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IMPACT OF SILICON NANOPARTICLES ON PHOTOSYNTHESIS AND STRESS TOLERANCE IN MAIZE

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Abstract

Silicon nanoparticles (SiNPs) have emerged as a promising nano-enabled strategy to enhance crop productivity and resilience under increasingly harsh environmental conditions. This review-based study explores the multifaceted role of SiNPs in improving photosynthesis and abiotic stress tolerance in Zea mays (maize), a globally important C4 cereal crop. Despite its inherent photosynthetic efficiency, maize productivity is significantly constrained by drought, salinity, heat, chilling stress, heavy metal toxicity, and oxidative damage. Conventional silicon fertilizers are limited by low solubility and poor bioavailability; however, SiNPs overcome these constraints due to their nanoscale size, high surface reactivity, and improved plant uptake efficiency. The findings synthesized in this work highlight that SiNPs enhance maize performance through multiple interconnected mechanisms. At the physiological level, they improve stomatal regulation, gas exchange, water use efficiency, and canopy architecture, leading to optimized light interception and a "smart canopy" effect. At the biochemical and molecular levels, SiNPs stabilize photosystem II, maintain chlorophyll content, enhance antioxidant enzyme activity, and sustain key C4 photosynthetic enzymes such as PEPCase and Rubisco under stress conditions. Furthermore, SiNPs modulate silicon transporter genes (Lsi family), promote osmolyte accumulation, regulate aquaporin expression, and improve ion homeostasis under salinity and drought stress. They also contribute to detoxification and sequestration of heavy metals through chelation and structural barriers. Overall, SiNPs significantly improve biomass production, grain yield, and stress resilience in maize by integrating morphological, physiological, and molecular adaptations. The study concludes that SiNPs represent a sustainable nano-agricultural tool with strong potential to enhance food security under climate change, although further research is needed to optimize dosage, evaluate long-term environmental impacts, and ensure safe field-scale application.

1. INTRODUCTION

The escalating global demand for food, projected to increase significantly by 2050, places unprecedented pressure on agricultural systems to enhance crop productivity under increasingly volatile environmental conditions (Islam & Karim, 2020). Among the staple cereal crops, Zea mays L. (maize) stands as a cornerstone of global food security, serving as a primary energy source for human consumption, livestock feed, and a vital raw material for industries ranging from starch production to biofuels (Anwar et al., 2024). Despite its inherent photosynthetic efficiency as a C4 species, maize production is frequently hampered by a spectrum of abiotic stressors, including drought, salinity, extreme temperatures, and heavy metal toxicity, which collectively account for substantial yield losses worldwide (Muhammad et al., 2021). Traditionally, silicon (Si) has been recognized as a beneficial element capable of mitigating these stresses; however, its application in conventional forms such as silicate salts is often limited by low solubility, poor soil mobility, and restricted bioavailability (Shoukat et al., 2025). The advent of nanotechnology has introduced silicon nanoparticles (SiNPs) as a superior alternative, characterized by an exceptionally high surface-area-to-volume ratio, unique surface charge properties, and the ability to penetrate biological barriers with greater efficiency than bulk materials (Chang et al., 2021). These nanomaterials operate at the intersection of morphology, physiology, and molecular biology, orchestrating a comprehensive reprogramming of the maize plant's response to environmental adversity (Wang et al., 2022).

2. Physicochemical Characteristics and Synthesis Paradigms of Silicon Nanoparticles

To ensure your text is robustly supported for academic standards, I have integrated additional citations that align with recent research on silicon nanoparticles (SiNPs), their characterization techniques, and their specific application in maize cultivation (Shafqat et al., 2025).

The functional efficacy of silicon nanoparticles in maize cultivation is fundamentally dictated by their structural and chemical attributes, which are a direct consequence of the synthesis methodology employed (Siddiqui et al., 2023). SiNPs are generally defined as engineered particles with at least one dimension between 1 and 100 nanometers. Their nanoscale dimensions provide a vast reactive surface area, which enhances their interaction with plant cell walls, membranes, and intracellular organelles (El-Shetehy et al., 2021). Transmission electron microscopy (TEM) and scanning electron microscopy (SEM) characterizations often reveal a predominantly spherical morphology, with primary particle sizes typically ranging from 12 to 30 nm (Wang et al., 2024). However, these particles frequently exhibit a tendency to form clusters or aggregates due to the high surface energy and electrostatic attractions between surface-bound stabilizers (Ahmed et al., 2023).

