



REVIEW ARTICLE

Nano-silica and silicon-based biostimulants for climate-resilient rice production: Mechanisms, applications and future prospects

Sasmitha S¹, Selvamurugan M^{2*}, Baskar M³, Suganya K¹, Parthasarathi R³ & Nageswari R^{3*}

¹Department of Environmental Sciences, Tamil Nadu Agricultural University, Coimbatore 641 003, Tamil Nadu, India

²Department of Environmental Sciences, Horticultural College and Research Institute for Women, Tamil Nadu Agricultural University, Tiruchirappalli 620 027, Tamil Nadu, India

³Department of Soil Science and Agricultural Chemistry, Anbil Dharmalingam Agriculture College and Research Institute, Tamil Nadu Agricultural University, Tiruchirappalli 620 027, Tamil Nadu, India

*Correspondence email - selvamurugan.m@tnau.ac.in; nageswari.r@tnau.ac.in

Received: 27 May 2026; Accepted: 10 July 2026; Available online: Version 1.0: 24 August 2026

Cite this article: Sasmitha S, Selvamurugan M, Baskar M, Suganya K, Parthasarathi R, Nageswari R. Nano-silica and silicon-based biostimulants for climate-resilient rice production: Mechanisms, applications and future prospects. *Plant Science Today*. 2026; 13(sp5): 1-11.
<https://doi.org/10.14719/pst.15725>

Abstract

Rice (*Oryza sativa* L.) is a staple food for over 3.5 billion people worldwide; however, its production is increasingly threatened by climate change-induced drought, soil salinity and heat stress. Silicon (Si) is a beneficial and quasi-essential element and has been researched extensively for mitigating the effects of abiotic stresses in rice. Recent advances have focused on developing highly bioavailable Si delivery systems, including nano-silica nanoparticles (SiNPs) and Si-based biostimulants. This review synthesises current knowledge on Si dynamics in soil-plant systems, the physicochemical properties of nano-silica and major application strategies reported for rice cultivation. Mechanistic areas covered include enhancement of abiotic stress tolerance (drought, salt and heat stress), activation of the antioxidant defence, maintenance of photosynthesis, nitrogen-use efficiency (NUE), hormonal signalling mechanisms and rice blast (*Magnaporthe oryzae*) and sheath blight (*Rhizoctonia solani*) resistance. Environmental safety issues, regulatory considerations and future perspectives in precision and sustainable agriculture are also discussed. The on-farm adoption barriers and key research needs are highlighted throughout. Unlike earlier reviews focused primarily on conventional Si fertilisation, this review emphasises recent advances in nano-silica technologies, Si-based biostimulants and their relevance to climate-resilient rice production.

Keywords: abiotic stress; biostimulants; drought; heat stress; nano-silica; nitrogen-use efficiency; *Oryza sativa*; rice blast; salinity; silicon

Introduction

Rice (*Oryza sativa* L.) is the staple food for more than 3.5 billion people worldwide and is cultivated on approximately 167 million hectares. Beyond its contribution to global food security, rice farming supports the livelihoods of nearly 144 million smallholder households, particularly across Asia and Africa (1). One of the most formidable challenges that will be faced by 21st century agriculture is meeting the projected demand for rice, which is expected to increase by approximately 25 % by 2050. This challenge is further intensified by the ongoing degradation of environmental conditions that support rice production.

Climate change is altering rainfall patterns, temperature regimes and cropping calendars, creating substantial uncertainty in rice production systems. Major rice-producing regions in South and Southeast Asia, in Sub-Saharan Africa and in Latin America are experiencing an increasing frequency and severity of episodic droughts (1). In the current scenario, 20 % of all the agricultural soil in the world is already affected by salinity and with sea-level rise,

declining groundwater levels and changes in precipitation, further increase in soil salinity is expected (2). Even during short periods of exposure, significant loss in yield has been experienced because of irreversible pollen sterility and spikelet abortion due to heat stress during critical reproductive stages, such as flowering and grain filling (3,4).

The addition of silicon (Si), which is known to play a role as a structural reinforcement and signalling and metabolic regulator in rice, has attracted considerable research interest as a strategy to enhance stress tolerance in rice (1, 5, 6). There is significant evidence from pot and greenhouse experiments highlighting beneficial effects of Si under abiotic stress; however, the past decade has seen an emergence of Si nano-formulations, which have enhanced bioavailability, surface reactivity and delivery compared to conventional sources of Si (5, 6). In the past decade, advanced Si nano-formulations such as colloidal nano-silica nanoparticles (SiNPs) and mesoporous silica nanoparticles (MSNs) have emerged, exhibiting enhanced bioavailability and delivery efficiency compared with conventional Si sources (5). It has been

reported that the high surface area increased reactivity and rapid dissolution of SiNPs into plant-available monosilicic acid improve Si uptake and stress alleviation in crops. The nano-scale Si enhances abiotic stress resilience in rice by promoting antioxidant defence, regulating hormonal signalling pathways, improving photosynthetic performance and activating Si transporter genes (low silicon (Lsi): Lsi1 and Lsi2), thereby enhancing Si acquisition under stress conditions (5). These findings highlight the potential of nano-silica as a more efficient Si delivery system for climate-resilient rice production.

Several reviews have addressed Si nutrition or nanoparticle applications in crops; however, a comprehensive synthesis focusing on nano-silica, Si-based biostimulants, climate resilience, precision agriculture and recent molecular advances in rice remains lacking. The goal of this review is to synthesise current knowledge related to soil chemistry, molecular biology and agronomic performance of nano-silica and Si-based biostimulants and to pinpoint gaps in knowledge and propose priority research. The role of nano-silica in climate-resilient rice production, highlighting its effects on Si uptake, antioxidant defence, stress signalling, photosynthetic efficiency and mitigation of abiotic stresses such as drought, salinity, heat and heavy metal toxicity, is illustrated in Fig. 1.

Silicon dynamics in rice systems

Silicon availability in soils

Silicon is the second most abundant element in the earth's crust (~28 % by mass), yet plant-available Si is often severely limited in intensively managed paddy soils. Most soil Si is locked in crystalline silicate minerals, such as quartz, feldspar and clay minerals that are not directly accessible to roots. Plants absorb Si as monosilicic acid $[\text{Si}(\text{OH})_4]$ from the soil solution, which occurs at concentrations of 0.1–0.6 mM depending on soil type, pH, temperature and organic matter content (1).

Tropical Oxisols and Ultisols, dominant in South and Southeast Asian rice lands, are highly weathered and frequently depleted in plant-available Si. Continuous rice cultivation combined with removal of Si-rich straw can progressively deplete soil Si reserves, a process commonly described as “silicon mining”, which contributes to declining Si availability in intensive rice production systems (1).

Uptake and transport mechanisms

Two cooperative transporters are at the core of the molecular mechanism underpinning Si uptake in rice. The Lsi1 is a nodulin 26-like intrinsic protein (NIP) aquaporin channel, which is expressed at the distal face of the exodermis and endodermis of the root and is involved in passive uptake of monosilicic acid from the rhizosphere to the root cell (7). Lsi2 functions as a secondary active efflux transporter located on the proximal side of root exodermal and endodermal cells. It mediates the export of monosilicic acid $[\text{Si}(\text{OH})_4]$ from the cytoplasm into the apoplast and xylem by utilising the proton (H^+) electrochemical gradient across the plasma membrane, thereby facilitating efficient root-to-shoot Si translocation from the root cells into the xylem against its concentration gradient by using the proton motive force (7). In the root pericycle, xylem loading of Si is mediated by a third transporter, Lsi3, while xylem unloading and Si re-distribution in the shoots is mediated by Lsi6 (7, 8).

The plant Si uptake system in rice has evolved to be one of the most efficient among terrestrial plant species and can sequester 4–14 % Si per dry weight in shoot tissues. Emerging evidence suggests that nano-silica application may enhance the expression levels of Lsi1 and Lsi2 under salinity stress, potentially increasing Si uptake capacity during adverse environmental conditions (6, 9).

