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(Review Article)

Increasing plant resistance with silicon applications

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Abstract

The mineral element silicon, accumulated in the leaves and roots of various plants, plays a crucial role in increasing resistance to various biotic and abiotic stresses. Although considered a mineral element that is not essential for plant life, silicon provides significant benefits. This mineral accumulated in tissues provides increased resistance of cells to mechanical stresses, reduced water loss through transpiration, increased resistance to sunlight, and reduced metal toxicity and salt stresses. Plants accumulate silicon differently, depending on their root type and functionality. Molecular studies have made it possible to identify the genes responsible for silicon accumulation. In the future, advances in this field could improve techniques for studying the mechanisms involved in silicon uptake, not only by increasing its availability within tissues but also by improving its storage capacity. Unfortunately, many plants cannot absorb silicon and, therefore, cannot benefit from the mechanisms that lead to increased resistance to various biotic and abiotic stresses.

This review aims to highlight the benefits obtainable with the use of silicon in those plants capable of absorbing it, particularly in the control of biotic and abiotic stresses.

Keywords: Biotic stress; Abiotic stress; Silicon; Plant growth; Increased resilience

1. Introduction

Silicon (Si) is among the minerals found most in the soil after oxygen, constituting 70 per cent of its mass. most commonly found in the soil after oxygen, constituting 70 per cent of its mass. In most soils, silicon concentrations are between 300 and 500 µM. Most plants contain silicon in their tissues. Although not involved in their metabolism, its deficiency can cause various problems, particularly resistance to abiotic stresses. Numerous studies have shown that silicon applications effectively increase resistance to fungal and bacterial diseases [1,2]. Silicon can reduce the spread of pathogenic fungi in plants such as rice, wheat, tomato, soya, and cucumber. In America, the application of silicon with fertilizers enables a reduction in fungal diseases in both the field and nursery. Various research has shown that using silicon in crops can reduce the lesions caused by fungi and the amount of spores detectable in each cut [3,4,5]. Microscopy studies have shown that silicon accumulates near the germination tube or on the fungi's hypha, reducing the attack's site with the host. Pot experiments have also shown how silicon acts as an antifungal against *Rhizoctonia solani* and white malaise in cucumber, barley, wheat, sugar cane, and oats. Silicon-based soil conditioners in nutrient solutions are successfully used to control white malaria [6,7]. In strawberries, an increase of silicon in the leaves has been shown to reduce the incidence of white blight. Silicon deficiency in cereal crops such as barley and wheat can lead to stunted growth and increased susceptibility to fungal diseases [8,9,10]. In horticulture, fungal infections and germination of fungal conidia are related to the silicon content of the nutrient solution. Foliar applications of silicon are effective in inhibiting powdery mildew development on vegetable plants and in viticulture [11,12,13]. Silicon applied to leaves is deposited on their surface and reduces the binding sites from which fungi can penetrate. Increased resistance

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also occurred against Pythium ultimum on Momordica charantia and cucumber [14,15]. This review will present various aspects of resistance mechanisms to biotic and abiotic stresses affected by silicon applications in pot and field crops.

2. Plant resistance to biotic stress mediated by silicon application

The mechanisms that may describe the increase in plant resistance against pathogens and abiotic stresses following the application of silicon are explained below. A first mechanism defines the Si deposited under the cuticle as a kind of physical barrier preventing the fungus from penetrating and the infection process from developing. Another mechanism identifies silicon as a possible modulator of host resistance to the pathogen. In fact, in plants to which SI has been administered, there is an increase in the production of phenols and phytoalexins in response to fungal attacks [16,17]. In cucumber plants, silicon induces chitinase and peroxidase activity.

Furthermore, in cereal crops, it was shown that the accumulation of glucanase and peroxidase transcripts could be associated with a low degree of colonization of the fungus Magnaporthe grisea following silicon treatments [18,19,20]. The exact nature of Si's interactions with biochemical pathways influencing disease resistance remains largely unknown (Table 1). Studies have shown that induction of systemic acquired resistance in cucumber results in increased expression of a gene encoding a proline-rich protein. The peptide derived from this protein has a cell wall-strengthening action at fungal penetration sites into epidermal cells [21,22,23]. Genetic studies on Arabidopsis showed a variation in expression of more than 4000 genes where pathogen intensity was attenuated in SI-treated plants [24,25].