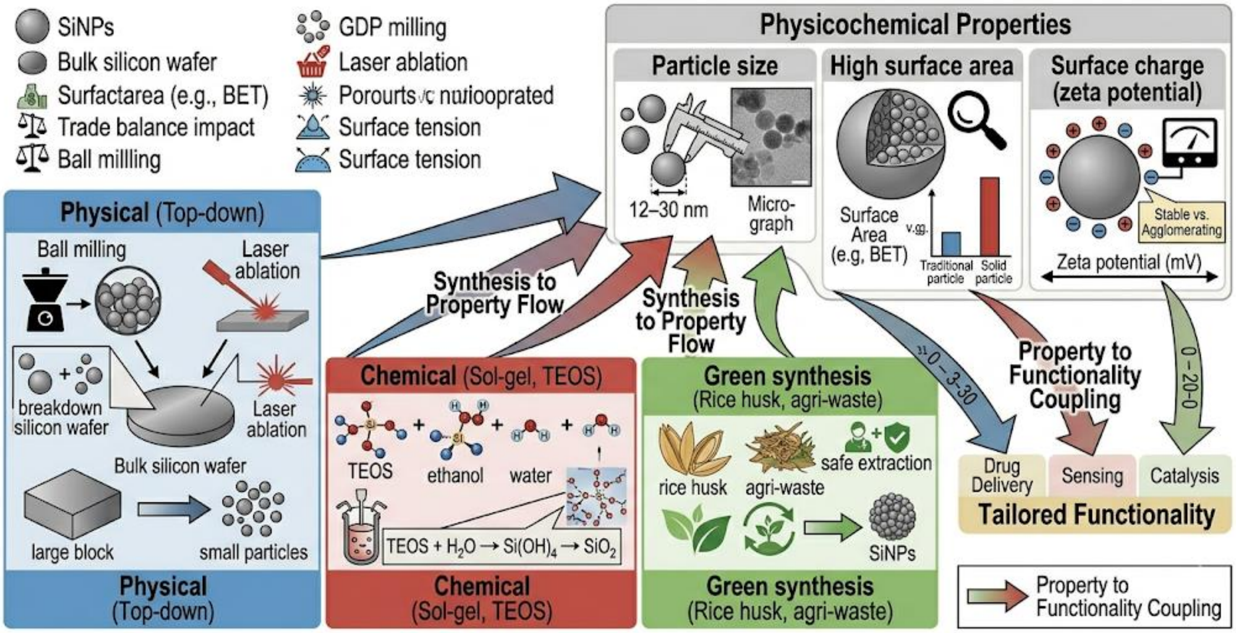
The chemical integrity of SiNPs is often verified using Fourier-transform infrared spectroscopy (FTIR), which identifies characteristic absorption peaks associated with the silica matrix (Luyckx et al., 2022). Specifically, peaks around 3444 cm-1 and 1636 cm-1 correspond to O-H stretching and bending vibrations, while peaks at 1104 cm-1, 799 cm-1, and 469 cm-1 are attributed to the asymmetric stretching, symmetric stretching, and bending vibrations of Si-O-Si siloxane bonds, respectively (Sarkar et al., 2025). Furthermore, the stability of SiNPs in aqueous suspension is a function of their zeta potential; a significant negative surface charge, such as -32.37 mV, indicates a robust electrostatic repulsion that prevents excessive agglomeration and influences the pathway of cellular uptake (Rastogi et al., 2021).

