemicellulose and callose, may act as molecular templates for silica deposition.

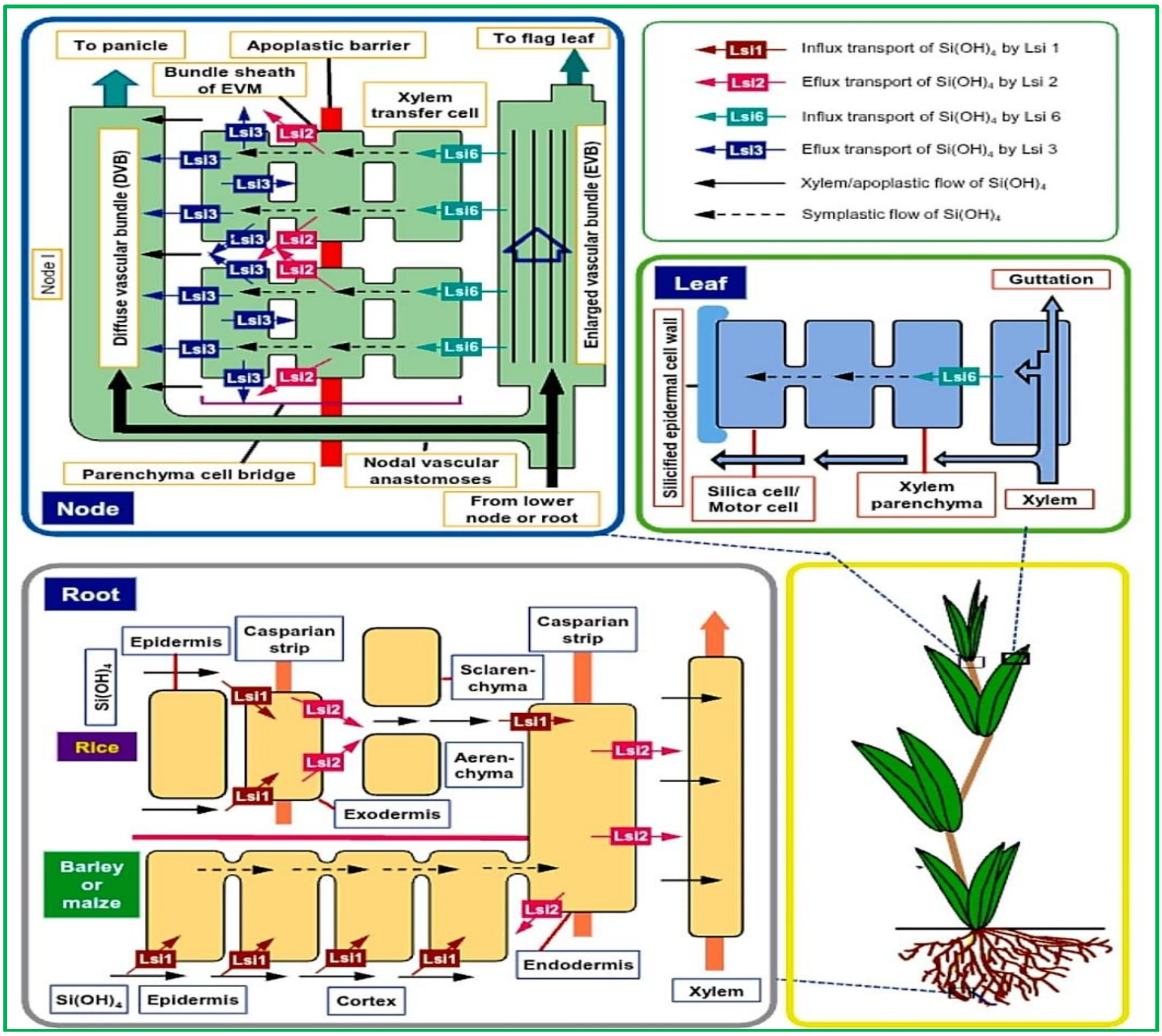

Figure 1: Schematic presentation of Si uptake, translocation, deposition and excretion in the plant as mediated by different Si-transporters.

ROS Generation and Antioxidant Systems in Plants

Reactive oxygen species (ROS) include superoxide radicals, singlet oxygen, hydrogen peroxide (H_2O_2), and hydroxyl radicals. These are produced during abiotic stresses particularly due to disturbances in photosynthetic electron transport. In electron transport chain, an excited electron leads to the formation of excited singlet chlorophyll, which is quite unstable and immediately gets converted to excited triplet chlorophyll. The transfer of excited energy from excited triplet chlorophyll of photosystem II (PSII) to the ground-state triplet oxygen leads to the formation of highly reactive singlet oxygen. Moderately reactive superoxide is also produced at PSI by the one-electron reduction of O_2 followed by conversion to H_2O_2 with the catalytic action of SOD, including FeSOD and Cu/ZnSOD.

