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Aparna Mohan
M.Sc. Student, Department of Soil
Science and Agricultural
Chemistry, College of Agriculture,
Vellayani, Thiruvananthapuram,
Kerala, India

Biju Joseph
Professor, Soil Science and
Agricultural Chemistry, FSRS,
Sadanandapuram, Kerala, India

B Rani
Professor and Head, Department
of Soil Science and Agricultural
Chemistry, College of Agriculture,
Vellayani, Thiruvananthapuram,
Kerala, India

R Gladis
Professor (Soil Science and
Agriculture Chemistry) and Head,
ARS, Thiruvalla, Kerala, India

Usha C Thomas
Professor, Department of
Agronomy, College of Agriculture,
Vellayani, Thiruvananthapuram,
Kerala, India

Corresponding Author:
Biju Joseph
Professor, Soil Science and
Agricultural Chemistry, FSRS,
Sadanandapuram, Kerala, India

Silicon nutrition in rice: From soil dynamics to sustainable crop management

Aparna Mohan, Biju Joseph, B Rani, R Gladis, Usha C Thomas

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Abstract

Rice is one of the largest silicon-accumulating crops, and adequate silicon nutrition is increasingly recognized as an important component of sustainable rice production. However, continuous cropping, removal of silicon-rich residues, and changing water management practices have reduced the availability of plant-accessible silicon in many rice-growing soils, increasing the risk of silicon deficiency and limiting crop performance under environmental stress. Silicon influences rice growth through multiple mechanisms, including efficient nutrient uptake and transport, improved nutrient use efficiency, enhanced structural reinforcement, and greater tolerance to abiotic and biotic stresses. Recent studies also demonstrate the importance of sustainable silicon management through residue recycling, silicon fertilizers, nano-silicon, and silicon-solubilizing microorganisms to replenish available silicon and improve crop productivity. These approaches not only enhance grain yield and quality but also contribute to improved resource use efficiency and long-term soil sustainability. Current evidence indicates that integrating conventional silicon fertilization with emerging biological and sustainable management practices can strengthen the resilience of rice production systems. Further long-term field validation under diverse agroecological conditions will be essential for developing efficient and economically viable silicon management strategies.

Keywords: Silicon, Rice (*Oryza sativa* L.), nutrient use efficiency, stress management, toxicity alleviation

1. Introduction

Rice (*Oryza sativa* L.) is one of the world's major staple food crops and provides the principal source of dietary energy for more than half of the global population, particularly in Asia, where it is central to food security (IRRI, 2013) ^[1]. Meeting the increasing demand for rice from a growing global population remains a major challenge because productivity is constrained by intensive cultivation, climate variability, and increasing abiotic and biotic stresses. Silicon (Si), a beneficial element for rice, has attracted considerable interest because it improves plant growth, reinforces structural integrity, and enhances tolerance to environmental stresses. Although silicon is not classified as an essential nutrient for higher plants, rice is among the highest silicon-accumulating crops, absorbing up to 300 kg Si ha⁻¹, with silicon comprising as much as 10% of shoot dry weight. Silicon deposited beneath the cuticle forms a cuticle-silica double layer that strengthens plant tissues and contributes to resistance against abiotic and biotic stresses (Dhanasekaran *et al.*, 2025) ^[11]. These characteristics highlight the importance of adequate silicon nutrition for sustainable rice production.

Silicon is the second most abundant element in the Earth's crust, accounting for approximately 28% of the lithosphere, yet only a small fraction is present in forms readily available for plant uptake (Rao & Susmitha, 2017) ^[41]. Most soil silicon exists as insoluble oxides and aluminosilicate minerals, whereas rice plants absorb silicon exclusively as monosilicic acid (H₄SiO₄) (Datnoff *et al.*, 2001) ^[9]. Continuous rice cultivation and the removal of silicon-rich crop residues gradually reduce the pool of plant-available silicon in many paddy soils, increasing the risk of silicon deficiency under intensive production systems (McCarty *et al.*, 2025). Water management practices also influence silicon availability. Under continuous flooding, reduced soil conditions promote the release of monosilicic acid into the soil solution (Tubaña & Heckman, 2015) ^[52]. In contrast, water-saving cultivation practices such as alternate wetting and drying (AWD) and aerobic rice cultivation modify soil redox conditions, which may reduce the availability of soluble

silicon under certain conditions.

This review provides an integrated overview of silicon dynamics in the soil–plant continuum, including silicon uptake and transport, interactions with essential nutrients, and the physiological mechanisms underlying silicon-mediated tolerance to abiotic and biotic stresses in rice. It also discusses recent advances in sustainable silicon management, with emphasis on crop residue recycling, chemical and natural silicon fertilizers, nano-silicon, silicon-solubilizing microorganisms, and the economic implications of silicon application. By integrating these aspects, this review aims to provide a comprehensive understanding of the role of silicon in enhancing the productivity, sustainability, and resilience of rice production systems

2. Biogeochemical Silicon Dynamics in the Soil-Plant Continuum

The availability of silicon (Si) in rice ecosystems is not merely a reflection of its total abundance in the Earth's crust, but rather the result of complex, continuous biogeochemical transformations between various soil fractions. In paddy environments, these dynamics are uniquely governed by soil granulometric composition, electrochemical changes, and shifting moisture regimes.

2.1 Soil Silicon Pools

Although silicon makes up about 28% of the Earth's crust by weight, much of it is not readily available for uptake by plants. Within the soil matrix, silicon exists in complex dynamic equilibria and is fractionated into five primary pools of varying thermodynamic stability: mobile Si (dissolved in the soil solution), adsorbed Si, organically bound Si, Si occluded in pedogenic oxides or hydroxides, and amorphous or biogenic Si (Tubaña & Heckman, 2015) ^[52]. Quantitative sequential extraction analyses highlight the fundamental paradox of silicon nutrition in agriculture. The plant-available mobile pool typically represents the smallest fraction, ranging from merely 14.4 to 44.6 mg kg⁻¹, whereas the thermodynamically resistant amorphous Si acts as the vastly larger reservoir, ranging from 8,019 to 16,667 mg kg⁻¹ (Pallavi & Prakash, 2019) ^[38]. Because rice roots absorb Si almost exclusively in the uncharged form of monosilicic acid (H₄SiO₄), this minute mobile pool is rapidly depleted during active vegetative and reproductive growth (Ashokan *et al.*, 2023) ^[5]. Consequently, to prevent acute deficiency in intensive cropping systems, the soil solution must be continuously replenished through the desorption of adsorbed Si and the slower weathering and dissolution of the amorphous and occluded pools.