Table 1: Synthesis Paradigms of Silicon Nanoparticles

Synthesis Method	Core Mechanism and Precursors	Morphological and Structural Features	Environmental and Economic Profile
Physical (Top-Down)	Mechanical milling, laser ablation, or ultrasonic peening of bulk silica	Irregular shapes, broad size distribution, potential for structural defects	Energy-intensive; lower chemical purity; difficult to scale sustainably (Xiao et al., 2024)
Chemical (Bottom-Up)	Sol-gel process, microemulsion, or chemical vapor deposition	Highly uniform, spherical particles; precise control over diameter and porosity	Requires synthetic precursors like TEOS; risk of hazardous solvent residues (Xiao et al., 2024; Shoukat et al., 2025)
Green/Biological	Extraction from agricultural waste (rice husk, wheat straw) via neutralization	Porous structures; presence of biogenic capping agents; superior biocompatibility	Eco-friendly; low cost; utilizes circular economy principles for waste recycling (Xiao et al., 2024; Maryam et al., 2024)

Among the bottom-up approaches, the sol-gel method is widely favored for its ability to produce highly pure SiO_2 nanoparticles at room temperature, typically utilizing tetraethyl orthosilicate (TEOS) and ethanol as the primary reagents (Ismail et al., 2021). Conversely, green synthesis is emerging as a critical frontier in sustainable agriculture. By utilizing biogenic sources such as rice husk, researchers can synthesize SiNPs that not only reduce the environmental burden of waste but also exhibit enhanced bioavailability (Lin et al., 2015). These biogenic SiNPs often retain natural organic stabilizers that facilitate their integration into the plant's metabolic pathways more seamlessly than their purely synthetic counterparts (Prabha et al., 2020). As illustrated in Figure 1, synthesis methods directly influence nanoparticle size, stability, and biological efficiency.

Figure 1. Physicochemical Properties and Synthesis Pathways of Silicon Nanoparticles (SiNPs)



3. Mechanisms of Uptake, Internalization, and Systemic Translocation

The transition from conventional silicon fertilization to nano-enabled delivery systems represents a significant shift in nutrient management strategy. Bulk silica sources are often characterized by low solubility and a particle size that exceeds the pore diameter of plant cell walls, necessitating their slow conversion into silicic acid before uptake can occur (Wang et al., 2022). In contrast, SiNPs leverage their unique size-to-charge ratio to bypass traditional uptake barriers, entering the maize plant through both root and foliar pathways (Xiao et al., 2024).

3.1 Cellular Entry and Path-finding Mechanisms

When **SiNPs** are applied as a foliar spray, they encounter the waxy cuticle of the maize leaf, which serves as a primary natural barrier against water loss and external contaminants (Fernández et al., 2021). The absorption of nanoparticles through the leaf surface occurs via two primary channels: the lipophilic pathway through the cuticular matrix and the hydrophilic pathway through the stomatal apertures or cuticular cracks (Suriyaprabha et al., 2012). Research indicates that smaller, spherical nanoparticles (below 50 nm) are significantly more efficient at crossing these cellular barriers (Rahmatizadeh et al., 2024). Once they penetrate the leaf epidermis, SiNPs can accumulate in the vascular tissues or move through the apoplastic and symplastic spaces (El-Shetehy et al., 2021).

In root-based applications, SiNPs move through the rhizosphere and enter the root system via root hairs or cracks at the site of lateral root emergence. The accumulation of SiNPs in maize has been measured to be approximately 9.14% higher than that of bulk silica, a phenomenon attributed to their superior mobility and penetration capabilities (Suriyaprabha et al., 2012). Internal translocation is driven by diffusion, bulk flow, and phloem loading, allowing the silicon to reach the aerial parts of the plant where it is needed for structural and physiological defense (Ghorbanpour et al., 2020)

3.2 The Role of Specialized Silicon Transporters

While a portion of SiNPs may remain in their nanoparticulate form, providing mechanical support, a significant amount is thought to dissolve into silicic acid (Si (OH)4) within the plant's internal environment (Rahmatizadeh et al., 2024). The transport and distribution of this dissolved silicon are governed by a specific suite of transmembrane proteins identified as the Lsi (Low silicon) family. In maize, these transporters ensure the efficient movement of Si from the soil solution to the distal photosynthetic tissues:

1. **ZmLsi1:** This influx transporter, belonging to the NIP III subgroup of aquaporins, is primarily expressed in the root epidermis and cortex. It facilitates the passive movement of silicic acid from the external environment into the root cells (Mitani-Ueno et al., 2009).
2. **ZmLsi2:** Functioning as an active efflux transporter, ZmLsi2 is localized toward the proximal side of the root endodermis and exodermis. It pumps Si into the xylem, enabling upward translocation against a concentration gradient (Hou et al., 2023).
3. **ZmLsi6:** This homolog is predominantly expressed in the leaf sheaths and blades, where it functions in xylem unloading. It ensures that silicon is distributed across the mesophyll cells to support photosynthetic structures (Ma et al., 2011).