Inner mitochondrial membrane consists of three key components, that is, complex I, II, and III of the mETC, are considered as the key sources of ROS. Complexes I and II generate superoxide at the matrix side of the inner mitochondrial membrane, whereas it is presumed that complex III produces superoxide at both sides of the inner mitochondrial membrane. Also, Peroxisome host photorespiration and b-oxidation of fatty acids that act as a major source of peroxisomal ROS.

In order to sustain ROS signalling, plants have evolved antioxidant defense mechanisms, such as, SOD, CAT, glutathione reductase (GR), ascorbate peroxidase (APX), monodehydroascorbate reductase (MDHAR), dehydroascorbate reductase (DHAR), glutathione peroxidase (GPX), glutathione *S*-transferase (GST), ascorbate, GSH, α-tocopherol, flavonoids, carotenoids, and proline (Pro). External Si- application causes apoplastic Si-deposition, resulting in blocking the movement of toxicants along the apoplastic routes. Furthermore, soluble Si also contributes to ROS detoxification by increasing the levels of various antioxidants, helping protection of cellular organelles from ROS-toxicity.

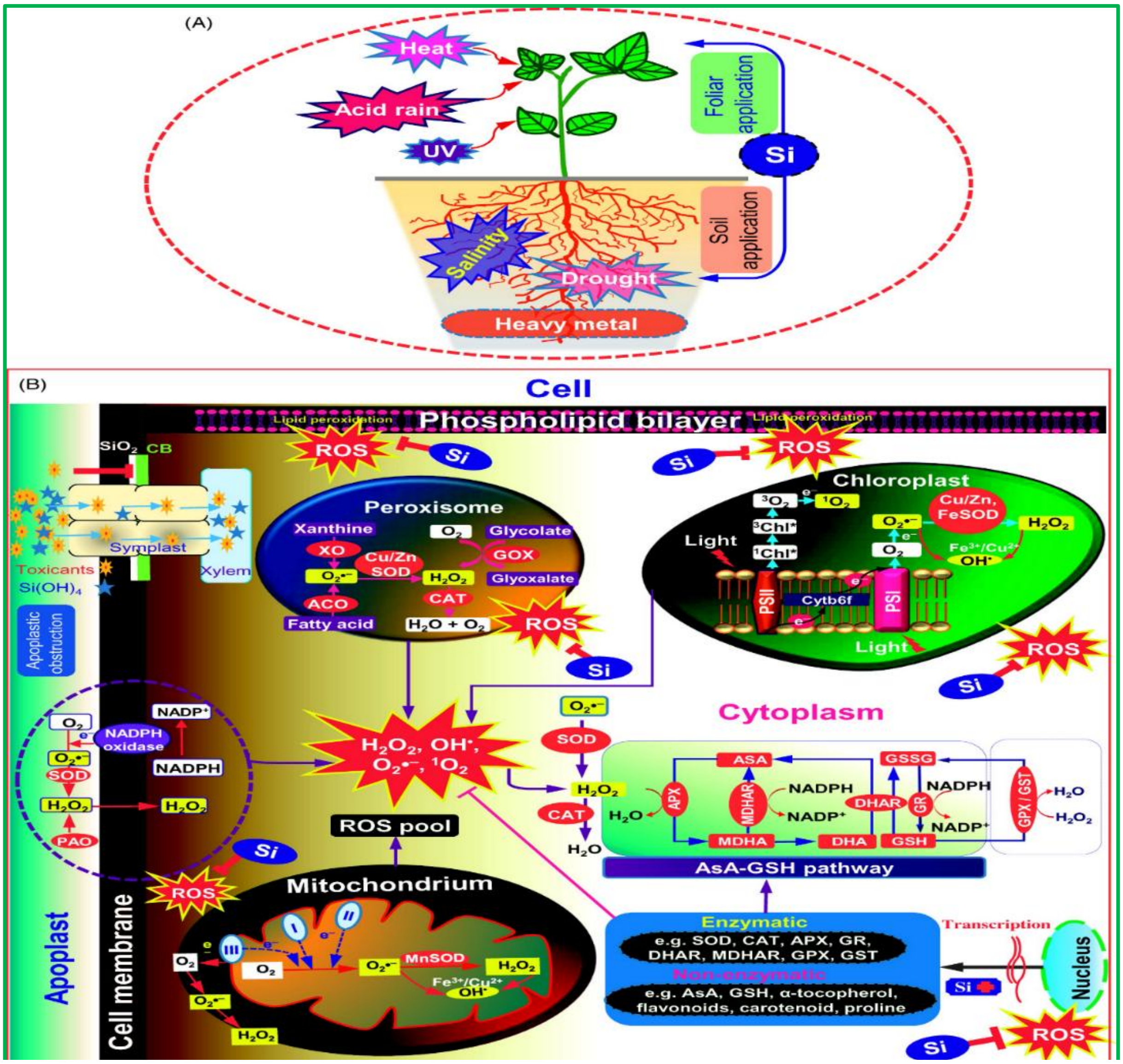

Figure 2: A schematic presentation of generation of reactive oxygen species (ROS) an Si-mediated oxidative stress protection in plants exposed to various abiotic stresses.

Role of Silicon in Mitigating Environmental Stress

Draught stress

Silicon application enhances drought tolerance in plants by regulating transpiration, water uptake, antioxidant defence, and stress-responsive signalling. Furthermore, the silica cuticle deposited on leaves reduces transpiration, while Si transporters such as Lsi1, a siliconpermeable aquaporin, facilitate Si influx into plants. Si also enhances root water uptake by increasing the expression of aquaporin genes, improves gas exchange, photosynthetic pigment content, and water-use efficiency in crops such as sugarcane, maize, rice, tomato, pepper, mangrove, and sorghum. In barley, Si regulates ABA biosynthesis and degradation, while in rice it modulates transcription factors such as OsNAC5 and OsDREB2A, activating stress-responsive genes through ABA-dependent and ABA-independent pathways. Si treated plants such as sugarcane, maize and wheat sugarcane showed increased activities of antioxidant enzymes such as SOD, CAT, POD, and APX, along with higher levels of AsA, GSH, and proline, resulting in reduced H_2O_2 and MDA accumulation.

Salinity stress

SI application enhances salinity tolerance in plants by optimal K^+/Na^+ ratio, regulating ionic and osmotic balance. It sequesters excess Na^+ in root vacuoles thereby limiting its transportation to shoots thereby reducing ion toxicity. Si also simulates the activity of antioxidant enzymes such as SOD, POD, CAT, APX, and GR, which reduce ROS accumulation, lipid peroxidation, MDA content, and membrane damage. In maize, 4 mM Si reduced leaf Na^+ and Cl^- accumulation under 60 mM salinity.

