Scientific Bulletin. Series F. Biotechnologies, Vol. XXX, No. 1, 2026
ISSN 2285-1364, CD-ROM ISSN 2285-5521, ISSN Online 2285-1372, ISSN-L 2285-1364

SILICON-BASED ELICITORS FOR SUSTAINABLE CROP PROTECTION

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Abstract

Silicon and its nano-formulations have emerged as powerful elicitors that activate plant immune responses and improve resistance against a wide range of pathogens in crops. Recent studies demonstrate that silicon-based products are able to penetrate root and leaf tissues, trigger systemic acquired resistance in a dose-dependent manner, and rely on salicylic acid signalling to confer broad-spectrum disease protection. Field and greenhouse trials across diverse species show that these formulations can reduce disease indices through physical reinforcement of cell walls, enhanced production of antioxidant enzymes, and priming of pattern-triggered immunity. In addition, to direct pathogen suppression, Si-based products act as biostimulants that modulate the plant microbiome, lower the need for synthetic pesticides, and thus diminish chemical residues in the environment, aligning with One Health goals that link plant health, ecosystem integrity, and human well-being. This review synthesizes current knowledge on the mechanisms of Si-elicited immunity, evaluates the efficacy of Si-based formulations for post-harvest and field protection of crops, and outlines research gaps and regulatory considerations needed to advance Si technologies as safe, sustainable tools within an integrated One Health framework.

Key words*: crops, elicitors, One Health, pathogens, silicon.*

INTRODUCTION

Global food security is under increasing pressure from a growing world population, climate change, and the mounting environmental costs of intensive agrochemical use. The demand for sustainable alternatives to synthetic pesticides and fungicides has intensified focus on naturally occurring compounds capable of bolstering plant immunity without direct toxic effects on target organisms or non-target species (Savvas & Ntatsi, 2015; Verma et al., 2024). In this setting, silicon (Si) has garnered significant interest from the scientific community and commercial interest as a low-cost, environmentally compatible plant protectant with broad-spectrum efficacy across multiple stress categories. Nano-enabled silicon formulations are now recognised as transformative tools for precision agriculture (Kah et al., 2019; Naidu et al., 2023).

Ranking second in crustal abundance, silicon is ubiquitous in agricultural soils worldwide, yet it is not classified as an essential nutrient for the majority of higher plants (Epstein, 1999; Ma and Yamaji, 2006). Despite this, an extensive body of experimental evidence accumulated over the past two decades demonstrates that silicon supplementation confers significant agronomic benefits, particularly under conditions of biotic and abiotic stress (Debona et al., 2017; Mukarram et al., 2025; Etesami and Jeong, 2018). When absorbed by plants predominantly as monosilicic acid ($Si(OH)_4$), silicon is deposited in epidermal tissues as amorphous silica, where it strengthens cell walls, reduces pathogen penetration, and activates a cascade of biochemical and molecular defence responses (Ma & Yamaji, 2006; Wang et al., 2017).

The evolution of nanotechnology has added a new dimension to silicon's agricultural utility. Silicon dioxide nanoparticles (SiO_2 NPs), mesoporous silica nanoparticles (MSNs), and organosilica nanoplatforms combine the intrinsic biological activity of silicon with advanced delivery capabilities, enabling controlled co-release of immune inducers and fungicides, stomatal penetration, and systemic

priming at field-relevant concentrations (El-Shetehy et al., 2021; Yan et al., 2024; Liang et al., 2025). These nano-enabled formulations represent a frontier in precision agriculture and are increasingly evaluated within integrated pest management (IPM) frameworks and the broader One Health paradigm (Lombi et al., 2019; Schaller et al., 2024). This review synthesises current knowledge on the mechanisms by which silicon-based products elicit plant immunity, evaluates nano-enabled formulations and their efficacy across key crop-pathosystems, explores the role of silicon in supporting soil microbiome health and postharvest protection, and outlines future priorities for research, formulation innovation, and regulatory harmonisation essential to unlock the complete benefits of silicon as a cornerstone of resilient crop protection.