Accumulation and deposition in rice tissues

Following xylem transport to the shoot, monosilicic acid is polymerised into amorphous silica ($\text{SiO}_2 \cdot n\text{H}_2\text{O}$) and deposited in specialised anatomical locations, particularly the epidermal cells, where a characteristic silica-cuticle double layer forms. This structure substantially reduces cuticular transpiration, mechanically reinforces the leaf surface and creates a physical barrier that impedes the penetration of fungal pathogens such as *Magnaporthe oryzae* and *Rhizoctonia solani*, while also reducing feeding damage by insect pests including brown planthopper (*Nilaparvata lugens*) and rice stem borer (*Scirpophaga incertulas*). Silicon also accumulates in the hull (lemma and palea) of rice grains, contributing to structural integrity. Silicification of root endodermal cells restricts apoplastic movement of toxic metals such as cadmium (Cd), arsenic (As) and aluminium (Al) with important implications for food safety (10–12). The uptake, translocation and accumulation of Si in rice plants, highlighting the roles of Lsi transporters, silica deposition sites and the resulting structural and physiological benefits that enhance stress tolerance, are illustrated in Fig. 2.

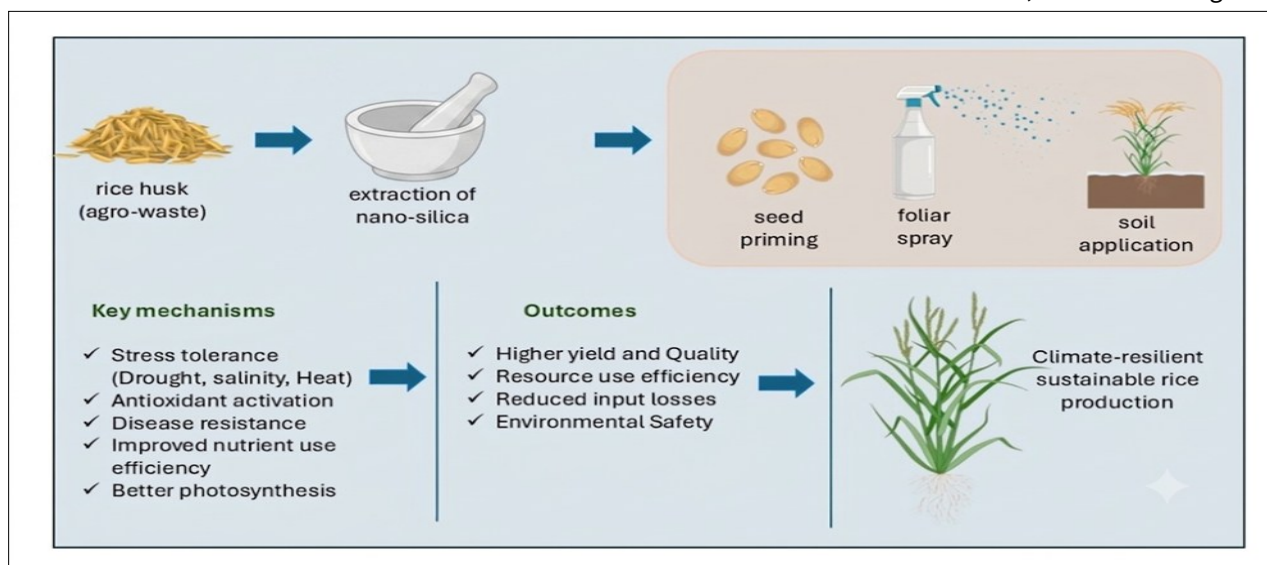


Fig. 1. The role of nano-silica in climate-resilient rice production.

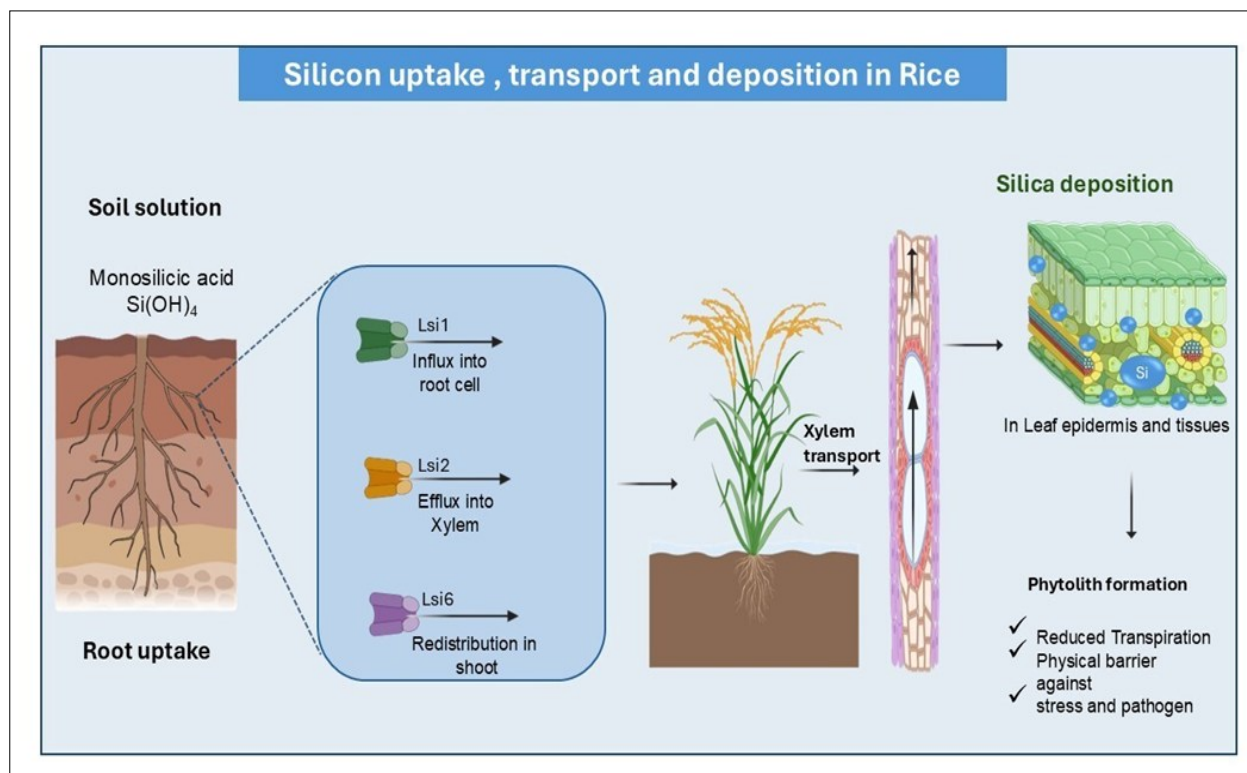


Fig. 2. Silicon uptake, transport and deposition mechanism in rice.

Nano-silica: Properties and agricultural relevance

Types and synthesis of nano-silica

Nano-silica encompasses a broad family of silicon dioxide nanoparticles (SiO_2 NPs) varying in physical structure and surface chemistry. Two major types are used in agriculture: (i) colloidal silica, comprising amorphous SiO_2 particles (1–100 nm) suspended in water, suitable for foliar sprays and fertigation; and (ii) MSNs, characterised by extraordinarily high surface areas ($>1000 \text{ m}^2 \text{ g}^{-1}$) and ordered internal pore networks capable of encapsulating and progressively releasing agronomic actives including plant hormones, micronutrients and biopesticides (5). A comparative summary of the principal nano-silica types and their agricultural applications is presented in Table 1.

Green synthesis using agricultural biomass, particularly rice husk (15–25 % SiO_2 on dry weight basis), is increasingly preferred over chemical synthesis for sustainability and cost reasons. Recycling rice husk into nano-silica reduces waste disposal problems, minimises open-field burning and creates value-added products within rice-based production systems. Alkali extraction of silica from thermally treated rice husk followed by acid precipitation yields highly pure amorphous nano-silica with physicochemical properties comparable to chemically synthesised equivalents (13, 14). This approach valorises a major agro-industrial waste stream, generating approximately 120 million tonnes of rice husk annually worldwide and aligns with circular bioeconomy principles (14–16). Green synthesis of

mesoporous silica nanoparticles from UKMRC-8 rice husk for agricultural application confirmed the suitability of this approach for crop use (17). The major Si sources used in rice production, together with their particle size, application methods and key advantages, are summarised in Table 2.

Physicochemical advantages over conventional silica

Nano-silica exhibits several distinct physicochemical advantages over traditional Si sources. The primary parameter is the specific surface area; a 10 nm silica particle presents about 500 times more surface per unit mass than a more conventional $5 \mu\text{m}$ silica particle, which directly translates into increased reactivity, solubility and biological availability (5). Nano-silica breaks down into plant-available monosilicic acid more quickly than larger particles of silica minerals, allowing rapid uptake of the mineral by plant roots during periods of stress.

