AgriCos e-Newsletter
ISSN: 2582-7049
AgriCos e-Newsletter
Open Access Multidisciplinary Monthly Online Magazine
Volume: 06 Issue: 01 January 2025 Article No: 04

Silicon in Pest Management: Mechanisms, Applications, and Future Prospects

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SUMMARY

Sustainable pest management is a critical component of modern agriculture, given the increasing concerns about environmental health, food security, and the adverse effects of chemical pesticides. One promising approach in this realm is the integration of silicon (Si) into pest management strategies. Silicon, recognized as a beneficial element for plant health, has been shown to enhance plant resistance to various biotic and abiotic stresses, including insect herbivory. The objectives of this article are to explore the role of silicon in plant physiology, its mechanisms in defending against insect pests, and its practical applications and limitations in agricultural settings. The significance of integrating silicon into insect pest management lies in its potential to reduce the reliance on chemical pesticides, mitigate pest resistance, and promote sustainable agricultural practices.

INTRODUCTION

Silicon, although not an essential nutrient, plays a significant role in plant growth, nutrition, and stress resistance (Epstein,1994). Plants absorb silicon primarily in the form of monosilicic acid ($Si(OH)_4$), which is soluble and readily available in the soil solution. Once absorbed, silicon is deposited as phytoliths (silica bodies) in plant tissues. These phytoliths act as a physical barrier against herbivores, pests, and pathogens, thereby enhancing the plant's defence mechanisms. Additionally, silicon strengthens cell walls and improves plant resilience to environmental stresses, such as drought, salinity, and heavy metal toxicity, by stabilizing plant structural integrity and promoting physiological balance (Epstein,2009).

Uptake and Deposition of Silicon in Plants

The uptake of silicon occurs through the roots and is an active process facilitated by specific silicon transporters. These transporters include influx transporters such as Lsi1 (a channel-type transporter) and efflux transporters like Lsi2 (an energy-dependent transporter), which work in tandem to mediate silicon movement into the root cells and its subsequent loading into the xylem (Ma *et al.* 2011). From the xylem, silicon is transported throughout the plant via the transpiration stream. Once it reaches various plant tissues, it is polymerized into silica ($SiO_2 \cdot nH_2O$) and deposited in areas such as the epidermal cells, cell walls, cuticles, and vascular tissues (Ma & Yamaji, 2015). This strategic deposition improves plant rigidity, reduces water loss, and creates a hostile environment for pathogens and pests. The accumulation of silicon varies significantly among plant species, with certain groups such as grasses (Poaceae) and horsetails (Equisetaceae) being more efficient silicon accumulators compared to dicots. This variation is largely due to differences in the expression and activity of silicon transporters (Mitani-Ueno & Ma, 2021).

Mechanisms of Silicon Absorption and Distribution

The absorption of silicon begins in the root epidermis, where the Lsi1 transporter facilitates the passive influx of silicic acid into root cells. Once inside, Lsi2 actively exports silicon into the stele for xylem loading (Ranjan *et al.* 2021). Environmental factors such as soil pH, temperature, and the availability of silicic acid significantly influence this process. In acidic soils, for example, silicon availability increases, enhancing its uptake.

Silicon-Mediated Plant Defence Mechanisms

Silicon plays a pivotal role in enhancing plant defence mechanisms against biotic stresses, particularly insect herbivory. These defences can be broadly categorized into physical barriers and biochemical changes, both of which interact synergistically to improve plant resistance.

Physical Barriers

One of the primary mechanisms by which silicon protects plants is through its role in strengthening plant tissues. Once absorbed as silicic acid, silicon is deposited as silica in cell walls, cuticles, and vascular tissues, where it fortifies structural integrity. This deposition enhances the rigidity and toughness of plant tissues, creating a formidable physical barrier that impedes insect feeding (Cai *et al.* 2009).

Increased Tissue Abrasiveness:

Silicon-enriched tissues are more abrasive, making it difficult for insects to chew or pierce plant surfaces. Chewing insects, such as caterpillars, experience increased wear and tear on their mandibles, which hampers their ability to consume plant material effectively. For piercing-sucking insects like aphids, the thickened epidermis reduces the ease of stylet penetration, thereby limiting nutrient extraction. This mechanical resistance results in reduced feeding efficiency, lower nutrient uptake, and slower growth rates for herbivores (Cai *et al.* 2009).

Reduced Palatability and Digestibility:

Silicon accumulation in plant tissues also decreases their palatability by altering texture and digestibility. The presence of silica particles can interfere with herbivore digestion, leading to lower nutritional benefits from plant consumption. Consequently, this discourages herbivores from feeding and contributes to their reduced fitness and survival (Cai *et al.* 2009).

Biochemical Changes

Beyond its role in forming physical barriers, silicon actively modulates plant biochemical pathways to enhance defence responses (Yu *et al.* 2022).