2.2 Factors Affecting Silicon Solubility

The availability of monosilicic acid in paddy soils is influenced by soil texture and physicochemical properties. Soil texture affects silicon retention and mobility, with fine-textured clay soils generally retaining more plant-available silicon because of their higher adsorption capacity, whereas coarse-textured sandy soils are more susceptible to silicon leaching and depletion (El-Sayed *et al.*, 2019) ^[14]. Soil pH also regulates silicon speciation. Under moderately acidic to neutral conditions, silicon is present predominantly as monosilicic acid (H₄SiO₄), the form readily absorbed by plants. As soil pH increases above approximately 8.9, monosilicic acid gradually dissociates into silicate anions (H₃SiO₄⁻), altering its adsorption behavior and influencing its availability to plants (Haynes, 2014) ^[18]. In flooded paddy soils, anaerobic conditions lower the soil redox potential, promoting the reduction of ferric (Fe³⁺) oxides to ferrous (Fe²⁺) forms. This process can release silicon associated with iron oxides into the soil solution, increasing the concentration of dissolved

monosilicic acid and enhancing silicon availability under flooded conditions (Schaller *et al.*, 2022) ^[44].

2.3 Impact of Water-Saving Cultivation Practices on Silicon Availability

The adoption of water-saving cultivation practices, such as aerobic rice cultivation and alternate wetting and drying (AWD), has introduced new challenges for silicon management in rice production. These practices are increasingly promoted in rice-growing regions, including India, to improve water-use efficiency in response to declining freshwater availability and increasing demand for sustainable rice production. Unlike continuously flooded paddy fields, aerobic cultivation maintains well-drained and oxidized soil conditions, resulting in higher soil redox potential. Under these conditions, the reduction of iron and aluminum oxides is limited, thereby decreasing the release of silicon associated with these minerals into the soil solution (Sommer *et al.*, 2006) ^[48].

Consequently, the concentration of plant-available monosilicic acid is generally lower under aerobic conditions than under continuously flooded soils (Tubaña & Heckman, 2015) ^[52]. The decline in silicon availability may be further aggravated in intensively cultivated rice systems where continuous cropping and limited silicon replenishment have progressively depleted the pool of plant-available silicon (Jinger *et al.*, 2022) ^[25]. Therefore, maintaining adequate silicon nutrition through appropriate silicon management practices, including silicon fertilization where required, may help sustain rice growth and productivity under water-saving cultivation systems.

3. Molecular Mechanisms of Silicon Uptake, Transport, Redistribution, and Deposition in Rice

3.1 Root Silicon Uptake System

Rice absorbs silicon predominantly as the uncharged monosilicic acid [Si(OH)₄] from the soil solution. The radial transport of silicic acid across the root exodermis and endodermis is regulated by Casparian strips, which restrict apoplastic movement and necessitate transporter-mediated transcellular transport before silicic acid enters the stele (Ma & Yamaji, 2015) ^[29]. To overcome these apoplastic barriers, rice employs a cooperative transcellular transport system comprising the influx transporter OsLsi1 and the efflux transporter OsLsi2. OsLsi1, a member of the Nod26-like major intrinsic protein (NIP) aquaporin subfamily, is polarly localized on the distal side of exodermal and endodermal cells, where it mediates the passive uptake of silicic acid into the symplast. In contrast, OsLsi2, a proton gradient-driven efflux transporter, is localized on the proximal side of the same cells and exports silicic acid toward the stele, thereby establishing an efficient directional transport pathway. Collectively, the coordinated actions of OsLsi1 and OsLsi2 establish an efficient transcellular pathway that enables selective silicon uptake across the root apoplastic barriers and into the root stele (Ma *et al.*, 2006; Ma *et al.*, 2007; Ma & Yamaji, 2015) ^[27, 28, 29].

3.2 Xylem Loading and Silicon Distribution

Once monosilicic acid reaches the root stele, its loading into the xylem is mediated by the efflux transporters OsLsi2 and OsLsi3. OsLsi3, localized in the root pericycle without polar localization, complements the function of OsLsi2 and facilitates efficient xylem loading for root-to-shoot silicon transport (Huang *et al.*, 2022) ^[10]. Silicon is subsequently transported through the xylem by the transpiration stream to the shoot, where OsLsi6, a NIP III aquaporin homolog of OsLsi1, is localized in the xylem parenchyma cells on the side facing the xylem vessels. OsLsi6 mediates the unloading of monosilicic acid from the xylem into

leaf tissues, thereby regulating silicon distribution and deposition within the shoot (Yamaji *et al.*, 2008) [56].

In addition to root-to-shoot transport, silicon redistribution within the rice shoot is regulated at Node I, which directs silicon toward developing panicles. This process depends on the distinct localization of three silicon transporters within different vascular tissues (Yamaji *et al.*, 2015) [57]. OsLsi6 unloads monosilicic acid from the enlarged vascular bundles, whereas OsLsi2 in the bundle sheath cells and OsLsi3 in the parenchyma bridge cells facilitate silicon transfer into the diffuse vascular bundles, promoting preferential transport to developing panicles (Yamaji *et al.*, 2015; Huang & Ma, 2024) [57, 19]. Together, these transporters coordinate long-distance silicon transport and its preferential distribution to aerial and reproductive tissues.

3.3 Cellular Silicon Deposition and Homeostasis

Following transport to the aerial tissues, monosilicic acid

becomes concentrated as water is lost through transpiration and subsequently polymerizes into amorphous silica ($\text{SiO}_2 \cdot n\text{H}_2\text{O}$), which is deposited beneath the cuticle and in specialized cells such as silica and bulliform cells. Proper silicon deposition is mediated by SIET4, an efflux transporter localized in epidermal cells and cells surrounding bulliform cells, where it exports silicic acid from leaf cells to the sites of silica deposition. Loss of SIET4 results in abnormal intracellular silica deposition without affecting total silicon uptake and accumulation (Mitani-Ueno *et al.*, 2023; Huang & Ma, 2024) [34, 19]. Rice maintains silicon homeostasis by regulating the expression of silicon transporter genes in response to silicon accumulation in the shoot. High silicon accumulation suppresses the expression of the root uptake transporters OsLsi1 and OsLsi2, and recent evidence indicates that OsLsi3 is regulated in a similar manner. However, the signaling mechanism underlying this regulation remains unclear (Mitani-Ueno *et al.*, 2016; Huang & Ma, 2024) [35, 19].