The small particle size of nano-silica allows it to penetrate stomatal apertures and hydrophilic cuticle pathways, which is not possible for bulk Si. This superior delivery efficiency consistently yields higher Si concentrations in leaf and stem tissues in rice with foliar applications of nano-silica as compared to equivalent doses of conventional silica (18, 19). These are essential properties for the development of smart Si delivery systems (SDSs) where surface functionalisation can be used to increase the leaf adhesion, to increase the retention time and to enable stimuli-responsive release of nano-silica particles (5).

Table 1. Comparative characteristics of major nano-silica types used in agriculture

Nano-silica type	Particle size (nm)	Surface area ($\text{m}^2 \text{ g}^{-1}$)	Synthesis method	Major agricultural applications	References
Colloidal silica	1–100	50–500	Sol-gel, Stöber process	Foliar spray, fertigation, stress mitigation	(5)
Mesoporous silica nanoparticles (MSNs)	50–300	500–1500	Surfactant-templated sol-gel	Controlled delivery of nutrients, hormones and pesticides	(5)
Rice husk-derived nano-silica	20–200	100–800	Rice husk combustion and extraction	Silicon supplementation and sustainable agriculture	(6)
Functionalised nano-silica	50–300	200–1200	Surface-modified silica nanoparticles	Targeted delivery of agrochemicals and biostimulants	(5, 6)

Table 2. Comparison of major silicon sources used in rice production

Silicon source	Form	Particle size	Primary application	Key advantage	References
Calcium silicate slag	Granular/powder	>10 µm	Soil basal	Long-lasting soil supply	(6, 11)
Potassium silicate	Soluble liquid	Ionic Si(OH) ₄	Fertigation/foliar	Immediate availability	(1, 18)
Colloidal nano-silica	Amorphous SiO ₂	10–100 nm	Foliar/seed priming	High bioavailability	(5, 19)
Mesoporous silica nanoparticles	Structured SiO ₂	50–200 nm	Foliar/soil	Controlled cargo release	(5)
Rice husk-derived nano-silica	Amorphous SiO ₂	20–80 nm	Foliar/soil	Sustainable, low-cost	(6, 11)

Silicon-based biostimulants in rice

Definition, classification and regulatory context

According to the European Union Fertilising Products Regulation (EU 2019/1009), plant biostimulants are products that stimulate plant nutrition processes independently of their nutrient content, enhancing nutrient-use efficiency, stress tolerance, crop quality or nutrient availability in the rhizosphere.

Silicon-based biostimulants occupy an important niche within this definition, acting through mechanisms distinct from classical nutrient provision (1). Unlike essential nutrients such as nitrogen (N), phosphorus (P) and potassium (K), Si is not universally recognised as an essential element because most plant species can complete their life cycle in its absence (4, 5). As a result, Si does not meet the traditional regulatory criteria for classification as a conventional plant nutrient in many jurisdictions. Instead, its beneficial effects are primarily associated with the stimulation of natural physiological, biochemical and molecular processes, including enhanced nutrient use efficiency, activation of antioxidant defence systems, improved tolerance to abiotic and biotic stresses and increased resilience under adverse environmental conditions (4, 5). These functions align closely with the regulatory definition of plant biostimulants, which emphasises the enhancement of plant performance independently of direct nutrient supply (EU 2019/1009). Consequently, Si-based products are frequently classified as biostimulants rather than conventional fertilisers in many regulatory systems.

Silicon-based biostimulants can be classified as: (i) mineral Si biostimulants, such as soluble potassium silicate and calcium silicate slag; (ii) nano-silica biostimulants, including colloidal silica suspensions and MSN-based delivery systems; and (iii) composite biostimulants combining Si with humic acids, seaweed extracts, amino acid formulations, plant growth promoting bacteria (PGPB) or mycorrhizal fungi. The composite category shows promising evidence of synergistic effects on stress tolerance and yield, pending field-scale validation (20, 21). The contribution of arbuscular mycorrhizal fungi, phosphate-solubilising bacteria and Si to phosphorus availability in the rhizosphere further highlights the potential of integrating Si with biological agents in biostimulant strategies (22). Composite formulations may provide synergistic benefits through simultaneous enhancement of nutrient acquisition, microbial activity, stress tolerance and plant defence responses.

Modes of application

The application of Si-based biostimulants in rice is governed by the target tissue, developmental stage and stress type. Soil basal incorporation of calcium silicate slag or fertigation with potassium silicate targets the Lsi1 and Lsi2 transporter system and provides the longest duration of Si supply through the growing season (1). Foliar application is a highly practical delivery route for nano-silica, particularly for mitigating acute abiotic stress at vegetative or reproductive stages; concentrations of 0.5–2.0 mM applied as foliar

sprays have been shown to significantly reduce heat and drought stress impacts in rice (18, 19).

Seed priming with nano-silica solutions (25–100 mg L⁻¹) represents a third promising strategy, improving germination uniformity, seedling vigour and early stress tolerance through epigenetic priming mechanisms. Studies consistently show improvements in germination index, seedling root length and shoot biomass under salt and drought conditions when seeds are primed with nano-silica prior to sowing (23, 24). The major mechanisms underlying nano-silica-mediated abiotic stress tolerance in rice, including enhanced antioxidant activity, osmotic adjustment, maintenance of photosynthetic performance, ion homeostasis and activation of stress-responsive signalling pathways, are summarised in Fig. 3.

Mechanisms of action in rice

Abiotic stress tolerance

Drought stress

Silicon mitigates drought stress via several synergistic physiological mechanisms. Deposition of Si at the cuticle-silica bilayer interface leads to lower water loss by leaves under water deficit; Si-mediated stomatal regulation maintains turgor pressure and water potential of leaves under water deficit (19). Silicon supplementation helps prevent the deterioration of the chloroplast membrane and mitigates the impacts of moderate water stress by reducing lipid peroxidation, thus maintaining the continuity of photosynthetic metabolism (5, 6).

Nano-silica has been particularly effective in enhancing drought tolerance. The drought-stressed plants treated with green synthesised nano-silica via both foliar and soil applications exhibited significant improvement in water relations and photosynthetic parameters in rice (25). During drought, the use of foliar application of SiO₂ NPs has also been reported to alleviate water stress and improve yield and quality of other crops such as potato and maize (26, 27), which further exemplifies the versatility of nano-silica during water stress. In salt-stressed rice, foliar nano-Si up-regulated antioxidant defence [superoxide dismutase (SOD), peroxidase (POD) and catalase (CAT)], down-regulated oxidative stress [malondialdehyde (MDA), hydrogen peroxide (H₂O₂)] and significantly improved root traits (length, surface area, volume and branching), which resulted in better water and nutrient uptake in salt-stressed rice (9). Similarly, at the molecular level, it was shown that silica activated redox signalling increases drought resistance and grain yield in rice (28).

Salinity stress

Salt stress induces three distinct forms of damage in rice: ionic stress due to accumulation of Na⁺, osmotic stress and secondary oxidative stress. They are alleviated by Si through (i) decreased Na⁺ uptake and vacuolar compartmentalisation, (ii) higher K⁺/Na⁺ ratio in leaves, (iii) increase in the production of osmoprotectants (e.g., proline, glycine betaine, soluble sugar) and (iv) upregulation of genes that regulate salt-stress responses, including SOS1, HKT1 and NHX1 ion