3. Resistance to bacterial diseases and insect pests

Studies have shown that the amount of silicon in the leaves of cereals is decisive for the attack of bacterial pathogens, particularly on rice; it is evident that resistance to Xanthomonas is directly proportional to the amount of silicon administered. The silicon-induced decrease in soluble sugars in the leaves leads to increased resistance to this pathogen. In vegetable plants such as tomato and cucumber, the administration of cucumber reduces bacterial wilt symptoms [26,27,28]. Silicon can inhibit attacks by woodworms, spiders, mites and cicadas. Low levels of silicon are generally found in attacked plants, while in various works, a positive relationship between Si content and cicada resistance has been shown [29,30]. Some researchers have pointed out silicon fertilization induces excellent resistance to aphids in cereals. As mentioned above, the protective effects of silicon are identifiable in the barrier effect formed by the deposition of silicon on the cell wall, which makes it difficult for the pathogen insect to penetrate plant tissue. In addition, plant production of defence metabolites increased after fertilization with silicon [31] (Table 2).

Table 1 Resistance to biotic stresses of some plant species treated with silicon [32]

Hosts	**Diseases**	**Pathogens**	**Resistance Mechanisms**
Rose	Powdery mildew	*Podosphaera pannosa*	Physical
Arabidopsis	Powdery mildew	*Erysiphe cichoracearum*	Physical, biochemical
Cucumber	Crown and root rot	*Pythium ultimum*	Biochemical
Cotton	Fusarium wilt	*Fusarium oxysporum*	Physical and biochemical
Lettuce	Downy mildew	*Bremia lactucae*	Physical and biochemical
Pea	Brown spot	*Mycosphaerella pinodes*	Biochemical
Potato	Dry rot	*Fusarium sulphureum*	Biochemical
Rice	Blast	*Pyricularia oryzae*	Physical, biochemical
Tobacco	Viral infection	*Tobacco ringspot virus*	Molecular

Table 2 Enzymes involved in the silicon-mediated resistance mechanism [32]

Hosts	**Diseases**	**Pathogens**	**Enzymes**
Pea	Leaf spot	*Mycosphaerella pinode*	Chitinase
Soybean	Target spot	*S Corynespora cassiicola*	Chitinases, peroxidases
Rice	Blast	*Magnaporthe oryzae*	Glucanase, peroxidase
Cucumber	Crown and root rot	*Pythium spp.*	Chitinase, peroxidases
Bean	Anthracnose	*Colletotrichum*	Superoxide dismutase

4. Silicon and plant resistance to abiotic stresses

Silicon fertilization can alleviate various abiotic stresses to which plants are frequently subjected, such as salinity, nutritional stress, metal poisoning, transplanting, drought, radiation, and thermal stress (Figure 1). Silicon can alleviate water stress by decreasing transpiration [33,34]. Transpiration in leaves occurs mainly through the stomata and cuticle. Si is deposited under the cuticle forming a protective layer that can slow down transpiration by up to 20-25%, as in some cereal crops. In horticulture, silicon stimulates photosynthesis in plants under salt stress, decreasing stomatal conductance and keeping transpiration rates stable. Experiments on cereals have shown a partial recovery of leaves treated with (PEG), which causes electrolyte leakage and lesions on the cell membrane following silicon treatments. Silicon can also protect plants from stress due to low temperatures and insolation. Silicon treatment can improve stem thickening, increasing culm wall thickness and the size of vascular bundles [35,36]. Si provided reduced water loss and increased tolerance to high temperatures as observed in some cereals where the loss of electrolytes, which occurs in these situations, was less pronounced following treatment with this mineral.

Figure 1 Effect of silicon treatment on the flowering of *Mammillaria cactus* following nutritional stress