SILICON AS A PLANT ELICITOR

Definition of Elicitors vs. Biostimulants

In plant protection science, elicitors are broadly defined as molecules that, upon recognition by plant cells, trigger defence responses without causing disease. Classical elicitors such as microbe-associated molecular patterns (MAMPs) and damage-associated molecular patterns (DAMPs) are detected by plant pattern recognition receptors, activating the pattern-triggered immunity (PTI) response. Silicon occupies a conceptually distinct but functionally overlapping category: it is neither a pathogen-derived signal nor a classical biostimulant, yet it primes plant defences in a manner that closely resembles induced resistance phenomena (Fauteux et al., 2005; Van Bockhaven et al., 2013). The breadth of silicon's benefits, spanning physical barriers, biochemical signalling, and abiotic stress relief, makes it unique among plant protection inputs (Cao et al., 2025).

The distinction between elicitors and biostimulants is relevant here. Biostimulants are defined by their capacity to improve nutrient use efficiency, tolerance to abiotic stress, and crop quality, independent of their nutrient content. Silicon satisfies most criteria for both categories: it reinforces physical barriers (an elicitor-type effect), activates biochemical signalling pathways (a priming effect), and improves photosynthetic efficiency and water use under stress (a biostimulant effect). Savvas and Ntatsi (2015) were among the first to formally position silicon within the biostimulant framework for horticultural crops, a classification now broadly accepted in the literature.

Silicon uptake and accumulation in plants

The primary route of silicon absorption in plants occurs via monosilicic acid ($Si(OH)_4$) dissolved in the soil solution, with substantial interspecific variation in the efficiency of this uptake process. Silicon (Si) accumulation in plants varies significantly across species. Silicon accumulation reaches its peak in commelinoid monocots within the angiosperm clade, especially among representatives of *Poales* and *Arecales*, where shoot silicon levels far exceed those of other monocot lineages. The *Gramineae* and *Cyperaceae* families within *Poales* are consistently identified as the strongest accumulators. In contrast, most plants, especially dicots, are poor Si accumulators (Kumar et al., 2017; Katz et al., 2021). Cereal crops and grasses, with rice and wheat as prime examples, display a remarkable capacity for silicon accumulation, with tissue concentrations reaching 10% dry weight or more, while many dicotyledonous crops accumulate silicon at lower but still functionally relevant levels (Ma et al., 2002; Deshmukh et al., 2017). Root-level silicon uptake efficiency is the principal factor accounting for these interspecific differences in accumulation.

Following root absorption, silicon is translocated via the xylem stream and subsequently polymerises into amorphous silica bodies (phytoliths), which accumulate in epidermal cells, intercellular spaces, and the sub-cuticular layer. These deposits are metabolically inert but alter the physical properties of plant tissues in ways that have profound implications for resistance to pests and pathogens (Ma &Yamaji, 2006; Kim et al., 2002). The silicon distribution within leaves follows both symplastic and apoplastic pathways, with recent studies clarifying the molecular regulation of local silicon allocation in rice leaf tissues (Coskun et al., 2019).

Integration into Integrated Pest Management (IPM) and One Health

Silicon-based products align closely with the principles of integrated pest management (IPM): prevention over cure, reduced reliance on synthetic chemicals, and preservation of ecosystem services. Because silicon enhances plant resistance through physiological priming rather than direct toxic action, it does not select for pest or pathogen resistance in the manner of conventional pesticides and poses minimal risk to beneficial arthropods, soil organisms, and non-target microorganisms (Reynolds et al., 2016; Denarié et al., 2025).

One Health is a holistic framework that acknowledges the intrinsic connections between plant health, animal welfare, human well-being, and broader environmental integrity, treating them as components of a single, integrated system. Silicon-based elicitors reduce pesticide inputs, limiting chemical runoff and contamination of water bodies, while also strengthening plants without toxic residues, improving food safety and farmworker health. They further support rhizosphere biodiversity, supporting the sustained health of soil systems and agroecosystem resilience (Lombi et al., 2019; Schaller et al., 2024). From a regulatory perspective, silicon is generally regarded as a low-risk input, facilitating adoption within organic and reduced-input production systems (Rajput et al., 2022).