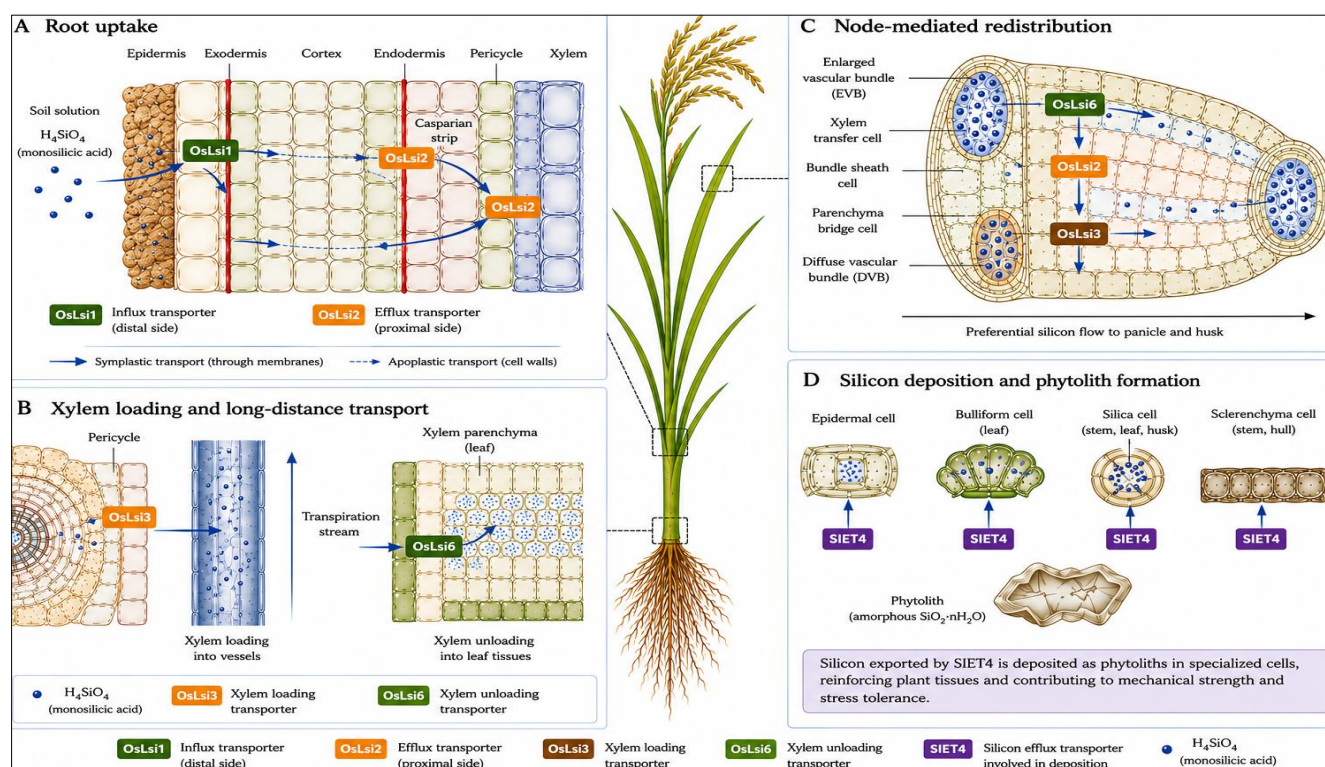


Fig 1: Molecular mechanisms of silicon uptake, transport, redistribution, and deposition in rice. Monosilicic acid (H_4SiO_4) is absorbed from the soil solution through OsLsi1 and exported into the stele by OsLsi2. OsLsi3 contributes to xylem loading, whereas OsLsi6 mediates xylem unloading and redistribution toward developing tissues. SIET4 exports silicon to specialized deposition sites, where it polymerizes into phytoliths that reinforce plant tissues and contribute to stress tolerance.

4. Silicon–Nutrient Interactions and Nutrient Use Efficiency

4.1 Silicon-Mediated Enhancement of Phosphorus Availability

Silicon and phosphorus interact through competitive adsorption reactions in soil because silicate and phosphate compete for adsorption sites on iron (Fe) and aluminum (Al) oxides. This competition reduces phosphate fixation and increases the concentration of plant-available phosphorus in the soil solution (Agostinho *et al.*, 2017) [2]. While recent studies have shown that it can influence iron mineral speciation in paddy soils, thereby promoting the release of phosphorus into more bioavailable forms (Jinger *et al.*, 2022; Schaller *et al.*, 2022) [25, 44].

Greater phosphorus availability improves phosphorus acquisition by rice, particularly under phosphorus-deficient conditions. Silicon application has been reported to increase soil Olsen-P, promote the transformation of phosphorus into more labile forms,

enhance the expression of the phosphorus transporter genes *OsPT2*, *OsPT4*, and *OsPT8*, and increase phosphorus accumulation in roots and leaves. Silicon also stimulates root organic acid secretion, enhances acid phosphatase activity, and enriches phosphorus-solubilizing microorganisms, thereby improving phosphorus mobilization and uptake. Together, these responses contribute to improved phosphorus-use efficiency and support more sustainable phosphorus management in rice production systems (Jiang *et al.*, 2025) [23].

4.2 Silicon-Mediated Enhancement of Nitrogen Use Efficiency

Nitrogen (N) is an essential macronutrient required for plant growth and development, whereas silicon (Si) is a beneficial element that accumulates in rice and contributes to improved growth, productivity, and tolerance to biotic and abiotic stresses. Previous studies have demonstrated a close interaction between

nitrogen and silicon during plant nutrition, with nitrogen availability influencing silicon accumulation and silicon reciprocally affecting nitrogen uptake, assimilation, and utilization. Although the molecular mechanisms underlying this interaction were initially unclear, subsequent studies have shown that silicon regulates multiple physiological and biochemical processes associated with nitrogen uptake, assimilation, and metabolism (Wu *et al.*, 2017) ^[54].

