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Silicon Mediated Post Harvest Protection: Mechanisms and Applications

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Abstract

Silica (Si) is a beneficial element that enhances plant resilience, productivity and postharvest stability. Although abundant in soil, its bioavailable form monosilicic acid (H_4SiO_4) is limited. Si uptake varies across plant species with high accumulators found in Poaceae, Equisetaceae, and Cyperaceae. Once absorbed, Si is deposited in cell walls, improving structural integrity and stress tolerance. It mitigates abiotic stress by regulating water balance, ion homeostasis, and antioxidant activity, it also enhances resistance against biotic stress through physical and biochemical defenses. In postharvest management, Si strengthens structural barriers, reduces ethylene biosynthesis, enhances antioxidant defense mechanisms, delay senescence and minimize deterioration. Studies have demonstrated its effectiveness in extending the shelf life of crops such as bananas, avocados and papayas by reducing respiration rate and pathogen-induced decay. Silicon-based treatments offer a sustainable alternative to synthetic preservatives, contributing to food security and reduce postharvest losses. Further research is needed to optimize Si formulations, application methods and molecular pathways to enhance its efficacy in crop management and storage.

Keywords: Silica, Plant Resilience, Postharvest Management, Shelf Life, Antioxidant Defense, and Sustainable Agriculture

Introduction

Elements are crucial for the survival and development of living organisms. Among the 92 naturally occurring elements, 17 are recognized as vital for plant growth and are categorized into macronutrients and micronutrients. Additionally, some elements, though not universally essential, support growth in specific plant groups and are referred to as beneficial elements. These include aluminum (Al), cobalt (Co), sodium (Na), selenium (Se) and silicon (Si) which

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aid plant adaptation and productivity under certain environmental conditions with their roles and required concentrations differing across species.

Silicon (Si), is the seventh most abundant element in the universe and the most predominant tetravalent metalloid in soil. In soil solutions, Si primarily exists as monosilicic acid (H_4SiO_4). Despite its abundance, Si is predominantly found in complexed forms as oxides and silicates rather than in a readily bioavailable state. The agronomically crucial form of Si for plant uptake is monosilicic acid. Plants exhibit substantial variation in Si accumulation, species within the Poaceae, Equisetaceae and Cyperaceae families are classified as high accumulators (>4%) while members of Cucurbitaceae, Urticaceae and Commelinaceae demonstrate moderate accumulation (2%–4%). Silicon is absorbed by plant roots as monosilicic acid and translocated to shoots where it polymerizes into amorphous silica and form protective layers in cell walls. Consequently, Si serves as a pivotal element in plant physiology, stress adaptation and sustainable agricultural productivity.

The Science of Silica: Enhancing Crop Resilience, Productivity and Shelf Life

Silicon nutrition has been extensively documented to enhance plant growth, yield and fortify tolerance against abiotic and biotic stresses. Silicon plays a crucial role in mitigating various abiotic stresses in plants, enhancing their resilience to adverse environmental conditions. It improves drought tolerance by reducing transpiration, maintaining water balance, and enhancing root growth. Silicon also strengthens plant cell walls, increasing resistance to lodging and salinity stress by regulating ion uptake and minimizing sodium accumulation. In cold stress conditions, it stabilizes membrane integrity and enhances antioxidant enzyme activity, reducing oxidative damage. Moreover, silicon alleviates heavy metal toxicity by limiting metal uptake and promoting detoxification mechanisms. It regulates nutrient balance, enhances photosynthetic efficiency, and improves chlorophyll content under stress conditions. Silicon also boosts resistance against UV radiation, temperature fluctuations, and oxidative stress by modulating metabolic pathways. Additionally, it promotes osmotic adjustment and enhances proline accumulation in plants facing water scarcity. The beneficial effects of silicon on plant physiology make it a valuable tool for sustainable crop management. Its strategic application can significantly enhance stress tolerance, improve crop productivity, and ensure food security. It reduces oxidative damage and maintain plasma membrane integrity by scavenging the reactive oxygen species (ROS) and boosts antioxidant enzyme activity. It also regulates ion homeostasis by restricting sodium uptake and enhancing the K/Na selectivity ratio. Computational studies reveal conserved aquaporin-like domains and NPA motifs in Si transporters, contributing to stress tolerance in plants. These benefits collectively sustain physiological functions and enhance crop productivity under stress conditions.