MECHANISMS OF SI-ELICITED IMMUNITY

Physical Reinforcement of Barriers

The most consistently documented mechanism by which silicon enhances plant resistance is the physical reinforcement of cell walls and epidermal tissues. Silicon deposition under the cuticular layer and within epidermal cell wall architecture enhances tissue rigidity, reducing the efficiency of penetration by fungi that rely on mechanical force (e.g., appressorium-generated turgor) or enzymatic degradation (e.g., cell wall-degrading enzymes produced by necrotrophic pathogens) to breach host tissues (Wang et al., 2017; Islam et al., 2020).

Evidence from rice systems indicates that the structural consolidation of cell walls driven by silicon application leads to a significant decrease in appressorial penetration by *Magnaporthe grisea* (Kim et al., 2002; Seebold et al., 2001), while in wheat, silicon accumulation at infection sites impedes the development of *Blumeria graminis* (Bélanger et al., 2003). SiO_2 NPs have more recently been demonstrated to inhibit sporulation and pathogenicity of *Fusarium brachygibbosum* infecting olive trees through membrane disruption and morphological damage (Belhedi et al., 2025).

Beyond fungal pathogens, silicon accumulation increases tissue abrasiveness, reducing the feeding efficiency of chewing insects by increasing the mechanical cost of herbivory (Reynolds et al., 2016; Alhousari & Greger, 2018; Acevedo et al., 2021). The modified surface properties of silicon-amended plants also affect sucking insects by modifying phloem accessibility and increasing the physical resistance of leaf surfaces (Singh et al., 2020; Denarié et al., 2025). Silicon as an IPM component for managing insect pests was comprehensively reviewed by Suganthy et al. (2024), confirming its potential as a pesticide-free alternative in several cropping systems.

Biochemical defence responses

Beyond its structural role, silicon modulates a suite of biochemical defence pathways. Silicon-treated plants consistently show elevated activities of antioxidant enzymes, including superoxide dismutase (SOD), peroxidase (POD), catalase (CAT), and phenylalanine ammonia-lyase (PAL), which collectively mitigate oxidative stress during pathogen attack and maintain cellular homeostasis under biotic unfavourable conditions (Etesami & Jeong, 2018; Liang et al., 2003; Verma et al., 2024). Enhanced production of phenolic compounds and phytoalexins has also been documented in silicon-amended wheat infected with powdery mildew, indicating that silicon promotes secondary metabolite production beyond simple enzyme activation (Rémus-Borel et al., 2005).

Under abiotic adversity, including salinity, drought, and heavy metal exposure, silicon-supplemented plants mount a more robust enzymatic antioxidant response, characterised by heightened SOD, CAT, and APX (ascorbate

peroxidase) activities that work in concert to quench excess ROS (reactive oxygen species) and prevent oxidative cellular damage. These effects overlap substantially with patterns recorded under biotic stress, pointing that silicon primes a generalised stress response network rather than pathway-specific immune circuits (Liang et al., 2007; Ranjan et al., 2021; Mariyam et al., 2024).

Molecular priming and signalling

Silicon operates at the molecular level by sensitising plant immune circuits, simultaneously enhancing PTI responsiveness and triggering SAR (systemic acquired resistance) through signalling pathways in which salicylic acid serves as the principal mediator. Silicon supplementation upregulates SA signalling, driving the expression of pathogenesis-related (PR) proteins and a cascade of downstream defence genes whose coordinated activity underpins the establishment of systemic resistance (Van Bockhaven et al., 2013; Wang et al., 2017). Silicon additionally fine-tunes the reciprocal interactions between SA, JA (jasmonic acid), and ET (ethylene) hormonal circuits, conferring a versatile priming state that renders plants simultaneously fortified against both biotrophic and necrotrophic infection strategies (Ranjan et al., 2021; Song et al., 2021).