In addition to its role in nitrogen metabolism, silicon alleviates the adverse effects associated with excessive nitrogen fertilization, including lodging susceptibility and suboptimal canopy architecture, by enhancing culm strength, tissue rigidity, and leaf erectness, thereby improving canopy structure and light interception (McCarty *et al.*, 2025). Silicon also enhances nitrogen use efficiency, particularly under low and moderate-nitrogen supply, by promoting nitrogen uptake, assimilation, and accumulation. Silicon application stimulates the activities of key nitrogen-assimilating enzymes, including nitrate reductase (NR), glutamine synthetase (GS), glutamate synthase (GOGAT), and glutamate dehydrogenase (GDH), while increasing nitrogen accumulation, photosynthetic performance, and grain yield. These beneficial effects are most pronounced under nitrogen-deficient or moderate nitrogen conditions and become less evident under excessive nitrogen application rates (Wei *et al.*, 2025) ^[53].

4.3 Silicon-Mediated Enhancement of Potassium Use Efficiency

Potassium (K) is essential for osmotic regulation, enzyme activation, photosynthesis, and assimilate transport, and its deficiency frequently limits plant growth under abiotic stress. Silicon improves potassium use efficiency by maintaining potassium homeostasis through enhanced potassium uptake, transport, and redistribution. In rice, silicon supplementation under salt stress increases root potassium uptake, shoot potassium distribution, and the expression of the potassium transporter genes *OsAKT1*, *OsHAK1*, and *OsSKOR*, thereby alleviating salt-induced potassium deficiency (Yan *et al.*, 2021) ^[58]. In addition, silicon promotes root-to-shoot potassium redistribution and modulates the expression of potassium transporters, including *HAK1*, *HAK4*, *AKT1*, *AKT2*, *SKOR*, and *KCO1*, improving potassium homeostasis and plant growth under potassium-deficient conditions (Beier *et al.*, 2022) ^[7]. The combined application of silicon and potassium further enhances photosynthetic performance, antioxidant capacity, membrane stability, biomass accumulation, and leaf potassium content while reducing iron-induced oxidative damage, highlighting the complementary role of silicon in maintaining potassium nutrition under stress (Ahmed *et al.*, 2023) ^[3]. Overall, silicon improves potassium use efficiency by enhancing potassium uptake, transport, and homeostasis, thereby contributing to improved stress tolerance and plant growth under adverse environmental conditions.

5. Silicon-Mediated Stress Tolerance in Rice

5.1. Alleviation of Metal and Heavy Metal Toxicity

Iron (Fe²⁺) Toxicity: Iron (Fe²⁺) toxicity is a major constraint in flooded rice ecosystems because anaerobic soil conditions increase the availability of soluble ferrous iron, resulting in excessive iron accumulation, oxidative stress, leaf bronzing, impaired photosynthesis, and yield losses (Becker *et al.*, 2005) ^[6]. Silicon application has been reported to alleviate iron toxicity by reducing iron accumulation and maintaining physiological functions under excess iron conditions. Silicon supplementation improves nutrient balance, particularly calcium and magnesium

nutrition, preserves net photosynthetic rate, stomatal conductance, electron transport, and grain yield components, and reduces spikelet sterility in rice exposed to excess iron (dos Santos *et al.*, 2020) ^[13].

Recent evidence further showed that foliar application of silicon increased silicon accumulation in rice tissues, reduced iron concentration in the flag leaves, maintained leaf greenness, improved the photon yield of photosystem II, and enhanced photosynthetic performance under excess iron conditions. These beneficial effects were more pronounced in the Fe-sensitive cultivar IR29 than in the Fe-tolerant cultivar Azucena (Praseartkul *et al.*, 2026) ^[40]. Field studies also demonstrated that soil application of silicon-rich amendments improved grain and straw yields while reducing iron toxicity in laterite-derived rice soils (Nagula *et al.*, 2016) ^[37]. Similarly, foliar application of potassium silicate reduced iron toxicity scores, suggesting its potential as a practical strategy for managing iron toxicity in lowland rice (Mini *et al.*, 2023) ^[33].

Aluminum (Al) Toxicity

Aluminum (Al) toxicity is a major constraint to crop production in acidic soils (pH < 5.0), where soluble Al³⁺ inhibits root elongation by affecting the root apex, particularly the transition zone (Jiang *et al.*, 2022) ^[22]. Excess aluminum accumulation alters cell wall properties, impairs nutrient and water uptake, and restricts plant growth. Although rice is relatively more tolerant to aluminum toxicity than many other cereal crops, prolonged exposure adversely affects root architecture, biomass accumulation, and productivity (de Freitas *et al.*, 2017) ^[10].

Manganese (Mn) Toxicity

Manganese (Mn) toxicity is a common constraint in acidic and poorly drained soils, where excessive Mn accumulation disrupts photosynthesis, induces oxidative stress, and causes characteristic brown necrotic spots on older leaves, ultimately reducing rice growth and productivity. Silicon alleviates Mn toxicity by decreasing Mn uptake and root-to-shoot translocation, thereby reducing Mn accumulation in the shoots (Che *et al.*, 2016) ^[8]. In addition to regulating Mn transport, silicon promotes the formation of Mn–Si complexes in root cells and induces anatomical changes in the leaves, including increased epidermal thickness and silica body deposition, which help reduce Mn-induced tissue damage and improve stress tolerance (Zanão Júnior *et al.*, 2019) ^[60]. Together, these responses contribute to improved manganese homeostasis and support rice growth under Mn-toxic conditions.