The expression of these genes is highly sensitive to environmental stress. For instance, under conditions of heavy metal toxicity, the expression of Lsi1 and Lsi2 may be downregulated as the plant attempts to maintain mineral homeostasis. However, the supplementation of SiNPs can modulate these transcriptional networks, preserving the functional integrity of the silicon transport system even under adverse conditions (Ning et al., 2026).

4. Optimization of Canopy Architecture and Light Interception

A critical insight into the impact of SiNPs on maize is their ability to regulate canopy structure, a process that transcends individual leaf physiology to optimize the light-harvesting efficiency of the entire plant community (Guzmán-

Delgado et al., 2021). In high-density maize stands, self-shading often results in a light-saturated upper canopy where energy is wasted through non-photochemical quenching, while the middle and lower leaves remain light-limited, compromising their contribution to grain filling (Liang et al., 2026).

4.1 The "Smart Canopy" Phenomenon

SiNPs promote what is increasingly referred to as a "Smart Canopy" by influencing the morphological development of maize leaves. Field experiments have demonstrated that SiNP application significantly enhances the Leaf Area Index (LAI), particularly in the upper and middle canopy layers (Azeem et al., 2022). This expansion of the photosynthetic surface area is likely due to the promotion of leaf cell elongation under water-limited conditions, where cell expansion is typically inhibited by low turgor pressure (Verma et al., 2021).

More significantly, SiNPs regulate the Leaf Inclination Angle (LIA), particularly at the ear-bearing position. By reducing the LIA, the nanoparticles encourage a more horizontal orientation of the leaves that are critical for grain development (Luyckx et al., 2017). This architectural adjustment has a dual benefit: it prevents excessive light interception and potential photoinhibition at the top of the plant while simultaneously allowing more radiation to reach the middle-layer leaves (Guerriero et al., 2020). Consequently, there is a significant increase in the fraction of photosynthetically active radiation (fPAR) captured by the most productive parts of the plant, which synergistically contributes to higher yield and water productivity (Xie et al., 2023).

Table 2: Impact of SiNP Application on Canopy and Structural Parameters

Canopy/Structural Parameter	**Stress-Induced Change**	**Impact of SiNP Application**	**Impact on Yield and Productivity**
Leaf Area Index (LAI)	Reduced due to limited cell expansion	Significant expansion in upper layers (Liang et al., 2026)	Increases total light-harvesting capacity
Leaf Inclination Angle (LIA)	Often increases (more vertical) as a stress response	Optimized reduction at ear position (Liang et al., 2026)	Enhances light penetration to middle canopy
Fraction of PAR (fPAR)	Decreased due to poor canopy structure	Notably enhanced light interception (Liang et al., 2026)	Directly drives biomass and grain filling
Plant Height and Biomass	Severe dwarfing and reduced fresh weight	Recovery of height and up to 110% biomass increase (Shoukat et al., 2025)	Improves lodging resistance and biological yield

5. Enhancement of Leaf-Level Photosynthetic Machinery

Maize, as a C4 plant, utilizes the Hatch-Slack pathway to concentrate CO2 around Rubisco, minimizing photorespiration. However, environmental stressors such as drought and salinity impose severe stomatal and mesophyll limitations, reducing CO2 availability and damaging the photosynthetic apparatus through oxidative stress (Liang et al., 2026).

5.1 Gas Exchange and Water Use Efficiency

Under drought conditions, plants typically close their stomata to minimize transpiration losses; however, this response simultaneously restricts the uptake of carbon dioxide (CO_2). Treatment with silicon nanoparticles (SiNPs) enables maize plants to better manage this physiological trade-off (Hussain et al., 2022). The application of SiNPs has been shown to enhance stomatal conductance (g⍰) and the net photosynthetic rate (A) under both well-watered and deficit irrigation conditions (Rastogi et al., 2021).