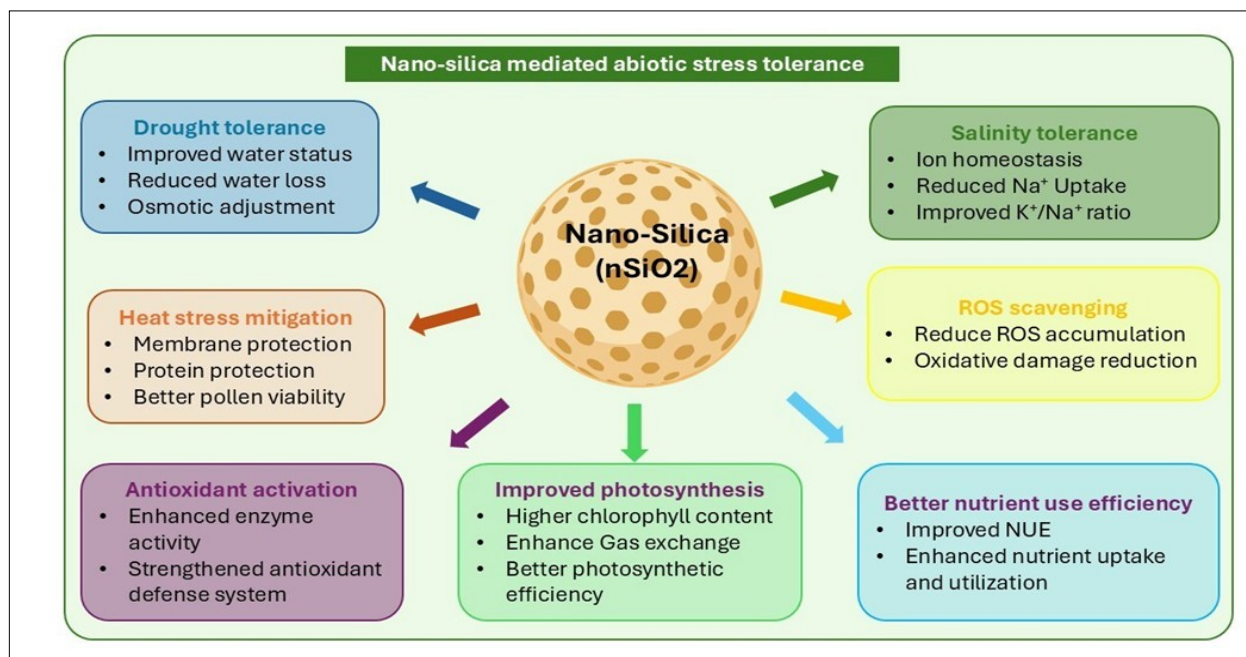


Fig. 3. Nano-silica mediated abiotic stress tolerance in rice.

transporters (9, 29, 30). The SiNPs have also been shown to improve the synthesis of osmolytes, antioxidant defence and the control of phytohormones in other grass species under combined drought–salt stress, showing the broad applicability of nano-Si across various plant species (31).

The rice straw SiNPs under salinity stress were demonstrated to improve the nutrient profile and activate the physiological and genetic repair mechanisms in rice through the upregulation of the expression of the HKT gene, enhanced absorption of K^+ and Ca^{2+} and decreased absorption of Na^+ (29). The application of SiO_2 NPs (15 kg hm^{-2}) to rice plants in saline water improved the grain filling, root development, activity of antioxidant enzymes in plants and chlorophyll content in rice and reduced the amylopectin crystallinity, leading to better rice grain quality in salt-tolerant varieties (23). The enhancements in root architecture and photosynthesis were also significantly observed in rice plants cultivated under NaCl stress with nano-Si (7). The antioxidant mechanisms involved in Si-mediated stress tolerance are discussed under “Enhancement of the antioxidant defence system”.

Heat stress

High temperature ($T > 35^\circ\text{C}$) will induce oxidative damage to reproductive tissue, spikelet sterility and reduce the fertilisation rate, which will lead to a decrease in seed set (3, 4). Previous studies have demonstrated that Si supplementation decreases the sterility of spikelets under heat stress and electrolyte leakage from leaf cells at high temperature, as well as preserve the structural integrity of photosystem II (PSII) (5, 19).

Molecular results indicate that SiNPs increase the accumulation of heat shock proteins (HSP70/HSP90), late embryogenesis abundant (LEA) proteins and kinases (MAPKs, CDPKs), which stabilise proteins and integrates reactive oxygen species (ROS)/ Ca^{2+} signalling under heat stress (6). Interactions between plant growth-promoting and silicate-solubilising bacteria with biogenic silica for regulating physiology and gene expression to provide heat stress tolerance in rice were demonstrated (21). Metabolomic analysis also revealed that Si increases the accumulation of proline, trehalose and glycine betaine, which play important roles in maintaining osmotic balance and membrane integrity under drought and heat stress conditions (6, 32). A comparative summary of the major abiotic stress types, their injury mechanisms and Si/nano-silica-mediated mitigation responses in rice is presented in Table 3.

Enhancement of the antioxidant defence system

The production of ROS [superoxide radicals ($\text{O}_2^\bullet$), hydrogen peroxide (H_2O_2) and hydroxyl radicals ($\bullet\text{OH}$)] occurs in considerable excess under nearly all abiotic stresses and plays a pivotal role in mediating cellular oxidative damage. Plants are equipped with an enzymatic antioxidant system to counterbalance ROS accumulation. This system includes SOD, CAT, POD, ascorbate peroxidase (APX) and glutathione reductase (GR). In addition, plants possess non-enzymatic antioxidants such as ascorbic acid, glutathione, carotenoids and tocopherols, which further contribute to cellular redox homeostasis and protection against oxidative damage.

Table 3. Summary of abiotic stress types, injury mechanisms and silicon/nano-silica mitigation responses in rice

Stress type	Primary injury mechanism	Silicon/SiNPs mitigation response	Key references
Drought	Stomatal closure, membrane damage, chlorophyll loss	Cuticle-Si barrier, antioxidant upregulation, root architecture improvement	(6, 19, 25, 28)
Salinity	Na^+ toxicity, osmotic stress, ROS accumulation	Na^+ exclusion, K^+/Na^+ balance, HKT/NHX gene activation	(9, 23, 29, 30)
Heat stress	Pollen sterility, PSII disruption, protein denaturation	HSP induction, PSII maintenance, proline accumulation	(3, 6, 21)
Heavy metals (Cd, As, Pb)	Oxidative stress, nutrient interference, growth inhibition	Cell wall adsorption, apoplastic restriction, antioxidant defence	(10, 11, 38)

SiNPs: nano-silica nanoparticles; Na: sodium; K: potassium; ROS: reactive oxygen species; Cd: cadmium; As: arsenic; Pb: lead; HSP: heat shock proteins; PSII: photosystem II.

The activity of this antioxidant system is consistently enhanced in stressed rice plants following Si supplementation. Silica nanoparticles can activate salicylic acid-mediated systemic acquired resistance (SAR), thereby improving plant defence against pathogens and other biotic stresses. In addition, silica nanoparticles enhance tolerance to abiotic stresses by stimulating antioxidant enzymes, improving ROS scavenging, maintaining cellular redox homeostasis and regulating stress-responsive physiological and molecular pathways (24). Cadmium toxicity in rice seedlings was reduced by using nano-Si and was correlated with the activation of antioxidant defence and adsorption to the rice seedling cell wall (33). In general, the antioxidant effect of nano-silica is more pronounced than that of traditional Si sources, which may be because it directly interacts with cell membranes and the ability of surface silanol groups to directly scavenge ROS (5, 6).

Improvement in photosynthesis and growth

The ability of Si to protect and enhance photosynthetic efficiency is one of its most agronomically important properties. Rice plants supplemented with Si generally exhibit higher chlorophyll concentrations, better maintenance of the photosynthetic electron transport chain and higher net CO₂ assimilation rates (19, 24). Part of these effects can be attributed to the influence of Si on chloroplast ultrastructure, such as the reduction of chloroplast swelling and disruption of thylakoid membranes, which are significantly less severe in rice plants treated with Si than in untreated plants under stress conditions.

Under non-stressed conditions, Si strengthens the epidermis of leaves, promoting an erect leaf posture that maximises canopy light interception and minimises inter-leaf shading in dense canopies, thereby enhancing light interception efficiency. Nano-silica treatment also resulted in higher leaf area index (LAI), stomatal conductance and soil plant analysis development (SPAD) chlorophyll values in pot and field conditions, which ultimately resulted in higher shoot biomass and grain yield (5, 18). The beneficial effects of SiNPs involve complex crosstalk among antioxidant defence systems, photosynthetic processes and phytohormone signalling pathways, highlighting the multifaceted nature of Si-mediated stress protection.

Silicon-nitrogen interaction and nitrogen-use efficiency

The nitrogen-use efficiency (NUE) of rice averages only 30–40 % globally, with a large proportion of applied nitrogen being lost through denitrification, leaching and ammonia volatilisation (1). Silicon improves NUE in several ways, such as upregulating genes involved in ammonium and nitrate acquisition; expanding the volume of soil accessible to the root system through increased root growth and improved root architecture; and enhancing the allocation of acquired nitrogen to productive plant organs, thereby improving the nitrogen harvest index (1).