Arsenic (As) and Cadmium (Cd)

Arsenic (As) and cadmium (Cd) are among the most hazardous toxic elements affecting rice production and grain quality because of their accumulation in plant tissues. Silicon reduces arsenic uptake, root-to-shoot translocation, and accumulation in rice. Molecular studies have shown that silicon regulates the expression of genes involved in arsenic transport and detoxification, including *OsLsi1*, *OsLsi2*, *OsNRAMP1*, and *OsABCC1*, thereby limiting arsenic transport and enhancing detoxification (Gao *et al.*, 2021) ^[16]. Cadmium toxicity also adversely affects rice growth because of excessive Cd accumulation. Silicon application decreases Cd accumulation by suppressing the expression of the Cd transporter genes *OsNramp5* and *OsHMA2*, thereby reducing Cd uptake and root-to-shoot translocation. In addition, silicon lowers Cd concentrations in the root cell sap and xylem sap, restricting Cd transport within the plant (Shao *et al.*, 2017) ^[45].

5.2 Silicon-Mediated Alleviation of Abiotic Stresses

5.2.1 Salinity Stress

Salinity adversely affects rice growth by disrupting water relations, ionic balance, and several physiological processes. Recent studies have shown that silicon supplementation improves salinity tolerance in rice. In rice seedlings, pre-treatment with silicic acid improved the growth performance of both the salt-sensitive cultivar BRRI dhan48 and the salt-tolerant cultivar Binadhan-10. Silicon application increased relative water content, proline accumulation, chlorophyll and carotenoid contents, while reducing electrolyte leakage, malondialdehyde accumulation, Na^+ accumulation, and the Na^+/K^+ ratio under saline conditions (Somaddar *et al.*, 2022) [47]. Consistent with these findings, Thorne *et al.* (2022) [51] reported that silicon fertilization reduced salt-induced growth inhibition in responsive rice cultivars by decreasing shoot Na^+ accumulation and improving biomass and grain yield. However, the magnitude of these responses varied among cultivars, indicating that the effectiveness of silicon supplementation is genotype dependent.

5.2.2 Drought (Water Deficiency) Stress

Water deficiency stress adversely affects rice growth by reducing biomass production, photosynthetic performance, and grain yield. A field study conducted at the Department of Rice Research, Tamil Nadu Agricultural University, Coimbatore, showed that foliar application of stabilized orthosilicic acid (0.6%) improved rice performance under water-deficit conditions. Silicon application increased leaf area, leaf area index, photosynthetic rate, total dry matter production, and grain yield across different rice genotypes. Among the genotypes evaluated, IIRRH-132, IIRRH-143, and KRH-4 recorded superior grain yield under drought stress following silicon application (Surendar *et al.*, 2025) [50].

5.2.3 Lodging Resistance

Lodging is a major constraint to rice production because it reduces yield and increases harvesting costs. Silicon application improves lodging-related traits, with both the application method and growth stage influencing its effectiveness. In MR219 rice, topdressing at the reproductive stage significantly increased tiller number, percentage of filled spikelets, panicle weight, silicon accumulation, and lignin content, and was more effective than foliar application in improving stem strength (Dorairaj *et al.*, 2020) [12]. Similarly, under dry cultivation, the optimal silicon application rate reduced the lodging index while increasing culm thickness, bending moment, break bending moment, bending stress, silicon content, lignin, cellulose, and grain yield (Jiang *et al.*, 2025) [23].

5.3 Silicon-Mediated Enhancement of Biotic Stress Resistance

5.3.1 Disease Resistance

Biotic stresses caused by pathogens and insect pests are major constraints to rice production, and silicon (Si) supplementation has been reported to enhance plant resistance against these stresses. Root-applied silicon significantly reduced *Meloidogyne graminicola* infection by decreasing nematode numbers, delaying nematode development, and promoting the accumulation of callose and phenolic compounds along with enhanced expression of ethylene-related defense genes, indicating the induction of host defense responses (Zhan *et al.*, 2018) [61]. Silicon also suppressed rice blast disease in the MR219 variety, where soil application of silica gel and foliar application of sodium silicate significantly reduced disease severity and showed higher silicon accumulation

in leaf tissues (Abed-Ashtiani *et al.*, 2012) [1].

5.3.2 Insect Resistance

Silicon is known to enhance plant resistance against insect pests through structural and physiological defense mechanisms. A two-season field experiment showed that soil test-based NPK combined with foliar application of 0.5% potassium silicate recorded the lowest stem borer incidence during both Kharif and Rabi seasons compared with other silicon treatments and conventional fertilization. The same treatment also produced the highest grain yield among the treatments evaluated, suggesting that silicon application can contribute to stem borer management while improving rice productivity (Mini *et al.*, 2023) [33].

6. Sustainable Silicon Management in Rice

6.1 Circular Economy and Crop Residue Recycling

Rice straw is an important reservoir of silicon, containing approximately 86% of the total Si absorbed by the crop, and therefore contributes substantially to Si cycling in rice production systems. Straw removal during harvesting exports considerable quantities of biogenic Si from the field, whereas recycling rice straw returns phytolith-rich residues to the soil. Marxen *et al.* (2016) [30] demonstrated that phytoliths in fresh rice straw dissolve rapidly during decomposition, releasing plant-available silicon and increasing its availability in paddy soils. In addition to direct straw incorporation, phytolith-rich rice-straw biochar has been shown to increase plant-available silicon and enhance plant Si uptake, although its effectiveness depends on soil pH and buffering capacity (Li *et al.*, 2019) [26].

The utilization of paddy straw also supports circular economy approaches by converting agricultural residues into value-added products rather than treating them as waste. Sharma *et al.* (2024) [46] highlighted several value-added applications of paddy straw and identified rice husk ash as a potential source for silica recovery, demonstrating additional opportunities for the productive utilization of rice-processing residues.

6.2 Silicon Fertilizers

6.2.1 Chemical Silicon Fertilizers

Chemical silicon fertilizers are widely used to supply plant-available silicon in rice cultivation. Calcium silicate, potassium silicate, sodium silicate, and nano-silica have been evaluated for their effects on rice growth, productivity, and stress tolerance. Foliar application of potassium silicate significantly increased grain and straw yields while reducing both biotic and abiotic stresses, particularly when combined with soil test-based NPK fertilization (Mini *et al.*, 2023) [33]. Likewise, sodium silicate enhanced grain yield and quality, with reproductive-stage application producing the greatest increases in grain yield, starch, and protein content (Anand *et al.*, 2018) [4]. Soil application of calcium silicate together with recommended NPK or leaf colour chart (LCC)-based nitrogen management improved yield attributes and nitrogen use efficiency (Yogendra *et al.*, 2013) [59]. The agronomic performance of chemical silicon fertilizers varies with the fertilizer source, application method, concentration, and crop growth stage.