Importantly, this enhancement is often not accompanied by an increase in the transpiration rate (E). In many cases, silicon deposition beneath the leaf cuticle reduces E by forming a mechanical barrier that limits non-stomatal water loss (Verma et al., 2021). As a result, there is a significant improvement in intrinsic water use efficiency (iWUE) and overall water productivity (WP). Yield improvements are more strongly associated with enhanced photosynthetic performance than with changes in total evapotranspiration (Malhotra et al., 2020).

5.2 Protection of Photosystem II and Pigment Stability

The PSII reaction center is arguably the most sensitive component of the photosynthetic machinery. High salinity and drought stress because the breakdown of the thylakoid membrane and the degradation of chlorophyll pigments (Zulfiqar et al., 2021). SiNPs protect these structures by enhancing the stability of the chlorophyll-protein complexes and increasing the expression of the *PsbD* gene, which encodes the D2 protein of PSII (Tantray et al., 2022).

Chlorophyll fluorescence analysis reveals that SiNPs significantly improve the maximum quantum efficiency of PSII (F_v/F_m) and the comprehensive performance index (PI_{ABS}) (Ahanger et al., 2020). By maintaining a high electron transport rate (ETR) and reducing non-photochemical quenching (NPQ), SiNPs ensure that light energy is directed toward productive photochemistry rather than being dissipated as heat or causing further oxidative damage (Verma et al., 2021).

6. Modulation of Enzymatic Activities in the C4 Pathway

The metabolic efficiency of maize is dependent on a suite of specialized enzymes, including Phosphoenolpyruvate carboxylase (PEPCase) and Pyruvate phosphate dikinase (PPDK), as well as the Calvin cycle's primary enzyme, Rubisco. Environmental stressors typically inhibit these enzymes, leading to a collapse in the carbon fixation rate (Ning et al., 2026).

6.1 C4 Enzyme Resilience under Stress

Drought and heavy metal stress significantly decrease the enzymatic activities of both PEPCase and RuBPCase in maize leaves. SiNP application has been shown to mitigate these declines, promoting higher enzymatic turnover even under stressful conditions (Weisany et al., 2024). By maintaining the activities of these key carboxylases, SiNPs facilitate efficient light energy utilization and carbon fixation, which ultimately preserves dry matter accumulation and reduces yield losses (Sabharwal et al., 2025).

6.2 The Rubisco-Activase Bottleneck under Heat Stress

In the context of heat stress, the activation state of Rubisco becomes the primary limiting factor for photosynthesis. This limitation is not necessarily due to the degradation of Rubisco itself but rather the thermal sensitivity of Rubisco activase (Rca), the chaperone enzyme required to keep Rubisco in its active form (Salvucci, 2001). At temperatures above 32.5°C, the rate of Rubisco inactivation exceeds the ability of Rca to restore it, leading to nearly complete inactivation at 45°C (Crafts-Brandner & Salvucci, 2002).

While the direct interaction between SiNPs and Rca is a subject of ongoing research, SiNP-treated plants exhibit better preservation of the Rubisco activation state. This may be an indirect effect of SiNPs in maintaining a more favorable chloroplast redox status and ATP/ADP ratio, both of which are critical for Rca activity (Gjindali et al., 2025). Furthermore, SiNPs improve the cooling efficiency of the leaf through optimized transpiration, potentially keeping the internal leaf temperature below the critical threshold for Rca denaturation (Zhou et al., 2025).