Increased yield was recorded with Si application at lower nitrogen application rates, which may be advantageous in reducing the amount of nitrogen used and associated losses to the environment in paddy systems (21). One of the emerging fields of research, which has yet to be economically validated at the farm scale, is the development of nano-silica co-formulations with nitrogen sources in controlled-release matrices (34).

Hormonal regulation and signalling pathways

The interactions between Si and plant hormonal signalling pathways are complex and not yet fully understood. Two major

immune hormones in plants, salicylic acid (SA) and jasmonic acid (JA), respond to Si treatment without incurring significant growth costs and both exhibit responses that are beneficial for disease resistance. The Si-induced activation of systemic acquired resistance (SA) pathway primes the plant for a more rapid response to subsequent pathogen challenges (35, 36).

The association between Si and abscisic acid (ABA) is especially important with respect to stress tolerance. The ABA causes stomatal closure to reduce water loss under drought conditions; however, prolonged exposure to high ABA concentrations can adversely affect photosynthesis and plant growth. Under moderate stress conditions, Si appears to promote partial stomatal reopening while also moderating excessive ABA accumulation by enhancing the cuticle, thereby reducing water loss through a more complex regulatory mechanism than ABA alone (6). The brassinosteroid signalling pathway has also been associated with salt stress tolerance in rice and was found to be activated under Si treatment. The genes involved in the brassinosteroid biosynthetic pathway and their downstream targets were identified as being upregulated following Si treatment (6, 20).

Role in pest and disease resistance

Rice blast (*M. oryzae*) and sheath blight (*R. solani*) are among the most destructive rice diseases worldwide, causing substantial yield and economic losses across major rice-growing regions.

Silicon has emerged as one of the most promising non-chemical approaches to rice disease management through a multi-layered mechanism of action that is inherently difficult for pathogens to overcome (35, 36).

Silicon deposition in the outer epidermal cell wall creates a mechanically reinforced surface that is substantially more resistant to penetration by fungal appressoria. Microscopic studies have demonstrated significantly reduced appressorial penetration success rates in Si-rich leaves and those that breach the epidermis encounter additional Si deposits in mesophyll cell walls. Beyond physical exclusion, Si actively primes innate immunity: Si-treated rice exhibits more rapid and robust activation of the hypersensitive response (HR) at infection sites, accelerated production of phenylpropanoid phytoalexins (momilactones and phytocassanes) and stronger induction of pathogenesis-related (PR) proteins, including PR-1, PR-2 (β -1,3-glucanases) and PR-3 (chitinases), upon pathogen encounter (35).

The SiO₂ NPs protect rice against *M. oryzae* through salicylic acid-mediated systemic acquired resistance, demonstrating that nano-silica bridges physical and biochemical resistance mechanisms simultaneously (35). The SiNPs play a critical role in mitigating biotic stress, including their effects against *R. solani* in rice (36). Silicon combined with rhizobacterial inoculants suppressed both leaf and panicle blast in upland rice under field conditions, highlighting the potential of composite biostimulant strategies (21). Silicon nanoparticles were similarly shown to alleviate biotic stress caused by *R. solani* in oat (*Avena sativa*), extending the evidence base for SiNP-mediated disease protection across cereals (37). Despite promising experimental evidence, additional field-scale studies are required to quantify the consistency of Si-mediated disease suppression across diverse agroecological environments. Beyond fungal pathogens, bacterial diseases such as bacterial leaf blight caused by *Xanthomonas oryzae* pv. *oryzae* also pose significant threats to rice production. Emerging evidence suggests

that Si may enhance resistance against bacterial pathogens by strengthening physical barriers and activating defence-related biochemical pathways. However, compared with fungal diseases, the role of Si and nano-silica in bacterial disease suppression remains insufficiently investigated and warrants further research (24, 26).

Impact on yield, grain quality and soil health

The ultimate measure of the effectiveness of Si-based interventions is their ability to improve grain yield and crop productivity under field conditions. There is broad consensus in the literature that rice grain yield is enhanced by an average of 10–17 % in response to Si application and is often most significant in soils that are naturally low in plant-available Si and under moderate to severe abiotic stress (1). The yield effects of nano-silica treatments have been found to be comparable to or better than those of traditional Si applications at significantly lower rates, with several studies reporting a 15–25 % yield improvement following foliar application of 50–100 mg L⁻¹ (23, 30).

Grain yields were 23–33 % higher in salt-tolerant rice varieties irrigated under saline conditions following SiO₂ NP application, along with improved grain appearance, taste and pasting properties due to reduced amylopectin crystallinity (23). Under controlled conditions, the critical role of application timing in determining the effectiveness of Si biostimulants on rice physiology and yield has been demonstrated, highlighting that optimal timing is crucial for achieving the best results (18).

In addition to yield, Si enhances several important commercial quality attributes of grain. The general observation is that Si-treated rice grains exhibit higher protein content, improved milling quality, reduced chalkiness and improved cooking quality indices (19, 23). The most fundamental Si management strategy is to incorporate rice residues back into the field, thereby avoiding straw removal or biomass burning; this practice restores plant-available Si while also benefiting soil organic matter, water retention and microbial habitat quality (1). Silicon amendments may influence rhizosphere microbial communities, including beneficial bacteria and mycorrhizal fungi, which contribute to nutrient acquisition and stress resilience. Representative studies demonstrating the effects of Si and nano-silica on rice yield and grain quality under different stress conditions are summarised in Table 4.

Silicon-mediated alleviation of heavy metal stress

Contamination of paddy soils with Cd, As and lead (Pb) represents a major challenge for sustainable rice production because these toxic elements reduce crop productivity and threaten food safety through their accumulation in edible grains. Silicon exhibits several mechanisms that mitigate heavy metal toxicity: (i) deposition of silica in the endodermal cell wall of roots prevents the passage of the metals through the apoplast; (ii) Si binds to sites on the root cell wall, thereby reducing the uptake of metal ions; and (iii) Si activates

antioxidant enzymes, which decrease oxidative damage caused by metals through protective physiological responses, complementing the antioxidant mechanisms described under “Enhancement of the antioxidant defence system” (10, 11, 38).

The SiNPs significantly decreased Cd uptake into shoot tissues and improved chlorophyll content in rice under Cd stress (38). As mentioned, use of Si-Fe nanoparticles has been reported to enhance oxidative tolerance and lower the uptake of lead by increasing the adsorption capacity of the cell wall to prevent lead stress in rice (10). Nano-Si application on leaves was found to reduce the Cd concentration in the rice grain, which is caused by the blockage of Cd from the straw to the grain (11). Further support for the use of nano-silica-mediated Cd remediation was provided by evidence that Cd uptake and nutritional homeostasis and antioxidative enzyme system were regulated by nano SiO₂ in barley seedlings, potentially applicable to other cereals (39).

Studies have shown that nano-Si can reduce Cd toxicity in rice seedlings by adsorbing onto the cell wall and inducing the antioxidant defence system (33). Alternative sources of nano-silica, such as e-waste from solar panels, have also been demonstrated to remediate Cd contamination in rice, suggesting sustainable and multifaceted production possibilities for nano-silica (40). Significantly lower Cd bioavailability was observed in the roots of rice plants following Si application to Cd-contaminated paddy soil (12). Mechanistic studies indicate that nanoscale silica is more effective than conventional silicate in inhibiting Cd uptake (41). Moreover, the combined application of Si and titanium oxide nanoparticles was shown to regulate metal transporters and oxidative stress, thereby enhancing Cd tolerance in rice (42). Another serious issue in flooded rice is As contamination, due to the similarity between the transport pathways of arsenite and silicic acid. Silicon application has been reported to decrease As uptake in rice by competing for transporter binding sites and inhibiting the translocation of As from roots to shoots. In addition, nanoparticle-based interventions have been found to reduce the physiological and oxidative stress effects of As in rice. However, further investigations are needed to evaluate the performance of nano-silica formulations for As remediation under a range of soil and water management scenarios (43).

