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Review Article

Mitigating heavy metal stress in rice (*Oryza sativa* L.): The role of silicon in enhancing plant resilience

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Rice (*Oryza sativa* L.) is one of the staple food crops globally. Rice is critical for global nutritional security, especially in Asia. Both geogenic and anthropogenic sources, such as the use of pesticides derived from agriculture, can contaminate farming soils with heavy metals. Long-term exposure to heavy metals through food, including rice intake, can result in cancer and non-cancer health effects, with Pb, Cd, and As being particularly hazardous. The importance of silicon was mainly demonstrated in reducing the negative impacts of heavy metals and other abiotic stresses on plants. Rice has a strong affinity for silicon, and when compared to other plant species, its root system has a noticeably better capability for absorbing silicon.

Keywords: *heavy metal toxicity, alleviation, silicon, Oryza sativa*

Introduction

Rice (*Oryza sativa* L.) is one of the staple food crops globally. Rice, in particular, is a typical Si accumulating species and can be able to accumulate Si at concentrations as high as 10% of shoot dry mass (Wang et al., 2016). The amount of heavy metal inputs into the soil has greatly increased as a result of human activity. The sustainability of agricultural production is disrupted by elevated levels of hazardous metals, which endanger public health and impact plant development and yield. Over the last few decades, silicon (Si) has emerged as one of the advantageous elements that helps plants cope with a variety of challenges. Si is the second most abundant mineral element in the soil and is beneficial for plant growth and stress resistance. The application of Si to soil has been reported to increase pH and decrease heavy metal phytoavailability (Gu et al., 2011).

Silicon in rice

Rice has specific mechanisms for assimilating silicon from soil as soluble silicic acid, and for unloading silicic acid into the xylem, through the aquaglyceroporins lsi1 and lsi2 (Ma & Yamaji, 2008). Rice, in particular, is a typical Si accumulating species and can be able to accumulate Si at concentrations as high as 10% of shoot dry mass (Cai et al., 2020). Since Si can improve leaf erectness and lodging resistance, it can improve light penetration through rice canopies, which benefits whole-plant photosynthesis and has been linked to increasing rice grain yields. While the number of panicles or the 1000-grain weight are not significantly affected, the application of Si increases the biomass of straw, the number of spikelets per panicle, and particularly the percentage of filled spikelets, hence improving grain output (Ando et al., 2002). The negative impacts of toxic metals/metalloids (e.g. Cd, Zn, Al, Fe, As) have been attenuated by Si application given that Si can reduce the uptake, translocation and bioconcentration of these metals/metalloids in the shoot, with positive impacts on the photosynthetic performance.

Mechanisms to alleviate heavy metal toxicity by Silicon in rice

The beneficial effect of silicon in detoxification can be attributed to both internal plant processes and external (growth media) factors, and the silicon-derived increase of plant tolerance to heavy metal toxicity. The external mechanism of elevating heavy metal tolerance is mainly due to the increased pH by silicate application, resulting in metal silicate precipitates that decrease the metal phyto-availability. In plants, Si affects the translocation and distribution of metals in various plant parts and allows them to survive under higher metal stress. The commonly acknowledged processes include the immobilization of toxic metals in the soil (at the soil level), the activation of antioxidants both enzymatic and non-enzymatic, metal co-precipitation, metal ion chelation, compartmentation, structural changes in plant tissues, and modifications to molecular responses (at the plant level). Either the elevated pH of the soil or the shifting metal speciation in the soil solution as a result of silicate complex formation caused the immobilization. It was discovered that applying Si-rich amendments (steel slag and fly ash) to rice raised the pH of the soil from 4.0 to 5.0–6.4 and reduced the phyto-availability of heavy metals by at least 60%, further inhibiting metal uptake (Bhat et al., 2019) (Figure 1).