Metal toxicity

Si immobilizes metal ions, form complexes and co precipitates with metals, thereby restricting their translocation to other plant parts. Si application modifies soil pH and metal availability, reducing their uptake by plants. Under metal stress, Si enhances the activity of antioxidant defense enzymes, thereby reducing ROS accumulation and oxidative damage. Additionally, Si influences gene expression relating to chlorophyll biosynthesis and enhances photosynthetic apparatus, thereby improving overall plant performance under heavy metal stress.

Temperature stress

Si application has and major role in regulating thermos tolerance in plants. Si application activates heat tolerance genes plays a crucial role in the activation of heat tolerance genes and the signalling cascades triggered by calcium (Ca2+), phospholipids, SA, ET, hydrogen peroxide, nitric oxide, as well as ABA. Si application enhances the production of HSPs, which protects the plants from heat stress. Furthermore, SI accelerates the production of phytohormones and strengthens the antioxidant system in plants. These combined effects help plants to improve their overall resilience to high temperatures.

SI also enhances cold tolerance in plants by inducing the expression of various genes, particularly transcription factors like DREB1A, DREB1B, and DREB1C (82). Additionally, Si enhances antioxidant enzyme activities during cold stress and regulates hormonal balance and micronutrient homeostasis, promoting cold tolerance in maize plants. Si enhances rubisco enzyme activity, stomatal closure, and pigment production in chilling conditions. By modulating physio-biochemical processes Si supplementation has been shown to mitigate UV radiation stress and mechanical injury in diverse plant species.

Conclusion

Silicon agronomy represents a sustainable strategy to mitigate the adverse impact of environment. The benefits of silicon application extends from soil to the crop, improving soil aggregation, nutrient availability, microbial activity, and the immobilization of toxic metals while enhancing plant water relations, photosynthesis, ion homeostasis, antioxidant capacity, phytohormonal regulation, and structural integrity. By regulating reactive oxygen species through enzymatic and non-enzymatic antioxidant systems, Si helps in protecting cellular components from stress induced oxidative damage. Si should have viewed as an essential component in climate-resilient and sustainable crop production rather than merely a supplementary nutrient. Future research should not only focus on understanding the molecular mechanisms underlying Si-mediated stress tolerance, but also developing efficient crop- and location-specific Si management strategies.

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