Environmental safety and regulatory considerations

Amorphous silica nanoparticles are generally considered less hazardous than crystalline silica and many metal-based nanoparticles because they are naturally associated with soil systems and can gradually dissolve into monosilicic acid under environmental conditions. Their environmental fate is influenced by particle size, aggregation behaviour, surface chemistry and soil characteristics, which determine their persistence and bioavailability (5, 6). However, critical dose-response relationships exist, concentrations below approximately 100–500 mg L⁻¹ consistently promote plant growth and stress tolerance, whereas very high concentrations (above 1000 mg L⁻¹) may cause phytotoxic effects

Table 4. Representative studies on yield and grain quality responses to silicon and nano-silica in rice

Si source	Rate/concentration	Stress condition	Yield/quality outcome	References
SiO ₂ NPs	15 kg hm ⁻²	Salinity	+23–33 % grain yield; improved grain quality	(23)
Green nano-Si	Foliar + soil	Drought	Improved water relations and photosynthesis	(25)
Nano-Si	Foliar	Salinity	Enhanced root architecture; antioxidant defence	(9)
Si biostimulant	Multiple concentration	Controlled	Timing-dependent yield and physiology improvement	(18)
Rice straw SiNPs	Various	Salinity	Improved biomass, nutrient profile, HKT expression	(29)
Nano-silicon	Various	Drought	Silica-activated redox signalling; enhanced yield	(28)

SiO₂ NPs: silicon dioxide nanoparticles; SiNPs: silicon nanoparticles; Nano-Si: nano-silica; Si: silicon.

through physical blockage of root pores or excessive production of ROS at the nanoparticle surface (5).

Regulatory frameworks governing nano-agrochemicals are still evolving. Under EU fertiliser legislation, nano-specific registration and characterisation are required, including particle size distribution, surface area and dissolution behaviour. Regulatory frameworks for rice production are still not harmonised across key countries in Asia. Therefore, it is imperative to standardise international protocols for nano-silica characterisation, efficacy testing and risk assessment to enable responsible innovation and improve farmer access (5). Adoption barriers for smallholder farmers, including formulation costs and limited access to supply chains, should be addressed through appropriate policy and market development measures. An in-depth review of the multifunctional applications and environmental impacts of nanotechnology in *Oryza sativa* cultivation systems covers several of these regulatory aspects (34).

Integration with sustainable and precision agriculture

The science of Si nutrition and precision agriculture technologies is offering promising new solutions for sustainable rice production under a changing climate. Stimuli-responsive nano-delivery systems capable of releasing active compounds in response to environmental cues, such as pH fluctuations, pathogen activity or temperature changes, represent a promising approach for improving input-use efficiency (5, 33).

Site specific Si management may become feasible through nutrient management platforms using sensors, which would combine soil Si sensors, spectroscopic Si assessment of leaf Si, drone canopy imaging and machine learning-based decision-support algorithms within each field or irrigation command area. Likewise, with respect to maize production, SiNPs were found to enhance water productivity and yield under mild regulated deficit irrigation (RDMI), suggesting the potential use of SiNPs for precision water management by regulating the physiological processes of photosynthesis and canopy structure (44). The use of Si management, together with high Si accumulating rice genotypes engineered with Lsi transporters, PGPB that produce Si and circular bioeconomy-based nano Si production from rice husk, will further boost the agronomic and environmental benefits (13, 14, 21). Economic analyses are needed to determine whether the precision delivery of Si-based products provides sufficient agronomic benefits to justify implementation costs.

Challenges and research gaps

Despite substantial advances in Si biology and nano-silica research, several scientific, technological, economic and regulatory challenges continue to limit their large-scale adoption in rice production systems. The most significant limitation is the scarcity of long-term, multi-location, multi-season field trials performed under farmer representative conditions. The vast majority of the published evidence comes from controlled greenhouse or growth chamber experiments or from single-season small plot trials, which restricts the extent to which the results can be generalised (5, 6). Another important research gap is the limited availability of economic analyses evaluating the cost-effectiveness of Si and nano-silica applications under farmer-field conditions. Although several studies have demonstrated improvements in yield, grain quality and stress tolerance, comprehensive assessments of production costs, return on investment, scalability and affordability for smallholder farmers remain scarce. Future investigations should

integrate agronomic, environmental and economic evaluations to support evidence-based adoption of Si-based technologies in rice production systems (4, 25).

Standardisation in dosing, formulation properties and application techniques for nano-silica is also a pressing need. There is an extremely large variation reported in particle size (ranging from 2 to 100 nm), surface chemistry, carrier materials and application concentrations in published studies, making cross-study comparisons very difficult (5). Knowledge synthesis would be significantly advanced by internationally recognised reference standards for agricultural nano-silica, similar to reference fertilisers in conventional agronomy. The molecular targets of nano-silica in plant cells, the long-term fate of repeated SiNP applications in soil microbial communities and the consistency of responses across diverse agroecological environments remain poorly understood (6, 36, 43).

Future prospects

Several future research directions appear particularly promising. Nano-enabled Si fertilisers that combine Si with controlled-release nutrient carriers represent a promising strategy for synchronising nutrient availability with crop demand while minimising environmental losses (34). The development of nano-silica-urea composite with better nitrogen retention compared with conventional urea in flooded paddy systems is in progress and needs to be demonstrated at the farmer level.

Investment needs to be expedited in the use of the rice husk silica to implement circular bioeconomy approaches. Globally, rice processing generates approximately 120 million tonnes of rice husk annually. Upon controlled combustion, this biomass produces rice husk ash (RHA), which is rich in amorphous silica and serves as an important raw material for nano-silica synthesis and it can be converted into agricultural nano-silica for re-application to rice crops, which creates a closed-cycle value chain in line with sustainability principles (13, 14, 16). Based on the idea of multiple benefits per single application, a composite formulation of biostimulants containing nano-silica and microorganisms such as bacteria that enhance the bioavailability of Si (e.g., *Bacillus subtilis*, *Enterobacter* spp.) and nitrogen-fixing bacteria or phosphates solubilising bacteria is proposed, which has yet to be validated at the field scale.

CRISPR-Cas9-mediated upregulation of the expression of Lsi transporters and stress-induced marker selection for Si accumulation could greatly enhance the agronomic importance of Si nutrition in molecular breeding (7, 8). Such strategies, along with innovations in nano-silica delivery systems, could lead to rice varieties that are intrinsically more resilient to stresses and require less reliance on repeated external inputs. Antioxidant activity and photosynthetic parameters were found to be regulated by SiO₂ NPs, even in wild rice-derived lines, demonstrating that nano-Si strategies are genetically applicable (45).

Regulatory and adoption challenges for genetically enhanced rice varieties

Despite the fact that genetic engineering of Si uptake genes through CRISPR-Cas9 genome editing has great potential to increase stress tolerance in rice, the deployment of GM and gene-edited rice is limited by regulatory, economic and public acceptance concerns. Significant variations exist in the policies and regulations of major rice-producing countries regarding genetically modified organisms

(GMOs). While India has adopted a conservative approach towards the commercialisation of GM food crops, China has recently accelerated the approval process for genetically modified varieties of selected crops. Indonesia and other countries in Southeast Asia are considering biosafety, environmental and socioeconomic issues before large-scale deployment.

Apart from regulatory issues, public perception, market acceptance, intellectual property (IP) concerns and biosafety assessment costs are likely to slow the rapid adoption of GE rice cultivars. Therefore, future studies need to integrate molecular breeding approaches with regulatory compliance, stakeholder engagement and socioeconomic assessment to support the responsible release of Si-efficient and climate-resilient rice varieties.

Conclusion

This review is based on substantial and growing evidence regarding the complex functions of Si and nano-silica in ensuring sustainable climate-smart rice production. Mechanistic evidence of Si deposition, induction of antioxidant enzymes, activation of Lsi1 and Lsi2 transporters, modulation of hormonal signals and exclusion of pathogens help explain the observed agronomic effects (4–6, 24). The benefits of nano-silica formulations over conventional Si sources include enhanced bioavailability, improved delivery efficiency and greater effectiveness in managing stress, particularly under acute stress conditions. Nano-silica formulations often provide greater bioavailability and delivery efficiency than conventional Si sources, although their effectiveness may vary according to formulation characteristics, application methods and environmental conditions.