6.2.2 Nano-Silicon Fertilizers

Nano-silicon represents a recent advancement in silicon fertilization, with silica nanoparticles possessing unique physicochemical properties that distinguish them from conventional silicon sources. Owing to their high surface-area-to-volume ratio, silica nanoparticles exhibit altered physicochemical properties, including solubility, reactivity, and transport within

plants, compared with bulk materials (Naaz *et al.*, 2023) ^[36]. In field-grown rice, foliar application of silica nanoparticles enhanced leaf area index, dry matter production, grain yield, and biological yield while reducing the adverse effects of water stress (Elshayb *et al.*, 2021; Gopal *et al.*, 2023) ^[15, 17]. Under salt stress, foliar application of nano-silicon improved ion homeostasis and antioxidant responses, thereby reducing oxidative damage in rice seedlings (Xiong *et al.*, 2025) ^[55].

6.2.3 Natural Silicon Fertilizers

Natural silicon fertilizers utilize silicon-rich minerals and agricultural by-products as sustainable sources of plant-available silicon. Materials such as diatomaceous earth, rice husk, rice husk ash, and other agricultural residues improve silicon nutrition either through direct soil application or by recycling silicon-rich residues back to the soil, thereby supporting subsequent crop uptake (Sahebi *et al.*, 2015) ^[43]. Among these materials, diatomaceous earth has been widely investigated and significantly increased grain and straw yields when applied together with standard fertilizer practices, indicating its suitability as a silicon amendment for rice cultivation (Pati *et al.*, 2016) ^[39].

6.3 Silicon-Solubilizing Biofertilizers

Biological solubilization increases the availability of silicon through the activity of silicate-solubilizing microorganisms capable of mobilizing insoluble silicate minerals. Several microorganisms, including *Bacillus caldolyticus*, *Bacillus mucilaginosus* var. *siliceous*, *Proteus mirabilis*, *Pseudomonas*, and *Penicillium*, have been reported to mobilize silicon from natural silicate minerals, thereby increasing silicon availability and uptake by plants (Meena *et al.*, 2014) ^[32]. Field studies by Subhash (2020) ^[49] further demonstrated that silicon-solubilizing bacteria, applied alone or together with calcium silicate, improved nutrient availability, reduced metal toxicity, and increased grain yield, straw yield, nutrient uptake, and soil health in rice. Collectively, these studies indicate that silicon-solubilizing microorganisms can enhance silicon availability and support sustainable rice production.

6.4 Economic Benefits of Silicon Nutrition

The agronomic benefits of silicon application can be reflected in improved economic returns through increased grain yield, better grain quality, and reduced yield losses under adverse growing conditions. In rice, silicon supplementation has been reported to improve productivity and grain quality, particularly under drought, dry cultivation, and iron toxicity, by promoting root growth, photosynthetic activity, and grain filling while reducing undesirable grain characteristics such as chalkiness and excess protein accumulation (Jiang *et al.*, 2023). These improvements in crop performance contribute to greater profitability. Rao *et al.* (2018) ^[42] demonstrated that the combined application of fine silica (50 kg ha⁻¹) and rice husk ash (250 kg ha⁻¹) recorded the highest gross income (₹164,470 ha⁻¹), net income (₹72,503 ha⁻¹), and benefit–cost ratio (1.78), indicating that appropriate silicon nutrition can enhance the economic viability of rice cultivation.

7. Future Perspectives and Conclusion

Despite significant advances in understanding the role of silicon in rice, several important research gaps remain. Future studies should prioritize long-term field evaluation of silicon management practices across diverse agroecological conditions while accounting for differences in soil properties, rice genotypes, and cultivation systems. Greater attention is also needed to optimize silicon sources, application methods, application rates,

and application timing through precision nutrient management to improve silicon-use efficiency. In addition, emerging approaches, including nano-silicon fertilizers, silicon-solubilizing microorganisms, and the recycling of silicon-rich agricultural residues, require comprehensive field evaluation to determine their agronomic performance, economic feasibility, and environmental sustainability. Addressing these challenges will facilitate the development of efficient and climate-resilient silicon management strategies for sustainable rice production.

Silicon plays an important role in improving rice growth, nutrient use efficiency, and tolerance to abiotic and biotic stresses through a combination of physiological, biochemical, and structural mechanisms. The evidence discussed in this review indicates that integrating silicon fertilization with complementary approaches, such as crop residue recycling, biological silicon solubilization, and nano-silicon technologies, can improve silicon availability and support stable rice production. However, the effectiveness of these strategies is influenced by soil characteristics, cultivation practices, environmental conditions, and rice genotype. Continued multidisciplinary research integrating plant physiology, soil science, agronomy, microbiology, and nanotechnology will strengthen our understanding of silicon-mediated processes and support the development of practical and sustainable silicon management strategies for future rice production.

References

1. Abed-Ashtiani F, Kadir JB, Selamat AB, Hanif AHBM, Nasehi A. Effect of foliar and root application of silicon against rice blast fungus in MR219 rice variety. *Plant Pathol J*. 2012;28(2):164-171.
2. Agostinho FB, Tubana BS, Martins MS, Datnoff LE. Effect of different silicon sources on yield and silicon uptake of rice grown under varying phosphorus rates. *Plants*. 2017;6(3):35.
3. Ahmed SF, Biswas A, Ullah H, Himanshu SK, Tisarum R, Cha-um S, *et al.* Interactive effects of silicon and potassium on photosynthesis and physio-biochemical traits of rice (*Oryza sativa* L.) leaf mesophyll under ferrous iron toxicity. *Plant Stress*. 2023;10:100203.
4. Anand L, Sreekanth B, Jyothula DPB. Effect of foliar application of sodium silicate on yield and grain quality of rice. *Int J Chem Stud*. 2018;6:1711-1715.
5. Ashokan A, Anand S, Aparna B, Mini V. Silicon uptake mechanism and its multidimensional influences on stress mitigation in rice (*Oryza sativa* L.). *Int J Plant Soil Sci*. 2023;35(4):16-24.
6. Becker M, Asch F. Iron toxicity in rice—conditions and management concepts. *J Plant Nutr Soil Sci*. 2005;168:558-573.
7. Beier S, Marella NC, Yvin JC, Hosseini SA, von Wiren N. Silicon mitigates potassium deficiency by enhanced remobilization and modulated potassium transporter regulation. *Environ Exp Bot*. 2022;198:104849.
8. Che J, Yamaji N, Shao JF, Ma JF, Shen RF. Silicon decreases both uptake and root-to-shoot translocation of manganese in rice. *J Exp Bot*. 2016;67(5):1535-1544.
9. Datnoff LE, Snyder GH, Korndörfer GH. Silicon in agriculture. Vol. 8. Amsterdam: Elsevier B.V.; 2001.
10. de Freitas LB, Fernandes DM, Maia SCM, Fernandes AM. Effects of silicon on aluminum toxicity in upland rice plants. *Plant Soil*. 2017;420:263-275.
11. Dhanasekaran SK, Jawahar S, Gurusamy A, Ragavan T, Prabhakaran J, Sivakumar T, *et al.* A review on silicon nutrition for sustainable rice production. *Plant Sci Today*.