Silicon does not function as a classical elicitor by binding to specific pattern recognition receptors, but rather operates as a 'priming agent' that potentiates faster and stronger defence activation upon challenge. This priming effect reduces disease severity without constitutively activating costly immune responses, representing an energetically efficient strategy for enhancing resistance (Fauteux et al., 2005; Coskun et al., 2019). Nano-silicon formulations appear to amplify this priming capacity by enabling more efficient cellular uptake and sustained release of bioavailable silicon, as demonstrated in rice sheath blight models using MSN-based delivery systems (Liang et al., 2025).

Interaction with the Plant Microbiome

Silicon exerts significant indirect effects on plant protective responses through its documented ability to shift the composition of soil microbial assemblages in the root zone. Silicon-treated soils show enrichment of beneficial bacterial taxa including *Sphingomonas* spp. and *Streptomyces* spp., which contribute to disease suppression through the release of bioactive compounds capable of suppressing fungal growth and competition with pathogens residing in the soil matrix (Verma et al., 2022; Song et al., 2021). Biocontrol organisms such as *Trichoderma* spp. and *Pochonia chlamydosporia* are preserved or enhanced in silicon-treated rhizospheres, providing synergistic disease suppression without disrupting existing IPM programmes (Verma et al., 2021).

Applied silicon, whether as soluble silicic acid or SiO_2 nanoparticles, degrades into monosilicic acid and is ultimately incorporated into the natural silicon cycling of the soil, supporting beneficial soil microorganisms and maintaining rhizosphere health rather than accumulating as a persistent pollutant (Mukarram et al., 2022; Schaller et al., 2024). This property is particularly relevant from a One Health perspective, as it ensures that silicon application does not disrupt soil biodiversity or the microbial services upon which sustainable crop production depends.

NANO-ENABLED SILICON FORMULATIONS

Silicon Dioxide Nanoparticles (SiO_2NPs)

Silicon dioxide nanoparticles represent the most extensively studied class of nano-silicon formulations in agriculture. The nanoscale dimensions of SiO_2 NPs - typically ranging from 10 to 100 nm - generate a disproportionately large surface area relative to particle volume, a property that underpins their superior capacity for dissolution, chemical interaction, and translocation within plant tissues when set against conventional silicon sources (Yan et al., 2024; Mukarram et al., 2022). Their reduced particle dimensions enables penetration through stomata and root cell walls, facilitating direct interaction with cellular components and achieving more uniform silicon distribution within plant tissues compared to conventional silicate fertilisers (El-Shetehy et al., 2021).

El-Shetehy et al. (2021) demonstrated in a landmark investigation published in Nature Nanotechnology that hat when SiO_2 NPs were supplied at rates of 50-200 mg L^{-1} enhanced disease suppression capacity in *Arabidopsis thaliana* towards *Botrytis cinerea* and *Pseudomonas syringae* through SAR operating via salicylic acid-dependent regulatory circuits, with efficacy comparable to or exceeding that of chemical resistance inducers. Comparable results have been documented in wheat (Abdelrhim et al., 2021) and rice (Cai et al., 2008), with SiO_2 NPs activating antioxidant enzyme networks and reducing pathogen-induced oxidative damage. The capacity of SiO_2 NPs to prime systemic immunity makes them particularly attractive for foliar application in high-value crops where uniform systemic coverage is difficult to achieve with soil-applied silicon.

Mesoporous Silica Nanoparticles (MSNs)

Silica-based nanostructures featuring a well-defined mesoporous framework constitute characterised by a highly ordered pore structure with large specific surface areas (typically 500-1200 m^2 g^{-1}) and tunable pore sizes, making them excellent nanocarriers for the controlled delivery of agrochemicals, immune inducers, and biological control agents (Liang et al., 2020). MSNs are particularly valued for their dual capability: harbouring immune-priming agents such as salicylic acid (SA) within their mesoporous interior while simultaneously permitting surface functionalisation with stimuli-responsive gatekeeping systems- an advancement that has redefined possibilities in precision crop protection. (Liang et al., 2025).