An increase in yields and dry weight on cereals has been demonstrated even on soils with the low phosphorus content. Silicon in these situations can change the availability of P, its presence in the soil being in the form of silicic acid, which does not dissociate at pH levels below 8. Experiments show that silicon does not alter phosphorus uptake; on the contrary, an increase in Si guarantees greater internal mobility of phosphorus, distributed in inorganic form. Therefore, more beneficial effects of Si on plant growth under P deficiency conditions can be attributed to increased internal availability of P due to a reduction in Fe and Mn uptake. Silicon can alleviate the damage caused by P by reducing P-induced transpiration. It can also form deposits in the root cells of many species, creating a barrier to the movement of P from the roots. In vegetable plants that deposit silicon in the roots, a reduction in P uptake has been demonstrated [37,38]. The occurrence of desiccation in plants is significantly reduced in plants pre-treated with silicon, especially when nitrogen fertilization is high, which may contribute to increased stem breakage or increased susceptibility to disease [39]. Silicon applications allow a reduction in the protein content of some cereals. Si increases the oxidation of ferrous iron to ferric iron, reducing toxicity. Several studies have shown that silicon can decrease cadmium uptake and make plants more tolerant [40,41]. Some authors have reported silicate application prevents excessive Cd uptake in strawberries on sandy soil. In these plants, a low Cd concentration was found in the vegetative tissues but not in the roots. Aluminium (Al) toxicity is a significant factor limiting acidic soil production. Al in ionic form inhibits root growth and nutrient uptake. Silicon can minimize this problem, as observed in several kinds of cereal. The results showed that non-toxic Si and Al complexes form in the solution. The soothing effect of Si on aluminium toxicity varies between different plant species, probably due to differences in aluminium tolerance and different mechanisms that come into play.

5. Beneficial effects of silicon in salt stress

Beneficial effects of silicon addition in the case of salt stress have been found on various cereal, vegetable and ornamental crops, where shoot and root growth under conditions of high NaCl concentration can be improved by the addition of Si, which can halve the Na concentration in the tissue due to a reduction in induced transpiration [42]. Silicon can affect the structure, integrity and function of plasma membranes by modifying stress-dependent lipid peroxidation. Salt stress mitigation and enhanced antioxidant activity have been found in vegetable plants (Figure 2). No difference in water uptake was noted in salt-stressed plants, whereas in silicon-treated plants, the water content was increased by 50%. These results show that Si can improve water storage in plant tissue. Silicon is also able to improve light interception by increasing photosynthesis. This effect is essential in high-density cultivation and cases of high nitrogen fertilization. Silicon can promote cell elongation, probably due to Si-induced increased cell wall extensibility. Many data suggest a role for Si in increasing root elongation and forming mechanical barriers that make cell walls rigid [43].

Figure 2 Effect of silicon treatment on cabbage plants under salt stress conditions

6. Plants' ability to absorb silicon

The ability of plants to absorb silicon varies significantly between plant species (Figure 3). The extent of accumulation probably varies depending on the ability of roots to absorb Si. Roots absorb silicon as silicic acid when the pH in the solution is below 9. Test results indicate that Si concentrations in root cells are higher than in external solutions [44]. Kinetic studies have also shown that xylem loading is the primary determinant of high levels of Si accumulation in tissues. Studies on mutants deficient in Si uptake have shown that silicon uptake is significantly lower, while there is no difference in the uptake of other nutrients. After roots absorb, Si is translocated to the shoots via the xylem. Once in the shoots, the silicic acid concentrates, due to the loss of water, and polymerizes [45,46,47]. The polymerization process converts the silicic acid into the colloidal form and, finally, as the concentration increases, into silica gel. In plants, most of the Si is present in silica gel. The distribution of Si in tissues is controlled by transpiration [32]. Silicon accumulates more in older tissues because it is not mobile within the plant. Silicon uptake is a process that is probably controlled by several genes so studies will involve the isolation and characterization of genes for Si uptake in different species [48,49]. However, most plants cannot accumulate Si sufficiently to benefit from it. Genetic engineering techniques will be required to increase root uptake and tissue storage capacities to enhance the ability to overcome biotic and abiotic stresses.

Figure 3 Effect of silicon treatment on root growth of basil plants

7. Conclusion

Silicon is among the most abundant mineral elements in the soil. Several plants can accumulate it in their leaves and roots, with several benefits related to increased resistance to disease. Although it is considered a non-essential element, the benefits of plants treated with silicon are considerable. In particular through its ability to increase the resistance of plant species to various biotic and abiotic stresses. Plants benefit by accumulating it in their tissues, which results in increased mechanical strength and rigidity. However, it can also stimulate various defence mechanisms by actively increasing resistance to disease. Nevertheless, vegetable species differ in their ability to accumulate silicon due to the different abilities of roots to absorb this element. Genetic studies have revealed the presence of specific genes coding for Si transport. The encoded proteins have high specificity for silicon. Further studies on other genes and the implementation of molecular techniques will allow a better understanding of the mechanisms behind Si uptake. In many plants, this uptake mechanism does not work well, and the levels of silicon accumulated are not beneficial in defence against biotic and abiotic stresses. Only molecular biology studies and advanced genetic engineering techniques could lead these species to accumulate more significant quantities of Si, improving their resistance mechanisms.

Compliance with ethical standards

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