Induction of Defence-Related Genes:

Silicon application has been shown to upregulate the expression of genes associated with plant defence. These genes encode enzymes such as chitinases, peroxidases, and polyphenol oxidases, which degrade insect exoskeletons, detoxify reactive oxygen species, and strengthen cell walls, respectively (Singh *et al.* 2020).

Production of Secondary Metabolites:

Silicon-treated plants exhibit an increase in the synthesis of secondary metabolites, such as phenolics, flavonoids, and tannins. These compounds act as chemical deterrents to herbivores by interfering with their digestion and metabolic processes. For example, phenolic compounds can inhibit digestive enzymes in herbivores, while flavonoids serve as antioxidants that protect plant cells from oxidative damage (Ye *et al.* 2013).

Phytohormone-Mediated Defence:

Silicon enhances the plant's hormonal defence pathways, particularly those mediated by jasmonic acid (JA) and salicylic acid (SA). The JA pathway, which is triggered in response to insect herbivory, plays a critical role in activating defence genes and producing volatile organic compounds (VOCs) that repel herbivores or attract their natural enemies. Silicon also amplifies the crosstalk between the JA and SA pathways, ensuring a robust and coordinated defence response (Ye *et al.* 2013).

Silicon and Insect-Plant Interactions

The interaction between silicon, plants, and insect herbivores encompasses both direct and indirect effects, which collectively reduce herbivory and enhance plant resilience.

Direct Effects of Silicon on Insect Herbivores:

The deposition of silica in plant tissues directly impacts insect feeding behaviour. Chewing insects like caterpillars and grasshoppers experience significant mandibular wear, making it increasingly difficult to process plant material. Similarly, piercing-sucking insects such as aphids and whiteflies struggle to penetrate the hardened plant tissues, leading to reduced feeding efficiency and slower population growth. Over time, this direct interaction results in a decline in herbivore fitness and reproductive success (Reynolds *et al.* 2009).

Indirect Effects Through Enhanced Plant Defences:

Silicon indirectly influences insect-plant interactions by priming plants for enhanced defensive responses. Silicon application stimulates the production of defensive enzymes (e.g., lipoxygenases and protease inhibitors) and secondary metabolites that deter herbivores or inhibit their growth. Additionally, silicon-enriched plants emit higher levels of VOCs, which can attract natural enemies of herbivores, such as parasitoids and predators. For instance, parasitoid wasps are more likely to locate aphids on silicon-treated plants due to the altered volatile profile. This dual effect—reducing herbivore fitness while enhancing the efficacy of natural enemies—creates a more robust biological control system (Leroy *et al.* 2019).

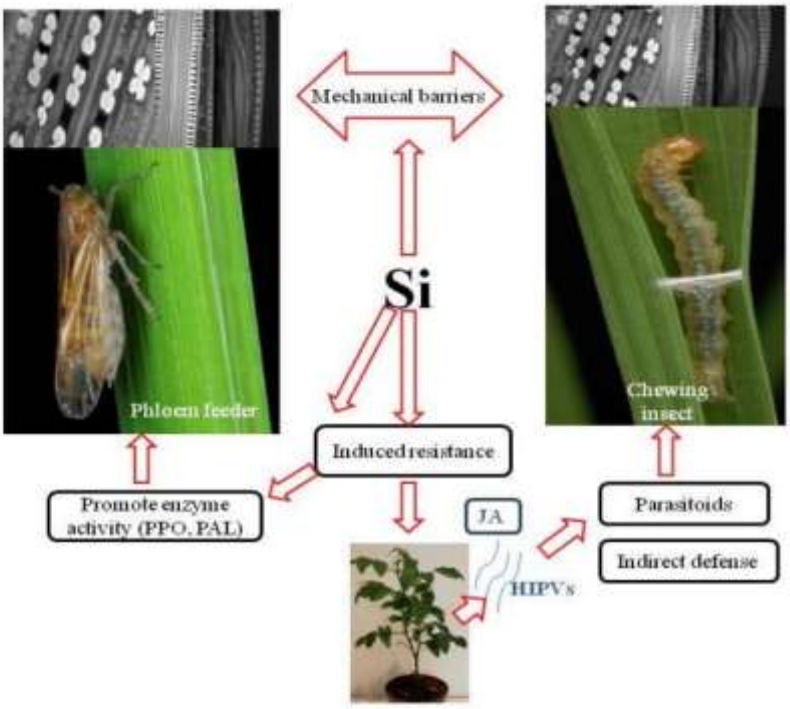

Fig: Silicon-Mediated Plant Defence Mechanisms

Application Methods and Practical Considerations of Silicon in Agriculture

Silicon supplementation in agriculture plays a crucial role in enhancing plant growth, strengthening physical and biochemical defences, and reducing pest and disease pressures. However, the practical application of silicon depends on multiple factors, including the mode of application, environmental conditions, and crop-specific responses.