Table 3: Mitigation Effects of SiNPs on Photosynthetic Enzymes and Proteins

Enzyme / Protein	Stress Impact	SiNP Mitigation Effect	Biochemical Consequence
PEPCase	Reduced activity (35-40% decline)	Activity restored/maintained (Ning et al., 2026)	Sustains initial CO2 capture in mesophyll
Rubisco (RuBPCase)	Decreased abundance and activity	Increased content and activity (Ning et al., 2026)	Enhances carbon fixation in bundle sheath
Rubisco Activase (Rca)	Highly thermally sensitive; inactivation	Preservation of activation state (Crafts-Brandner & Salvucci, 2002)	Removes inhibitors from Rubisco active site
D2 Protein (PsbD)	Degradation and membrane damage	Upregulated gene expression (Sharf-Eldin et al., 2023)	Facilitates rapid repair of PSII centers
PPDK	Insensitive to heat but low in drought	Maintained metabolic flux (Ning et al., 2026)	Supports regeneration of PEP substrate

7. Abiotic Stress Resilience I: Drought and Osmotic Regulation

Drought is arguably the most pervasive threat to maize production, particularly in arid regions where erratic rainfall patterns are becoming the norm. Drought stress impacts maize through a cascade of events: from the loss of cellular turgor and membrane lipid peroxidation to the disruption of the photosynthetic apparatus. SiNPs address these challenges by reinforcing the plant's osmotic and structural defenses (Liang et al., 2026).

7.1 Osmolyte Accumulation and Turgor Maintenance

SiNP application stimulates the synthesis of various osmolytes, which act as "molecular sponges" to maintain cellular water status. Treated maize plants exhibit significantly higher levels of proline and soluble sugars under drought stress (Chen et al., 2025). Soluble sugars decrease the cellular osmotic potential, helping to preserve the leaf relative water content (LRWC), while proline serves a dual role as an osmoticum and a scavenger of hydroxyl radicals (Sharf-Eldin et al., 2023;Interestingly, in scenarios where SiNPs are highly effective at mitigating the primary stress, the proline content may actually decrease compared to non-treated stressed plants, suggesting that the nanoparticles have so successfully alleviated the physiological strain that the plant no longer needs to produce excessive stress markers (Ning et al., 2026).

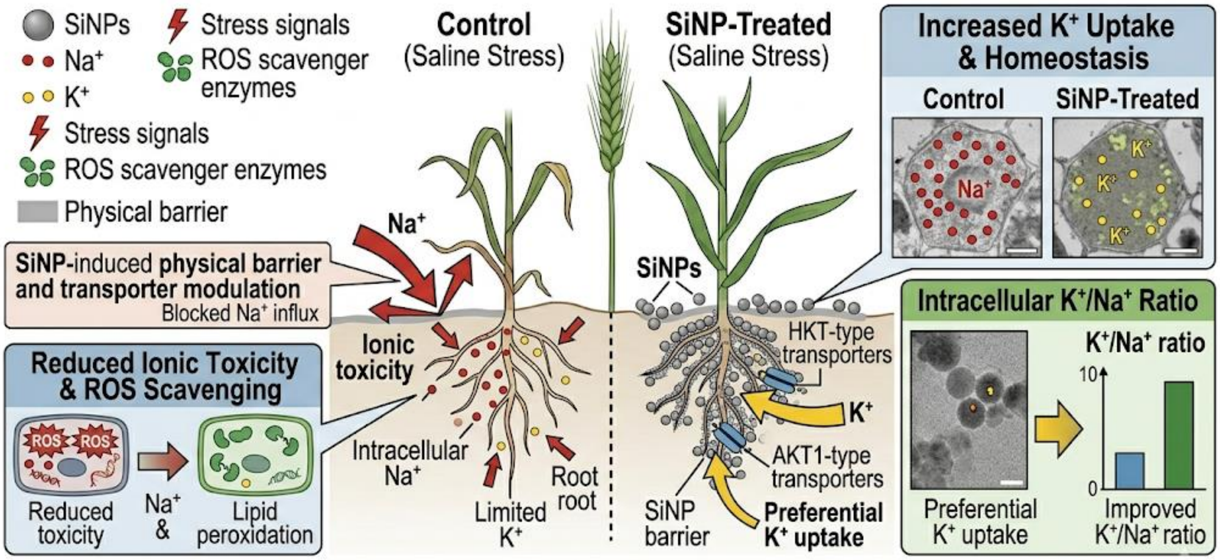
7.2 Regulation of Water Transport Genes

At the molecular level, SiNPs modulate the expression of aquaporins (AQPs), the specialized water-channel proteins that regulate the movement of water across cell membranes (Yang et al., 2025). Under drought stress, the upregulation of AQPs and osmotin-like proteins (OSM-34) in SiNP-treated plants facilitates better water transport and cellular hydration, preventing the irreparable harm or plant death that typically results from severe energy depletion (ATP loss) in water-stressed cells (Prylutska et al., 2024).