A particularly innovative development is the MSN-ss-SA system reported by Liang et al. (2025), in which SA is covalently conjugated to disulfide-doped mesoporous silica nanoparticles (MSNs-ss-NH_2) via amide bonds. This architecture enables dual stimuli-responsive release activated by glutathione (GSH) and amidase, both being elevated at infection sites in plant tissues. Given their approximate particle diameter of 90 nm, MSNs-ss-SA can access the internal leaf environment of rice by passing through stomatal pores and deliver SA and bioavailable silicon concurrently, significantly enhancing resistance to rice sheath blight by activating physical barrier formation, antioxidant defence, and key immune genes including CsNPR1, CsPR1, CsERF004, and CsWRKY50.

Organosilica nanoplatforms

Organosilica nanoplatforms extend the capabilities of conventional MSNs by embedding organic bridging groups into the silica skeletal structure, enabling the co-delivery of chemically distinct actives with independent, controllable release kinetics. The CYM@MON-SA system developed by Zhang et al. (2025) exemplifies this approach: the plant immune inducer SA is grafted onto disulfide-bridged mesoporous organosilica nanoparticles (MON-NH_2), while the fungicide cymoxanil (CYM) is loaded into the mesopores. Dual stimuli-responsive release triggered by GSH and amidase enables synergistic disease management, with the SA component simultaneously priming plant immunity while CYM suppresses fungal growth. Importantly, the CYM@MON-SA formulation demonstrated a 3.22-fold increase in CYM photostability compared to technical-grade CYM, addressing a key limitation of conventional fungicide formulations. The triple-stimuli-responsive organosilica systems described by Song et al. (2025) represent further advances in this direction, offering pH, GSH, and chitinas-responsive pesticide release specifically triggered by pathogen infection.

Similar dual-function systems have been developed using pH, redox, and enzyme-responsive nanocarriers loaded with strobilurin fungicides and delivered to mitochondrial targets, offering improved selectivity for fungal pathogens and reduced toxicity to plant cells (Wu et al., 2025). The convergence of nano-delivery technology with plant immunity induction represents a paradigm shift in crop protection, moving away from single-mode-of-action inputs towards multifunctional, precision systems aligned with IPM principles.

Nano-Silicon Chelates and Nano-Silicon Foliar Sprays

Nano-silicon chelates and nano-silicon foliar sprays represent a more commercially accessible tier of nano-enabled silicon application, bridging the gap between

laboratory-scale nanoparticle synthesis and farm-scale implementation. Field-relevant concentrations of 50-200 mg L^{-1} of nano-silicon applied as foliar sprays have demonstrated significant effects on salt and drought stress tolerance, ion homeostasis, and disease indices in multiple crop species including feverfew, sugarcane, and citrus (Esmaili et al., 2022; Mvondo-She et al., 2021; Rachappanavar et al., 2024). The high surface area and improved bioavailability of nano-silicon relative to bulk silicates contribute to more consistent responses at lower application rates, reducing the material cost of silicon supplementation. The comparative efficacy of different silicon compound formulations delivered by foliar route has been systematically evaluated, confirming that nanoformulations generally outperform conventional silicate sprays for disease suppression at equivalent concentrations (Laane, 2018).

EFFICACY ACROSS CROPS AND PATHOSYSTEMS

Cereal crops

Graminaceous crops, particularly rice and wheat, have been the primary focus of silicon efficacy research given their naturally high silicon accumulation capacity. In rice, silicon supplementation consistently reduces blast severity caused by *Magnaporthe oryzae*, with disease index reductions of 30-60% reported across multiple studies (Seebold et al., 2001; Cai et al., 2008). Silicon application also suppresses sheath blight caused by *Rhizoctonia solani*, bacterial blight caused by *Xanthomonas oryzae*, and brown planthopper infestations through combined physical and biochemical mechanisms (Verma et al., 2024).

In wheat, silicon reduces powdery mildew (*Blumeria graminis*) severity through cell wall silicification and the induction of antifungal compounds, among which phenolic compounds and pathogen-suppressing phytoalexins feature prominently (Bélanger et al., 2003; Rémus-Borel et al., 2005). Both root-applied potassium silicate and foliar silicon sprays are effective delivery routes for wheat, with the efficacy dependent on timing and concentration. The effect of silicon on *Fusarium crown* and root rot in tomato (Huang et al., 2011) and *Fusarium wilt* in banana (Fortunato et al., 2012) further extends the documented spectrum of silicon-mediated resistance to economically significant soilborne diseases.