- 2025;12(1):1-9.
12. Dorairaj D, Ismail MR, Sinniah UR, Tan KB. Silicon mediated improvement in agronomic traits, physiological parameters and fiber content in *Oryza sativa*. *Acta Physiol Plant*. 2020;42:38.
 13. dos Santos MS, Sanglard LMPV, Martins SCV, Barbosa ML, de Melo DC, Gonzaga WF, *et al*. Silicon nutrition mitigates the negative impacts of iron toxicity on rice photosynthesis. *Ecotoxicol Environ Saf*. 2020;189:110008.
 14. El-Sayed AA, Abou Seeda MA, Yassen AA, Sahar MZ, Khater A. Silicon in soils, plants and its important role in crop production: a review. *Middle East J Agric Res*. 2019;8(4):983-1004.
 15. 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 EHR1 growing under water regime conditions. *Materials*. 2021;14(5):1150.
 16. Gao Z, Tang X, Ye M, Gul I, Chen H, Yan G, *et al*. Effects of silicon on the uptake and accumulation of arsenite and dimethylarsinic acid in rice (*Oryza sativa* L.). *J Hazard Mater*. 2021;409:124442.
 17. Gopal D, Prasad TNVKV, Pradeep T, Rami Reddy CB, Nirmal Kumar A, Naseeruddin R, *et al*. Effects of nanoparticulate delivery of silicon on the growth and yield of rice (*Oryza sativa* L.). *Silicon*. 2024;16:1-11.
 18. Haynes RJ. A contemporary overview of silicon availability in agricultural soils. *J Plant Nutr Soil Sci*. 2014;177:811-822.
 19. Huang S, Ma JF. Silicon transport and its "homeostasis" in rice. *Quant Plant Biol*. 2024;5.
 20. Huang S, Yamaji N, Sakurai G, Mitani-Ueno N, Konishi N, Ma JF. A pericycle-localized silicon transporter for efficient xylem loading in rice. *New Phytol*. 2022;234(1):197-208.
 21. International Rice Research Institute. Rice almanac. 4th ed. Los Baños: International Rice Research Institute; 2013. p. 283.
 22. Jiang D, Wu H, Cai H, Chen G. Silicon confers aluminium tolerance in rice via cell wall modification in the root transition zone. *Plant Cell Environ*. 2022;45:1765-1778.
 23. Jiang H, Jiang Z, Zhang H, Li Y, Li W, Gao K, *et al*. Silicon nutrition improves lodging resistance of rice under dry cultivation. *Plants*. 2025;14(3):361.
 24. Jiang H, Xu X, Sun A, Bai C, Li Y, Nuo M, *et al*. Silicon nutrition improves the quality and yield of rice under dry cultivation. *J Sci Food Agric*. 2024;104:1897-1908.
 25. Jinger D, Dhar S, Dass A, Sharma VK, Paramesh V, Parihar M, *et al*. Co-fertilization of silicon and phosphorus influences the dry matter accumulation, grain yield, nutrient uptake, and nutrient-use efficiencies of aerobic rice. *Silicon*. 2022;14(9):4683-4697.
 26. Li Z, Unzué-Belmonte D, Jean-Thomas C, Vander Linden C, Struyf E, Ronsse F, *et al*. Effects of phytolith rice-straw biochar, soil buffering capacity and pH on silicon bioavailability. *Plant Soil*. 2019;438(1-2):187-203.
 27. Ma JF, Tamai K, Yamaji N, Mitani N, Konishi S, Katsuhara M, *et al*. A silicon transporter in rice. *Nature*. 2006;440:688-691.
 28. Ma JF, Yamaji N, Mitani N, Tamai K, Konishi S, Fujiwara T, *et al*. An efflux transporter of silicon in rice. *Nature*. 2007;448:209-212.
 29. Ma JF, Yamaji N. A cooperative system of silicon transport in plants. *Trends Plant Sci*. 2015;20(7):435-442.
 30. Marxen A, Klotzbücher T, Jahn R, Kaiser K, Nguyen VS, Vetterlein D, *et al*. Interaction between silicon cycling and straw decomposition in a silicon deficient rice production system. *Plant Soil*. 2016;398(1):153-163.
 31. McCarty JS, Sharma N, Kumar R, Lalrammawii C, Dwivedi N, Srivastava H, *et al*. Impact of silicon fertilization on crop growth, productivity and nutrients enhancement in rice: a review. *Plant Sci Today*. 2025;12(1):1-10.
 32. Meena VD, Dotaniya ML, Coumar V, Rajendiran S, Kundu S, Rao AS, *et al*. A case for silicon fertilization to improve crop yields in tropical soils. *Proc Natl Acad Sci India Sect B Biol Sci*. 2014;84:505-518.
 33. Mini V, Parvathy S, Rahanabai H. Effect of silicon application on abiotic and biotic stress management in rice in Typic Ustipsamments of Kerala, India. *Pharma Innov J*. 2023;12(8):2063-2065.
 34. Mitani-Ueno N, Yamaji N, Huang S, Yoshioka Y, Miyaji T, Ma JF. A silicon transporter gene required for healthy growth of rice on land. *Nat Commun*. 2023;14(1):6522.
 35. Mitani-Ueno N, Yamaji N, Ma JF. High silicon accumulation in the shoot is required for down-regulating the expression of Si transporter genes in rice. *Plant Cell Physiol*. 2016;57(12):2510-2518.
 36. Naaz H, Rawat K, Saffaullah P, *et al*. Silica nanoparticles synthesis and applications in agriculture for plant fertilization and protection: a review. *Environ Chem Lett*. 2023;21:539-559.
 37. Nagula S, Joseph B, Gladis R. Silicon nutrition to rice (*Oryza sativa* L.) alleviates Fe, Mn and Al toxicity in laterite derived rice soils. *J Indian Soc Soil Sci*. 2016;64(3):297-301.
 38. Pallavi T, Prakash NB. Pools of silicon in soils and their contribution to rice. *J Indian Soc Soil Sci*. 2019;67(2):211-220.
 39. Pati S, Pal B, Badole S, Hazra GC, Mandal B. Effect of silicon fertilization on growth, yield, and nutrient uptake of rice. *Commun Soil Sci Plant Anal*. 2016;47(3):284-290.
 40. Praseartkul P, Tisarum R, Sotesaritkul T, Srisawad N, Chaum S, Arunyanark A, *et al*. Foliar silicon application mitigates iron toxicity in rice plants by modulating morpho-physiological traits. *J Soil Sci Plant Nutr*. 2026;26:6718-6729.
 41. Rao GB, Susmitha P. Silicon uptake, transportation and accumulation in rice. *J Pharmacogn Phytochem*. 2017;6(6):290-293.
 42. Rao GB, Yadav PPI, Syriac EK. Effect of silicon fertilization on yield attributing factors, yield and economics of rice cultivation. *J Pharmacogn Phytochem*. 2018;7(2):1381-1383.
 43. Sahebi M, Hanafi MM, Siti Nor Akmar A, Rafii MY, Azizi P, Tengoua FF, *et al*. Importance of silicon and mechanisms of biosilica formation in plants. *Biomed Res Int*. 2015;2015:396010.
 44. Schaller J, Wu B, Amelung W, Hu Z, Stein M, Lehnendorff E, *et al*. Silicon as a potential limiting factor for phosphorus availability in paddy soils. *Sci Rep*. 2022;12(1):16329.
 45. Shao JF, Che J, Yamaji N, Shen RF, Ma JF. Silicon reduces cadmium accumulation by suppressing expression of transporter genes involved in cadmium uptake and translocation in rice. *J Exp Bot*. 2017;68(20):5641-5651.
 46. Sharma S, Pappu A, Asolekar SR. Sustainable recycling of paddy straw through development of short-fiber-reinforced composites: exploring gainful utilization of agricultural waste. *Clean Technol Environ Policy*. 2024;26(1):109-127.
 47. Somaddar U, Dey HC, Mim SK, Sarker UK, Uddin MR, Ahmed NU, *et al*. Assessing silicon-mediated growth performances in contrasting rice cultivars under salt stress. *Plants*. 2022;11(14):1831.