There are some critical gaps: field-level evidence is lacking across various agro-ecological zones; detailed ecotoxicological assessments of SiNPs in complex agricultural ecosystems are limited; and optimal formulation and application methods for specific stresses and soil types have not yet been established. There is an immediate need for multi-year, multi-location field trials, progressive regulatory frameworks and standardised formulation protocols (5, 36). Silicon application alone cannot address all challenges associated with climate-smart rice production but represents one of several components of a comprehensive climate-smart rice production system, which also encompasses the utilisation of improved germplasm, precision water management, soil health restoration and the responsible use of nanotechnology. Multi-location and multi-season field validation of Si and nano-silica technologies across different agroecological zones should be prioritised in future research. Further studies are needed to develop standard nano-silica formulations, establish standard application procedures, identify molecular targets and signalling pathways associated with stress tolerance, evaluate long-term environmental and ecotoxicological effects and develop feasible delivery systems for smallholder farming systems. The full potential of these interventions, including Si nutrition, molecular breeding, precision agriculture and climate-smart crop management, can further promote the sustainable intensification of rice production in the context of climate change (4, 5, 25, 26). This review integrates recent advances in nano-silica technologies, Si-based biostimulants, molecular mechanisms, environmental considerations and precision agriculture applications within a unified framework for climate-resilient rice production.

Acknowledgements

The authors also grateful to the Department of Soil Science and Agricultural Chemistry and Department of Environmental Sciences, Tamil Nadu Agricultural University, Coimbatore, for providing the necessary academic environment and resources. Constructive suggestions from colleagues and reviewers that helped improve the manuscript are also gratefully acknowledged.

Authors' contributions

SS conceptualised the review topic, conducted the literature survey, compiled and analysed the literature, prepared the figures and tables and wrote the original draft of the manuscript. SM supervised the work, provided scientific guidance, critically reviewed the manuscript and edited the final version. BM, SK, PR and NR contributed to the literature collection, interpretation of scientific findings, manuscript revision and improvement of the intellectual content. All authors have read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interest to declare.

Ethical issues: None

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used ChatGPT (OpenAI) in order to improve grammar, language clarity and overall manuscript readability. After using this tool/service, the authors reviewed and edited the content as needed and takes full responsibility for the content of the publication.

References

1. Pontigo S, Ribera A, Gianfreda L, Mora ML, Nikolic M, Cartes P. Silicon in vascular plants: uptake, transport and its influence on growth and stress tolerance. *Planta*. 2015;242(1):23–37. <https://doi.org/10.1007/s00425-015-2333-1>
2. Munns R, Tester M. Mechanisms of salinity tolerance. *Annu Rev Plant Biol*. 2008;59:651–81. <https://doi.org/10.1146/annurev.arplant.59.032607.092911>
3. Prasad PV, Boote KJ, Allen LH. Adverse high temperature effects on pollen viability, seed-set, seed yield and harvest index of grain-sorghum are more severe at elevated carbon dioxide due to higher tissue temperatures. *Agric For Meteorol*. 2006;139(3–4):237–51. <https://doi.org/10.1016/j.agrformet.2006.07.003>
4. Resentini F, Orozco-Arroyo G, Cucinotta M, Mendes MA. The impact of heat stress in plant reproduction. *Front Plant Sci*. 2023;14:1271644. <https://doi.org/10.3389/fpls.2023.1271644>
5. Yan G, Huang Q, Zhao S, Xu Y, He Y, Nikolic M, et al. Silicon nanoparticles in sustainable agriculture: synthesis, absorption and plant stress alleviation. *Front Plant Sci*. 2024;15:1393458. <https://doi.org/10.3389/fpls.2024.1393458>
6. Song Y, Sher M, Hu Y, Wang L, Hua Z, Zhou X, et al. Nano-scale silicon intervention for improving abiotic stress resilience in rice: mechanistic insights and practical applications. *PeerJ*. 2026;14:e20599. <https://doi.org/10.7717/peerj.20599>
7. Mitani-Ueno N, Ma JF. Silicon transport and its homeostasis in rice. *Quant Plant Biol*. 2024;5:e19. <https://doi.org/10.1017/qpb.2024.19>