Horticulture and fruit crops

In horticultural systems, silicon has demonstrated efficacy against powdery mildew in cucumber (Liang et al., 2005), grape (Bowen et al., 1992), and multiple other species, with both root-applied and foliar silicon treatments reducing mycelial development and sporulation. In citrus, silicon-based treatments have shown promise against *Penicillium digitatum* (Liu et al., 2010; Moscoso-Ramírez & Palou, 2014) in storage-phase settings, while field applications have suppressed various biotic stresses associated with citrus production (Mvondo-She et al., 2021).

In banana and citrus, Si-based treatments reduced Fusarium wilt and Penicillium decay without adversely affecting populations of endophytic biocontrol fungi such as *Pochonia chlamydosporia* and *Trichoderma* spp., preserving ecosystem services essential for IPM (Verma et al., 2021). Silicon treatments in grape and citrus have also maintained ascorbic acid, phenolic, and flavonoid contents in fruit, preserving nutritional quality and extending shelf life without introducing synthetic residues - a direct benefit for food safety and human health within the One Health framework (Rachappanavar et al., 2024).

Postharvest protection

Postharvest decay is a major contributor to food loss globally, with fungal pathogens including *Botrytis cinerea*, *Penicillium digitatum*, and *Rhizopus stolonifer* causing significant losses in fruits and vegetables. Silicon-based postharvest treatments, including sodium silicate dips and potassium silicate sprays, reduce decay indices by inducing physiological resistance in harvested tissues and by exerting a degree of direct antifungal activity through membrane damage mechanisms (Bi et al., 2006; Liu et al., 2010). Unlike conventional synthetic fungicides, silicon does not leave toxic metabolites on fruit surfaces, making it compatible with organic

certification standards and aligned with consumer demands for pesticide-free produce.
Sodium silicate treatment of Hami melons reduced *Trichothecium roseum* and other postharvest pathogens while simultaneously activating antioxidant enzyme systems and reducing oxidative stress in harvested fruit (Bi et al., 2006). Potassium silicate treatments on oranges demonstrated preventive and curative efficacy against *Penicillium italicum* and *P. digitatum* (Moscoso-Ramírez & Palou, 2014). SiO_2 nanoparticle coatings on citrus and grape maintained ascorbic acid and polyphenol contents while inhibiting *Botrytis* development, extending marketable shelf life without synthetic residues (Rachappanavar et al., 2024).

SILICON-BASED PRODUCTS IN THE ONE HEALTH CONTEXT

Environmental health benefits

Silicon-based products and their nano-enabled formulations represent a unique class of biological actives that embed deeply within the One Health concept by simultaneously advancing environmental, human, and animal health while sustaining productive crop systems (Schaller et al., 2024).
Applied silicon, whether as soluble silicic acid or SiO_2 nanoparticles, is ultimately deposited as amorphous silica (phytoliths) in plant tissues, where it provides its protective functions, and subsequently cycles back into the soil silicon pool upon crop residue decomposition. This dynamic does not generate persistent chemical residues, contrasting sharply with the environmental fate of many synthetic pesticides that accumulate in soil, surface water, and aquatic ecosystems (Lombi et al., 2019).
Silicon amendments attenuate the phytotoxic impact of heavy metals such as arsenic and cadmium in polluted soils by trapping these contaminants within the rhizospheric zone, reducing their translocation to above-ground plant tissues, thereby protecting soil and water quality (Mariyam et al., 2024). By restoring natural silicon cycles disrupted in intensive agriculture - where repeated harvesting of silica-rich biomass depletes soil silicon pools - silicon-based products foster a circular-economy approach that supports long-term agroecosystem resilience (Schaller et al., 2024; Rodriguez & Rombola, 2025).