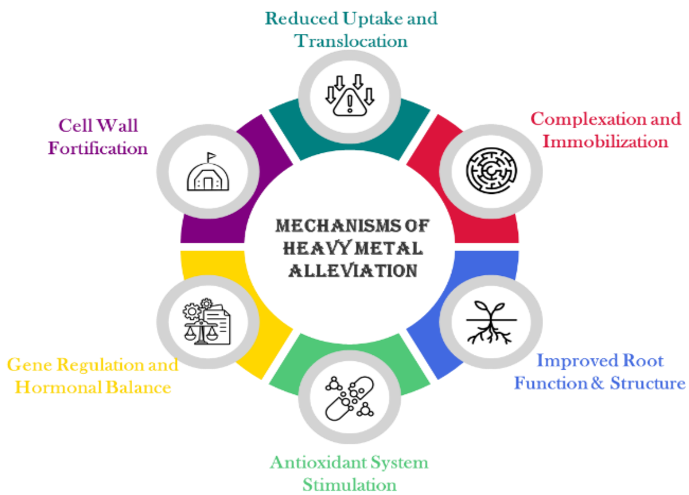

Figure 1. Mechanism of heavy metal alleviation

Cadmium

Plants and animals are negatively impacted by cadmium (Cd), one of the most hazardous heavy metals in the environment. Cd buildup can have harmful effects on crops, which include preventing normal cell division, decreasing the photosynthetic efficiency of leaves, intensifying lipid peroxidation in cell membranes, and preventing the activity of antioxidant enzymes (Genchi et al., 2020). All of these effects inhibit normal plant growth and reduce yield. Si mostly reduces Cd toxicity in rice crops by influencing Cd uptake and transportation in plants. Si can decrease Cd absorption under Cd stress by controlling the expression of associated genes that carry Cd from the external solution into the cells in rice plant roots (Lin et al., 2017). Si binds to hemicellulose that has a net negative charge in cells, which prevents Cd absorption and causes co-deposition on the cell wall. When silicon covalently bonds to heavy metals, unstable silicates are created. These silicates are then broken down into silicon dioxide (SiO2), which reduces toxicity (Singh et al., 2023).

Iron

Wetland rice (*Oryza sativa* L.) plants frequently exhibit excess iron (Fe), which hinders crop growth and output. In the vegetative stage, the effects of Fe toxicity on rice plants have been associated with decreases in net CO_2 assimilation rate due to stomatal and non-stomatal limitations of photosynthesis, including photochemical impairments of photosystem II (PSII) as noted through PSII photoinactivation and/or photooxidation (Dos Santos et al., 2020). Excess Fe during the reproductive stage causes notable decreases in the number of tillers and spikelet fertility, which ultimately lowers rice grain yields. Since Si can decrease the uptake, translocation, and bioconcentration of these metals/metalloids in the shoot, the detrimental effects of toxic metals/metalloids (such as Cd, Zn, Al, Fe, and As) have actually been decreased by Si application. Si can mitigate the effects of toxicity on rice via decreased Fe concentrations in both leaf and root tissues, increased activity of the antioxidant system with concordant reductions in lipid peroxidation, which ultimately leads to a lower impact of Fe on the growth of Si-treated plants (Chalmardi et al., 2014).

Arsenic

Food security and human health are seriously threatened by soil arsenic contamination. The movement and transformation of As in the soil-rice system can be efficiently controlled by diatomaceous earth, a typical exogenous mineral of silicon. As-induced toxicity in plants might result in decreased biomass and plant yields. Reactive oxygen species (ROS) concentrations rise in response to soil stress, which damages membrane-bound organelles oxidatively, raises organic acids, and alters proline metabolism and antioxidants. However, enzymatic and non-enzymatic substances, their gene expression, plant growth, and biomass, and oxidative stress were all significantly increased by the application of Si (Gupta et al., 2015). By increasing the cell wall's ability to immobilize As, promoting more As accumulation in the husk by controlling the expression of transporter genes, and promoting As adsorption by iron plaque development on the rice root surface, the application of DE decreased the amount of As in brown rice. The use of DE reduced the harmful effects of As in rice and controlled the activities of antioxidant enzymes. Arsenic enrichment in the hull was enhanced and arsenic transport to rice was prevented by the application of the exogenous mineral silica (Tang & Zhao, 2021). Administration of silicon decreased the amount of arsenic in rice roots, which in turn decreased the amount of arsenic absorbed by the shoots. Arsenite uptake and translocation were reduced either due to the decreased expression of Lsi1 and Lsi2 or due to competitive inhibition at Lsi2 by Si application. Si-mediated decreases in the buildup of oxidative stress indicators and changes in antioxidant enzyme activity in arsenate-stressed seedlings may have caused this. Under arsenic stress, silicon supplements increased the enzymes that synthesize starch, which increased the production of starch and decreased the amount of reducing and non-reducing sugar. Disturbances in polyamine homeostasis under arsenate stress was partially revived with Si supplementations leading to enhanced production of all the three polyamines putrescine, spermidine and spermine along with reduction in H_2O_2 content, lipid peroxidation and consequently oxidative stress (Das et al., 2022).