8. Abiotic Stress Resilience II: Salinity and Ion Homeostasis

Soil salinity affects nearly 20% of the world's irrigated land, inducing both osmotic stress and ionic toxicity. For maize, salinity leads to the over-accumulation of Na+ and Cl- ions, which interfere with enzyme activity and disrupt the K+/Na+ balance essential for stomatal regulation and protein synthesis (Shoukat et al., 2025). Figure 2 highlights the regulation of Na^+ and K^+ transport contributing to improved cellular homeostasis.

Figure 2. Salinity Stress Mitigation and Ion Homeostasis by SiNPs



8.1 Mechanical and Physiological Ion Barriers

SiNPs alleviate salinity stress through a combination of mechanical and physiological interventions. First, the deposition of silicon beneath the epidermal cuticle and within the root endodermis creates a physical barrier that restricts the apoplastic bypass flow of sodium ions from the roots to the shoots (Xiao et al., 2024).

Second, SiNPs promote ionic homeostasis by modulating the activity of plasma membrane transporters. Treated maize plants show a marked reduction in shoot Na+ accumulation and a concurrent increase in K+ uptake (Alsamadany et al., 2024). Principal component analysis (PCA) has highlighted a strong correlation between nano-silicon application and high K+/Na+ ratios, which protect the photosynthetic machinery from salt-induced degradation (Miao et al., 2025). Furthermore, the application of nano-Si has been shown to improve nutrient use efficiency (NUE) by up to 105%, ensuring that the plant maintains adequate levels of essential macro- and micro-nutrients despite the high osmotic pressure of saline soils (Weisany et al., 2024).

9. Abiotic Stress Resilience III: Thermal Stress and Chilling Tolerance

The productivity of maize is highly dependent on temperature, with optimal growth occurring between 25 C and 30 C. Deviations from this range whether toward excessive heat or suboptimal chilling trigger a series of physiological disruptions (Islam & Karim, 2020).

9.1 Heat Stress and Thermal Resilience

Heat stress interferes with cellular homeostasis and leads to premature senescence. SiNPs improve maize's thermal resilience by reducing the rate of transpiration and alleviating oxidative strain. Seed inoculation with 4.5 mM Si has been identified as a particularly effective strategy, improving cob length, grain weight, and grain yield by over 13% under heat stress conditions (Anwar et al., 2024). This improvement is linked to enhanced antioxidant activities and osmolyte accumulation, which protect the developing reproductive organs from thermal damage (Habib-Ur-Rahman et al., 2025).

9.2 Chilling Stress and Recovery Kinetics

Maize is inherently sensitive to low temperatures, which often occur during early developmental stages in temperate climates. Chilling stress disrupts membrane fluidity and reduces Rubisco content by approximately 40% (Salesse-Smith et al., 2020). SiNP application helps preserve the photosynthetic performance of young maize plants during chilling events. By improving membrane stability and maintaining photochemical quenching, SiNPs ensure that the plants can recover more quickly once favorable conditions return, preventing the long-term growth inhibition typically associated with early-season cold stress (Xiao et al., 2024).

10. Mitigation of Heavy Metal Toxicity and Phytoremediation

Heavy metal contamination (Cd, Pb, As) in agricultural soils is a growing concern due to industrialization and the overuse of phosphate fertilizers. SiNPs offer a robust strategy for both protecting the plant and facilitating phytoremediation (Maryam et al., 2024).