Human health benefits

Postharvest decay and pesticide residues are major contributors to food loss and chronic dietary exposure to hazardous chemicals. Silicon-based elicitors reduce both simultaneously. Unlike conventional fungicides, silicon does not leave toxic metabolites on fruit surfaces, ensuring safer consumption and facilitating access to organic and premium markets (Rachappanavar et al., 2024).
The reduction of pesticide use also lowers occupational exposure risks for farmworkers, a key human health benefit recognised within One Health frameworks (Lowry et al., 2019). Furthermore, silicon-enhanced plant immunity reduces crop losses to pathogens and pests, stabilising food supply chains and prices, particularly in developing regions where banana and citrus exports are economic lifelines.
Silicon supplementation in crops has been linked to enhanced nutritional quality of harvested produce, including higher ascorbic acid, phenolic, and antioxidant contents, with direct implications for dietary health (Rachappanavar et al., 2024). Nano-silicon formulations that avoid leaving residues on fruit surfaces while improving quality indices represent a promising alignment of agricultural innovation with public health goals.

Regulatory landscape

From a regulatory perspective, silicon-based products are generally regarded as safe inputs with low toxicity to humans and non-target organisms (Rajput et al., 2022). Most commercial silicon formulations (potassium silicate, sodium silicate, silicic acid) are registered as fertilisers or plant strengtheners rather than as pesticides in most jurisdictions, which simplifies regulatory approval but also limits the marketing claims that producers can make about their protective effects.
Nano-silicon formulations present additional regulatory challenges, as SiO_2 nanoparticles are subject to nanomaterial-specific assessment frameworks in the European Union (REACH) and comparable regulatory structures in other

jurisdictions (Ding et al., 2023; Iavicoli et al., 2017).

The development of standardised toxicological and ecotoxicological testing protocols for nano-silicon products, encompassing impacts on beneficial soil microorganisms and non-target biota, is a priority for facilitating market approval and building stakeholder confidence (Mukarram et al., 2025).

SILICON AND ABIOTIC STRESS TOLERANCE

Substantial experimental evidence has consolidated the view of silicon as a multifaceted agent capable of reinforcing plant tolerance to an array of abiotic challenges, from drought and salinity to heavy metal burden and nutritional imbalance (Debona et al., 2017; Etesami and Jeong, 2018; Thorne et al., 2020). These stress-mitigating effects contribute indirectly to crop protection by maintaining plant vigour and reducing susceptibility to secondary pest and disease outbreaks under stressful environmental conditions. Improved water use efficiency, enhanced photosynthetic stability, and reduced ion toxicity have all been reported in silicon-amended plants, supporting the view that silicon enhances overall crop resilience rather than targeting single stress factors (Cooke & Leishman, 2016; Verma et al., 2024).

Under drought stress, silicon maintains cellular water balance through regulation of stomatal conductance and accumulation of compatible solutes. Under salt stress, silicon reduces ion toxicity by immobilising excess Na^+ and Cl^- in cell walls and vacuoles, keeping ionic homeostasis and membrane integrity. Under heavy metal stress, silicon sequesters toxic metals in the rhizosphere and at the root level, reducing their translocation to shoots and fruit - a critical food safety consideration where contaminated soils are used for production of edible crops (Mariyam et al., 2024; Liang et al., 2007).

As climate change compounds the frequency and intensity of both biotic and abiotic stressors in agricultural systems, the multipronged protective action of silicon becomes increasingly pertinent, where crops are ever more exposed to combined stress scenarios. Silicon application that simultaneously reduces fungal disease pressure and improves drought tolerance offers a strategic advantage for climate-smart crop management, reducing the need for multiple separate inputs and lowering the overall agrochemical burden on farm systems (Schaller et al., 2025; Mukarram et al., 2025).

RESEARCH GAPS AND FUTURE PRIORITIES

Regardless of the extensive documentation base supporting silicon's role in crop protection, several critical knowledge and implementation gaps limit its widespread adoption as a mainstream component of sustainable agriculture.

Mechanistic research. Future work must employ advanced molecular profiling, including CRISPR-based gene knockout studies and phosphoproteomics, to fully identify the receptors mediating SiO_2 nanoparticle responses in fruit crops and to clarify the downstream hormonal (SA/JA/ET) and MAPK signalling pathways. A comprehensive molecular map of silicon-primed immunity would enable rational design of formulations targeting specific resistance pathways for particular crop-pathogen combinations (Coskun et al., 2019; Mukarram et al., 2025).