Chromium

Treatment with chromium resulted in a substantial rise in lipid peroxidation (as malondialdehyde; MDA) and a decrease in growth, photosynthetic pigments, and protein. However, by lowering MDA levels, root-to-shoot Cr transfer, and Cr accumulation, Si addition reduced Cr toxicity and encouraged rice development (Tripathi et al., 2012). The contribution of exogenous silicon (Si) to rice seedlings' increased tolerance to hexavalent chromium (Cr VI). Si supplementation reduced these anomalies, but Cr negatively impacted chloroplasts containing mesophyll cells, the integrity of xylem and phloem, and the length of leaf epidermal cells and stomatal frequency. Si treatment reduced Cr buildup and root-to-shoot Cr transport, reducing Cr toxicity and promoting rice development.

Zinc

Excessive zinc stress impeded rice growth and reduced net photosynthesis, stomatal conductance, intercellular CO_2 concentration, chlorophyll concentration, chlorophyll fluorescence, and the leaf chloroplast structure was disrupted, resulting in reduced starch granule size and quantity, disintegrating and absent thylakoid membranes, and uneven swelling. Reduced P and K+ levels and slower development were the results of excess zinc. Reduced absorption and translocation of excess zinc are the primary causes of Si-assisted zinc tolerance in rice; however, a greater binding of zinc in the cell wall of less bioactive tissues may also play a role. Si increased photosynthesis by activating and regulating some genes linked to photosynthesis in response to high-Zn stress. The reduction of zinc toxicity in heavy metal-tolerant individuals may be due to the formation of a zinc-silicate complex. Zinc concentration in xylem sap decreased with Zinc + Si treatments, according to xylem exudate analysis, suggesting that Si supplementation inhibits zinc translocation. Zinpyr-1 fluorescence test and Energy-dispersive X-ray spectroscopy analysis revealed a decrease in concentration of biologically active zinc and co-localization of zinc and Si in the cell wall of less active tissues, particularly in root sclerenchyma (Gu et al., 2012). Si-mediated zinc tolerance in rice has been attributed to a reduction in the uptake and translocation of zinc. Additionally, binding of zinc in the cell wall decreased the concentration of available zinc.

Conclusion

The crucial function of silicon in preventing a number of abiotic stressors is the main topic of this review. In order to maintain sustained output, agronomy can employ silicon effectively as a substitute for the widely used conventional fertilizers. Si-induced reduction of heavy metal uptake, root-shoot translocation, chelation, complexation, upregulation of antioxidative defense responses, and regulation of gene expression are the mechanisms involved in alleviation of heavy metal toxicity in plants. Therefore, soil nutrition with fertilizers containing plant-available silicon may be considered a cost-effective way to shield plants from various stresses, improve plant growth as well as yield, and attain sustainable cultivation worldwide.

Author contributions

Conceptualization – Ashok Subiramaniyan, Chandrasekaran Perumal, Ashokkumar Natarajan, Selvakumar Gurunathan. Writing (original draft) - Shruthika Mohan, Sangeetha Selvam. Writing (review & editing) - Shruthika Mohan, Sangeetha Selvam, Ashok Subiramaniyan, Chandrasekaran Perumal, Ashokkumar Natarajan, Selvakumar Gurunathan.

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