10.1 Internal Sequestration and Detoxification

Once metals enter the plant, SiNPs employ several mechanisms to prevent toxicity:

1. **Root Anatomy Modification:** Silicon modifies the anatomy of maize roots, influencing the development of Casparian bands and suberin lamellae. These anatomical changes act as a physical filter, significantly reducing the translocation of toxic ions from the root to the shoot by up to 48% (Ma et al., 2011).
2. **Chelation and Phytochelatins:** Under Arsenic stress, SiNPs induce the synthesis of root exudates and phytochelatins (PCs), which bind and sequester as in vacuoles. The formation of SiNP-As (III)-PC complexes further facilitates the safe storage of the metal in plant biomass (Chang et al., 2021).
3. **Antioxidant Support:** SiNPs serve as co-enzymes that activate the antioxidant defensive mechanisms of both the shoot and root, scavenging reactive species like the hydroxyl radical and reducing MDA content (Sarkar et al., 2025).

Table 4: SiNP Mitigation Strategies for Heavy Metal Toxicity in Maize

Heavy Metal	Primary Toxicity Pathway	SiNP Mitigation Strategy	Outcome in Maize
Cadmium (Cd)	Disruption of root morphology; oxidative damage	Vacuolar sequestration; endodermis thickening (Ning et al., 2026)	27.3% grain yield increase under stress
Lead (Pb)	Membrane deterioration; low pigmentation	Translocation inhibition (Maryam et al., 2024)	Enhanced shoot and root development
Arsenic (As)	Inhibits ATP; damages PSII and Rubisco	Phytochelatin induction and soil immobilization (Maryam et al., 2024)	Prolific root growth in polluted soil

11. Potentiation of Antioxidant Defense Systems

The common denominator across almost all forms of abiotic stress in maize is the overproduction of reactive oxygen species (ROS). If left unchecked, ROS lead to the peroxidation of membrane lipids, the denaturation of proteins, and the inactivation of photosynthetic enzymes. SiNPs act as a powerful biochemical primer, enhancing the plant's endogenous antioxidant capacity (Shoukat et al., 2025).

12. Synergistic Applications and Multi-Nanoparticle Interaction

Modern agricultural strategies are increasingly exploring the combination of SiNPs with other beneficial elements to produce additive effects on maize health (Verma et al., 2021).

13. Future Perspectives and Environmental Considerations

While the benefits of SiNPs in maize cultivation are well-documented, their integration into large-scale agriculture requires a nuanced understanding of their long-term environmental fate (Shafqat et al., 2025).

13.1 Hormetic Effects and Dose Sensitivity

The response of maize to SiNPs often follows a hormetic pattern, where low to moderate concentrations (e.g., 50-300 mg/L) promote growth and stress resilience, while supra-optimal doses can trigger toxicity. High concentrations of SiNPs have been shown in some models to induce mitochondrial dysfunction and gene misregulation, underscoring the importance of precise application protocols (Xiao et al., 2024).

13.2 Nanotechnology as a Sustainable Tool

The porous nature of mesoporous SiNPs makes them ideal nanocarriers for the controlled release of other agrochemicals, such as urea or pesticides. SiO2-based globules can withhold significant amounts of water and nutrients, releasing them slowly over 180 days. This functionality not only provides a buffer against drought but also minimizes the environmental leaching of fertilizers into groundwater (Wang et al., 2022).

14. Conclusion

Silicon nanoparticles (SiNPs) exert profound positive effects on photosynthesis and abiotic stress tolerance in maize through multiple interconnected mechanisms operating at morphological, physiological, biochemical, and molecular levels. By promoting an optimized “smart canopy” architecture, enhancing stomatal regulation, stabilizing the photosynthetic apparatus (PSII, Rubisco, C4 enzymes), and robustly activating antioxidant defenses, SiNPs enable maize plants to maintain higher rates of carbon assimilation and biomass accumulation even under severe drought, salinity, heat, chilling, and heavy metal stress. Their nanoscale properties facilitate superior uptake and translocation compared to bulk silicon, while modulating key silicon transporters (ZmLsi family) and osmolyte accumulation ensures better water and ion homeostasis. Green synthesis routes further enhance environmental sustainability by valorizing agricultural waste. These improvements culminate in substantial gains in grain yield, water productivity, and overall resilience, making SiNPs a powerful nano-fertilizer and stress alleviator for sustainable maize production in the face of climate change and resource limitations. Future research should focus on optimizing dosage and application methods, long-term field performance, interactions with other nano-materials, and integration into precision agriculture systems to fully unlock their potential for global food security.

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