The application of silicon in postharvest management has demonstrated significant potential in enhancing produce quality, reducing postharvest losses and improving storage stability. Through its dual role in strengthening structural barriers and activating plant defense mechanisms, silicon effectively mitigates pathogen induced deterioration and extends shelf life. These benefits make silicon-based treatments a promising alternative to synthetic preservatives, aligning with sustainable agricultural practices.

Enhancing Post-Harvest Stability Through Silicon Supplementation: Mechanisms and Applications

Fresh fruits and vegetables play a crucial role in global nutrition, health, food security and economic development. However, these perishable commodities suffer from significant postharvest losses. Over the years, extensive research and innovative strategies have been explored to mitigate these losses and enhance the shelf life of fresh produce. Among these approaches, the application of silica has emerged as a promising solution for reducing postharvest deterioration and improving produce quality.

Silicon has been widely studied for its role in improving postharvest quality in crops such as rice, legumes, vegetables and fruits. Silicon-based compounds effectively reduced the postharvest disease severity and extend shelf life. Silicon enhances plant resistance to fungal diseases through two primary mechanisms. Firstly, it accumulates in cell walls, creating a structural barrier that restricts pathogen penetration (physical defense). Secondly, silicon actively stimulates the plant’s innate defense responses, enhancing resistance to infections. Researchers proved that silicon application has been shown to promote plant growth, yield and enhance overall quality compared to untreated plants. It also minimizes postharvest weight loss, reduces produce decay and extends shelf life during storage.

Research on ‘Hass’ avocado found that potassium silicate-maintained fruit quality by infiltrating the mesocarp. Sodium silicate dip treatments also improved storage life in papaya, apple, muskmelon and Chinese cantaloupe. Silica helps to reduce fungal infections and enhance fruit firmness. Various silicon formulations, including calcium silicate and biosilicate have shown promising results. Studies confirm that silicon application strengthens cell walls and delays senescence. Its role in postharvest management makes it a sustainable alternative to synthetic preservatives. Silicon based strategies improve marketability and reduce postharvest losses.

Silicon promotes polyamine synthesis and suppressing ethylene production. Ethylene and polyamine biosynthetic pathways exhibit metabolic competition due to their shared precursor, methionine. Silicon modulates this pathway by downregulating ethylene and 1-aminocyclopropane-1-carboxylic acid (ACC) synthesis, thereby influencing physiological responses. Si regulates PpERF21 and PpERF27 expression, inhibiting PpPG1 transcription and reducing polygalacturonase activity, thereby prevent quick ripening and post harverst loss.

Silicon treatment considerably reduced ethylene production, respiration rates and fungal rot development as compared to untreated control in banana. Si-treated fruit exhibited a substantially higher total soluble silicon content in peel. However, Si treatment had no significant effect on total Si content, total soluble solids and titratable acidity in banana pulp. Silica, effectively extending shelf life while preserving the organoleptic properties of the fruit.

Silicon imparts positive effect on antioxidant defense system. Silicon nutrition promotes the production of antioxidants and detoxifying enzymes that eliminate free radicals. Silicon enhances produce resilience by strengthening the antioxidant defense system and reduce post-harvest losses. Silicon optimizes water retention, limits transpiration and reinforces cell walls. Its deposition in epidermal layers forms a cuticle-silica composite that reinforces cellular structure and acts as a barrier against pathogens. This fortification increases fruit firmness, reduces enzymatic degradation and delays senescence. Si treatments effectively mitigate postharvest decay in fruits and vegetables.

Conclusion

Integrating silica into postharvest management offers a sustainable approach to reducing losses and improving fruit marketability. Further research is needed to optimize silicon formulations, delivery methods and application timings for different crops. The variability in silicon uptake across plant species and environmental conditions warrants in-depth studies to refine its agronomic utilization. Moreover, exploring nanotechnology-based silicon applications and integrating silicon treatments with other postharvest management strategies could enhance efficacy. Future research should also focus on the molecular mechanisms underlying silicon-induced stress resilience to develop targeted interventions for improving postharvest stability. Expanding the commercial adoption of silicon-based technologies will contribute to reducing global food losses, ensuring food security and promoting sustainable supply chains in the fresh produce industry.

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