Modes of Silicon Supplementation

Soil Amendments: As Silicate Fertilizers: Soil application of silicate-based fertilizers, such as calcium silicate, potassium silicate, or sodium silicate, is considered the most effective method for increasing silicon content in plant tissues. Once applied, these fertilizers release soluble silicic acid ($Si(OH)_4$), the plant-available form of silicon (Keeping, 2017). *Advantages*: Soil application ensures continuous uptake by plants through their root systems, particularly for silicon-accumulating crops like rice, sugarcane, and wheat. *Disadvantages:* The effectiveness of silicon uptake from soil amendments depends on factors such as soil pH, texture, and organic matter content. Silicon availability is higher in acidic soils but decreases in alkaline conditions.

Foliar Sprays: The foliar application involves spraying silicon solutions directly onto plant leaves. This method is particularly useful for crops grown in soils with low silicon availability or where soil application is not feasible (e.g., high pH soils) (Silva *et al.* 2023). *Advantages*: Foliar sprays offer a more immediate and targeted delivery of silicon to plant tissues, making it effective for short-term pest management and stress mitigation. *Disadvantages:* The limited translocation of silicon from leaves to other plant parts reduces its long-term effectiveness compared to soil amendments.

Factors Influencing Silicon Uptake

Multiple factors influence silicon uptake and its subsequent deposition in plant tissues:

Soil pH: Soil pH plays a significant role in determining the availability of soluble silicon. Silicon availability is highest in slightly acidic soils (pH 5.5–6.5) and decreases as pH rises. In alkaline soils, silicon forms insoluble compounds, limiting its uptake (Thakral *et al.* 2024).

Plant Species: Different plant species exhibit varying abilities to absorb and accumulate silicon. Plants can be categorized into: *High Silicon Accumulators*: Crops such as rice, sugarcane, wheat, and maize, actively absorb and store large amounts of silicon, *Intermediate Silicon Accumulators*: Crops like cucumber and pumpkin, which accumulate moderate levels of silicon, *Non-Accumulators*: Crops such as legumes and certain dicots that do not significantly absorb silicon, limiting the benefits of its application (Silva *et al.* 2023).

Environmental Conditions: Environmental factors such as temperature, soil moisture, and nutrient availability affect silicon uptake. High transpiration rates under warm and dry conditions can enhance silicon movement from roots to shoots.

Limitations and Challenges

Variability in Silicon Responsiveness: Silicon uptake and its benefits are highly variable across plant species. Silicon-accumulating plants, such as rice and sugarcane, respond well to silicon supplementation, whereas non-accumulators, like legumes and many dicots, show limited benefits.

Constraints in Non-Accumulating Crops: Non-silicon accumulating crops may not experience significant improvements in pest resistance or growth following silicon application, limiting its universal applicability.

Potential Trade-Offs with Other Agricultural Practices: While silicon has multiple benefits, excessive application may interfere with nutrient uptake, particularly phosphorus, and disrupt plant growth processes. Optimizing the timing, rate, and application method is essential to avoid such trade-offs.

Future Prospects and Research Directions

Advances in Understanding Silicon-Mediated Defence Mechanisms: Further research is needed to elucidate the molecular and biochemical pathways through which silicon enhances plant resistance. This includes understanding its interaction with phytohormones (e.g., jasmonic acid and salicylic acid) and its role in managing abiotic stresses, such as drought and salinity.

Development of Silicon-Efficient Cultivars: Breeding or genetically engineering crops with enhanced silicon uptake efficiency can improve the benefits of silicon application, even in non-accumulating species. This approach could enhance resilience to pests and environmental stresses while reducing input costs.

Use of Nanotechnology for Enhanced Silicon Delivery: Silicon nanoparticles (SiNPs) offer a promising alternative for efficient silicon delivery. SiNPs exhibit high reactivity and bioavailability, allowing for targeted delivery to plant tissues. They can suppress pathogen growth, reduce insect aggressiveness, and enhance plant defences more effectively than conventional silicon sources.

Large-Scale Field Validation Studies: While laboratory and greenhouse studies have demonstrated the benefits of silicon, large-scale field trials are needed to validate its efficacy across diverse agroecosystems. Long-term studies will also help assess the impacts of silicon application on soil health, crop yield, and pest dynamics.

CONCLUSION

Silicon holds significant potential in insect pest management by enhancing plant defence mechanisms, both physically and biochemically. While it offers several advantages, including sustainability and compatibility with IPM strategies, its application must be carefully considered in light of the variability in plant responses and potential trade-offs with other agricultural practices. Interdisciplinary research and practical implementation are crucial for optimizing the use of silicon in agriculture. By advancing our understanding of silicon-mediated plant defence mechanisms and developing more efficient methods of silicon delivery, we can further integrate silicon into sustainable agricultural practices, contributing to a more environmentally friendly and resilient food production system.

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