8. Huang Y, Zhao L, Ye M, Hu Y, Zhang Q, Konishi H. A pericycle-localized silicon transporter for efficient xylem loading in rice. *New Phytol.* 2022;234(1):197–208. <https://doi.org/10.1111/nph.17959>
9. Xiong J, Yang X, Sun M, Zhang J, Ding L, Sun Z, et al. Mitigation effect of exogenous nano-silicon on salt stress damage of rice seedlings. *Int J Mol Sci.* 2025;26(1):85. <https://doi.org/10.3390/ijms26010085>
10. Ghouri F, Sarwar S, Sun L, Riaz M, Haider FU, Ashraf H, et al. Silicon and iron nanoparticles protect rice against lead (Pb) stress by improving oxidative tolerance and minimizing Pb uptake. *Sci Rep.* 2024;14:6016. <https://doi.org/10.1038/s41598-024-55810-2>
11. Chen R, Zhang C, Zhao Y, Huang Y, Liu Z. Foliar application with nano-silicon reduced cadmium accumulation in grains by inhibiting cadmium translocation in rice plants. *Environ Sci Pollut Res.* 2018;25(3):2361–8. <https://doi.org/10.1007/s11356-017-0681-z>
12. Cai Y, Guo L, Shi Z, Lin H, Sun Y, Zhou X. The Cd sequestration effects of rice roots affected by different Si management in Cd-contaminated paddy soil. *Sci Total Environ.* 2022;849:157718. <https://doi.org/10.1016/j.scitotenv.2022.157718>
13. Chakroborty S, Pal K, Nath N, Singh V, Barik A, Soren S, et al. Sustainable synthesis of multifunctional nanomaterials from rice wastes: a comprehensive review. *Environ Sci Pollut Res.* 2023;30:101523–44. <https://doi.org/10.1007/s11356-023-29235-9>
14. Yuan S, Hou Y, Liu S, Ma Y. A comparative study on rice husk, as agricultural waste, in the production of silica nanoparticles via different methods. *Materials.* 2024;17(6):1271. <https://doi.org/10.3390/ma17061271>
15. Kumar PS, Yassin MM, Marimuthu S, Kalarani MK, Thiyageshwari S, Meenakshi G. Eco-friendly synthesis and characterization of amorphous nanosilica from rice husk. *Agric Sci Digest.* 2024;43(6):790–5. <https://doi.org/10.18805/ag.D-5792>
16. Imoisili PE, Jen T-C. Synthesis of biogenic mesoporous silica nanoparticles from rice husks waste materials via sol-gel method. *Biomass Conv Bioref.* 2025;15:29191–206.
17. Dorairaj D, Govender N, Zakaria S, Wickneswari R. Green synthesis and characterization of UKMRC-8 rice husk-derived mesoporous silica nanoparticle for agricultural application. *Sci Rep.* 2022;12:20097. <https://doi.org/10.1038/s41598-022-24484-z>
18. Velasco E, Aranda X, Houben F, Ribes J, Araus JL, García-Caparros P. Interactive effects of silicon formulations, concentrations and foliar application timing on rice physiology and yield. *Front Plant Sci.* 2026;16:1723079. <https://doi.org/10.3389/fpls.2025.1723079>
19. El-Okkiah SAF, El-Afry MM, Shehab Eldeen SA, El-Tahan AM, Ibrahim OM, Negm MM, et al. Foliar spray of silica improved water stress tolerance in rice (*Oryza sativa* L.) cultivars. *Front Plant Sci.* 2022;13:935090. <https://doi.org/10.3389/fpls.2022.935090>
20. Mukarram M, Ahmad B, Choudhary S, Konôpková AS, Kurjak D, Khan MMA, et al. Silicon nanoparticles vs trace elements toxicity: modus operandi and its omics bases. *Front Plant Sci.* 2024;15:1377964. <https://doi.org/10.3389/fpls.2024.1377964>
21. Chaganti C, Phule AS, Chandran LP, Sonth B, Kavuru VPB, Govindannagari R, et al. Silicate solubilizing and plant growth promoting bacteria interact with biogenic silica to impart heat stress tolerance in rice by modulating physiology and gene expression. *Front Microbiol.* 2023;14:1168415. <https://doi.org/10.3389/fmicb.2023.1168415>
22. Etesami H, Jeong BR, Glick BR. Contribution of arbuscular mycorrhizal fungi, phosphate-solubilizing bacteria and silicon to P availability in the rhizosphere of crops. *Front Plant Sci.* 2021;12:699618. <https://doi.org/10.3389/fpls.2021.699618>
23. Jin W, Li L, He W, Wei Z. Application of silica nanoparticles improved the growth, yield and grain quality of two salt-tolerant rice varieties under saline irrigation. *Plants.* 2024;13(17):2452. <https://doi.org/10.3390/plants13172452>
24. Elshayb OM, Nada AM, Ibrahim HM, Amin HE, Atta AM. Application of silica nanoparticles for improving growth, yield and enzymatic antioxidant for the hybrid rice EHRI growing under water regime conditions. *Materials.* 2021;14(5):1150. <https://doi.org/10.3390/ma14051150>
25. Wahi D, Bisht K, Gautam S, Salvi P, Lohani P. Green synthesized nano-silica: foliar and soil application provides drought recovery in rice. *Environ Sci Nano.* 2024;11(9):3624–38. <https://doi.org/10.1039/D4EN00275J>
26. Seleiman MF, Al-Selwey WA, Ibrahim AA, Shady M, Alsadon AA. Foliar applications of ZnO and SiO₂ nanoparticles mitigate water deficit and enhance potato yield and quality. *Agronomy.* 2023;13(2):466. <https://doi.org/10.3390/agronomy13020466>
27. Sharf-Eldin AA, Alwutayd KM, Abou El-Yazied A, El-Beltagi HS, Alharbi BM, Eisa MAM, et al. Response of maize seedlings to silicon dioxide nanoparticles (SiO₂NPs) under drought stress. *Plants.* 2023;12(14):2592. <https://doi.org/10.3390/plants12142592>
28. Kang Z, Lu J, Zheng S, Hu X, Wang L, Jiang L, et al. Silica-activated redox signaling confers rice with enhanced drought resilience and grain yield. *ACS Nano.* 2025;19(3):3752–63. <https://doi.org/10.1021/acsnano.4c14608>
29. Ijaz U, Ahmed T, Rizwan M, Noman M, Shah AA, Azeem F, et al. Rice straw based silicon nanoparticles improve morphological and nutrient profile of rice plants under salinity stress by triggering physiological and genetic repair mechanisms. *Plant Physiol Biochem.* 2023;201:107788. <https://doi.org/10.1016/j.plaphy.2023.107788>
30. Abdel-Halim MEF, Hegazy HS, Hassan NS, Naguib DM. Foliar silicon ions and silica nanoparticles from rice straw alleviate salt stress in rice. *Plant Physiol Biochem.* 2017;118:394–405. <https://doi.org/10.1016/j.plaphy.2017.06.003>
31. Khan I, Awan SA, Rizwan M, Huizhi W, Ulhassan Z, Xie W. Silicon nanoparticles improved the osmolyte production, antioxidant defense system and phytohormone regulation in *Elymus sibiricus* (L.) under drought and salt stress. *Environ Sci Pollut Res.* 2024;31(6):8985–99. <https://doi.org/10.1007/s11356-023-31730-y>
32. Sarkar MM, Rudra P, Paul P, Dua TK, Roy S. Enhanced adaptation to salinity stress in lentil seedlings through trehalose-functionalized silica nanoparticles: exploring silica-sugar absorption and oxidative balance. *Plant Physiol Biochem.* 2024;206:108309. <https://doi.org/10.1016/j.plaphy.2023.108309>
33. Riaz M, Kamran M, Fahad S, Wang X. Nano-silicon mediated alleviation of Cd toxicity by cell wall adsorption and antioxidant defense system in rice seedlings. *Plant Soil.* 2022;486:315–34. <https://doi.org/10.1007/s11104-022-05588-x>
34. Zhao W, Wang T, Dong H, Zhao W, Song K, Zhu N. Multifunctional roles and ecological implications of nano-enabled technologies in *Oryza sativa* production systems: a comprehensive review. *Plants.* 2025;14(4):528. <https://doi.org/10.3390/plants14040528>
35. Du J, Liu B, Zhao T, Xu X, Lin H, Ji Y, et al. Silica nanoparticles protect rice against biotic and abiotic stresses. *J Nanobiotechnol.* 2022;20(1):197. <https://doi.org/10.1186/s12951-022-01420-x>
36. Naidu S, Pandey J, Mishra LC, Chakroborty A, Singh A, Dwivedy AK, et al. Silicon nanoparticles: synthesis, uptake and their role in mitigation of biotic stress. *Ecotoxicol Environ Saf.* 2023;255:114783. <https://doi.org/10.1016/j.ecoenv.2023.114783>
37. Ahmad F, Jabeen K, Iqbal S, Umar A, Ameen F, Gancarz M, et al. Influence of silicon nanoparticles on *Avena sativa* L. to alleviate the biotic stress of *Rhizoctonia solani*. *Sci Rep.* 2023;13(1):15191. <https://doi.org/10.1038/s41598-023-41699-w>
38. Jalil S, Nazir MM, AL-Huqail AA, Ali B, Al-Qathanin RN, Asad MAU, et al. Silicon nanoparticles alleviate cadmium toxicity in rice (*Oryza sativa* L.) by modulating the nutritional profile and triggering stress-responsive genetic mechanisms. *Ecotoxicol Environ Saf.* 2023;268:115699. <https://doi.org/10.1016/j.ecoenv.2023.115699>

39. He S, Lian X, Zhang B, Liu X, Yu J, Gao Y, et al. Nano silicon dioxide reduces cadmium uptake, regulates nutritional homeostasis and antioxidative enzyme system in barley seedlings (*Hordeum vulgare* L.) under cadmium stress. *Environ Sci Pollut Res*. 2023;30:67552–64. <https://doi.org/10.1007/s11356-023-27130-x>
40. Hosain MT, Shahid M, Sarkar MIU, Zhang H, Rahman MM, Naidu R, et al. Alleviation of cadmium accumulation in rice through the application of nano silicon derived from solar panels e-wastes. *Sci Total Environ*. 2025;993:179994. <https://doi.org/10.1016/j.scitotenv.2025.179994>
41. Cui J, Jin Q, Li F, Chen L. Silicon reduces the uptake of cadmium in hydroponically grown rice seedlings: why nanoscale silica is more effective than silicate. *Environ Sci Nano*. 2022;9(5):1961–73. <https://doi.org/10.1039/D1EN00973G>
42. Lai M, Zhou X, Zhao Q, Li H, Ling T, Zheng J. Modulation of metal transporters, oxidative stress and cell abnormalities by synergistic application of silicon and titanium oxide nanoparticles: a strategy for cadmium tolerance in rice. *Chemosphere*. 2023;345:140439. <https://doi.org/10.1016/j.chemosphere.2023.140439>
43. Ghouri F, Shahid MJ, Liu J, Sun L, Riaz M, Imran M, et al. The protective role of tetraploidy and nanoparticles in arsenic-stressed rice: evidence from RNA sequencing, ultrastructural and physiological studies. *J Hazard Mater*. 2023;458:132019. <https://doi.org/10.1016/j.jhazmat.2023.132019>
44. Liang X, Liao Q, Guo P, Yang Z, Kang S, Du T, et al. Silicon nanoparticles enhance maize yield and water productivity via regulating photosynthesis and canopy structure under mild regulated deficit irrigation. *Front Plant Sci*. 2026;16:1691443. <https://doi.org/10.3389/fpls.2025.1691443>
45. Ashraf H, Ghouri F, Liang J, Xia W, Zheng Z, Shahid MQ, et al. Silicon dioxide nanoparticles-based amelioration of cadmium toxicity by regulating antioxidant activity and photosynthetic parameters in a line developed from wild rice. *Plants*. 2024;13(12):1715. <https://doi.org/10.3390/plants13121715>

Additional information

Peer review: Publisher thanks Sectional Editor and the other anonymous reviewers for their contribution to the peer review of this work.

Reprints & permissions information is available at https://horizonpublishing.com/journals/index.php/PST/open_access_policy

Publisher's Note: Horizon e-Publishing Group remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Indexing: Plant Science Today, published by Horizon e-Publishing Group, is covered by Scopus, Web of Science, BIOSIS Previews, Clarivate Analytics, NAAS, UGC Care, etc
See https://horizonpublishing.com/journals/index.php/PST/indexing_abstracting

Copyright: © The Author(s). This is an open-access article distributed under the terms of the Creative Commons Attribution License, which permits unrestricted use, distribution and reproduction in any medium, provided the original author and source are credited (<https://creativecommons.org/licenses/by/4.0/>)

Publisher information: Plant Science Today is published by HORIZON e-Publishing Group with support from Empirion Publishers Private Limited, Thiruvananthapuram, India.