Formulation and delivery innovation. Innovative nanocarrier technologies, including chitosan-Si composites and stimuli-responsive organosilica nanoplatforms, must be further developed to protect SiO_2 NPs from environmental degradation and enable controlled-release, synergistic co-delivery with microbial biocontrol agents. Smart, pathogen-responsive application systems that release their active payload only in the presence of disease-specific microenvironmental cues (pH change, GSH elevation, pathogen enzyme activity) represent the frontier of precision crop protection (Liang et al., 2025; Zhang et al., 2025; Wu et al., 2025).

Regulatory harmonisation and safety assessment. The priority is to harmonise fragmented global regulatory standards for SiO_2 nanoparticles by developing rigorous, standardised protocols for toxicological,

ecotoxicological, and chronic exposure assessment, including impacts on beneficial soil microbes and non-target arthropods. Coordinated international standards would expedite market entry and build the confidence of growers, processors, and consumers in nano-silicon products (Iavicoli et al., 2017; Ding et al., 2023).

Economic viability and scalability. Cost-effective green synthesis methods for SiO_2 nanoparticles using agricultural residues such as rice husk ash, coupled with life-cycle cost-benefit analyses demonstrating how reduced pesticide reliance and premium market access outweigh investment costs, are needed to drive broad adoption, particularly among smallholder farmers in resource-limited agricultural settings (Rajput et al., 2022; Schaller et al., 2024).

Climate resilience integration. Research must evaluate silicon's efficacy under realistic, combined biotic-abiotic stress scenarios common in changing climate conditions, and develop climate-smart application protocols that account for the overlapping consequences of thermal pressure, drought, and pathogen pressure on silicon performance (Schaller et al., 2025; Mukarram et al., 2025).

Integration with digital agriculture. Artificial intelligence and IoT sensor networks should be leveraged to predict disease outbreaks, optimise silicon spray timing and dosage, and utilise remote-sensing platforms to provide real-time feedback on silicon-induced physiological changes (e.g., enhanced chlorophyll fluorescence) for precision application (Yan et al., 2024; Schaller et al., 2024).

Socioeconomic and extension support. Successful farmer adoption requires development of IPM decision-support tools, practical training on silicon's triple-action benefits (disease control, stress tolerance, quality enhancement), and policy incentives such as subsidies or premium price access to accelerate uptake by smallholder farmers in silicon-responsive cropping systems (Artyszak, 2018).

Silicon, especially in nano-enabled formulations, functions as a versatile elicitor that simultaneously fortifies physical barriers, boosts biochemical defences, and primes immune signalling across a broad spectrum of crop-pathogen interactions. The meeting point between traditional silicon science and nanotechnology has spawned a new era of precision formulations, including MSN-based co-delivery systems and dual stimuli-responsive organosilica nanoplatforms, that dramatically expand the utility and efficiency of silicon in crop protection.

Robust evidence across diverse crops, from cereals to horticultural and fruit crops, demonstrates silicon's capacity to lower disease indices, reduce insect herbivory, extend postharvest shelf life, and improve tolerance to abiotic stress, all without generating persistent chemical residues. These properties position silicon as a genuinely multi-functional input aligned with IPM principles and the One Health framework, linking plant health, ecosystem integrity, and human well-being within a single, coherent sustainability paradigm.

Silicon-based products are not a standalone solution: crop species with low silicon uptake capacity, suboptimal application timing, and incompatibility with certain soil conditions can limit their efficacy. However, within the broader architecture of integrated crop production systems complemented by biocontrol agents, digital disease monitoring, and precision delivery technology- silicon offers a scientifically validated, environmentally sound, and economically viable pathway towards sustainable, low-input agricultural production. Targeted research, innovative formulation, and coherent regulatory pathways are essential to realise silicon's full potential as a cornerstone of twenty-first-century sustainable crop protection.

ACKNOWLEDGEMENTS

This research was carried out with the support of ADER 16.1.2. project "Research on the development of a food quality scheme along the food chain according to the One Health concept".

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