48. Sommer M, Kaczorek D, Kuzyakov Y, Breuer J. Silicon pools and fluxes in soils and landscapes—a review. *J Plant Nutr Soil Sci.* 2006;169(3):310-329.
49. Subhash AP. Isolation and *in vitro* screening of silicate solubilizing bacteria from paddy rhizosphere [MSc thesis]. Thrissur: Kerala Agricultural University; 2020. 131 p.
50. Surendar KK, Sritharan N, Sathiyavani E, Kumar KS, Venudevan B, Ramesh CT, *et al.* Influence of silicon on improving water deficit stress tolerance in rice genotypes. *J Adv Biol Biotechnol.* 2025;28(5):407-413.
51. Thorne SJ, Stirnberg PM, Hartley SE, Maathuis FJ. The ability of silicon fertilisation to alleviate salinity stress in rice is critically dependent on cultivar. *Rice.* 2022;15(1):8.
52. Tubaña BS, Heckman JR. Silicon in soils and plants. In: Datnoff LE, Elmer WH, Huber DM, editors. *Silicon and plant diseases.* Cham: Springer; 2015. p. 7-51.
53. Wei X, Wu G, Wang B, Jiang Z, Wei Z, Wang S, *et al.* Optimized application strategy of nitrogen-silicon (N-Si) fertilization improves nitrogen metabolism, grain yield, and growth of rice under dry cultivation. *BMC Plant Biol.* 2025;26(1):6.
54. Wu X, Yu Y, Baerson SR, Song Y, Liang G, Ding C, *et al.* Interactions between nitrogen and silicon in rice and their effects on resistance toward the brown planthopper *Nilaparvata lugens*. *Front Plant Sci.* 2017;8:28.
55. 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.
56. Yamaji N, Mitani N, Ma JF. A transporter regulating silicon distribution in rice shoots. *Plant Cell.* 2008;20(5):1381-1389.
57. Yamaji N, Sakurai G, Mitani-Ueno N, Ma JF. Orchestration of three transporters and distinct vascular structures in node for intervacular transfer of silicon in rice. *Proc Natl Acad Sci U S A.* 2015;112(36):11401-11406.
58. Yan G, Fan X, Zheng W, Gao Z, Yin C, Li T, *et al.* Silicon alleviates salt stress-induced potassium deficiency by promoting potassium uptake and translocation in rice (*Oryza sativa* L.). *J Plant Physiol.* 2021;258:153379.
59. Yogendra ND, Prakash NB, Malagi MT, Kumara BH, Kumar RM, Chandrashekar N. Effect of calcium silicate on yield and nitrogen use efficiency (NUE) of wetland rice. *Plant Arch.* 2013;13(1):89-91.
60. Zañão Júnior LA, Fontes RLF, Dias-Pereira J, Carvalho-Zañão MP, Pereira N. Manganese toxicity in rice plants mitigated by silicon effects on leaf tissues. *Semina Cienc Agrar.* 2019;40(6):2523-2534.
61. Zhan LP, Peng DL, Wang XL, Kong LA, Peng H, Liu SM, *et al.* Priming effect of root-applied silicon on the enhancement of induced resistance to the root-knot nematode *Meloidogyne graminicola* in rice. *BMC Plant Biol.* 2018;18(1):50.