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REVIEW ARTICLE

Impact of silicon fertilization on crop growth, productivity and nutrients enhancement in rice: A review

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Abstract

Silicon (Si), constituting around 27.7 % of the Earth's crust by weight, is the second most abundant element after oxygen (47 %). While not considered essential, silicon is beneficial for crop growth, especially for *Poaceae* family crops. Intensive cultivation or continuous mono-cropping of cereals like rice depletes soil silicon levels, which may lead to decreased rice yields. Rice can absorb and accumulate silicon metabolically, a trait not common in many upland crops. Beyond boosting rice yields, silicon offers multiple benefits, such as enhancing nutrient availability (N, P, K, Ca, Mg, S, Zn), reducing nutrient toxicity (Fe, Mn, P, Al) and mitigating biotic and abiotic stress in rice. Sufficient silicon also stabilizes rice plant culms, reducing lodging risks. Thus, silicon is crucial for plant growth and improving rice productivity at the agronomic level. This review focuses on the relationship between silicon and rice crops, their interactions with other elements and strategies for managing silicon in soils and plants to sustain rice productivity.

Keywords

silicon; lodging; rice yield improvement; nutrient availability; stress management

Introduction

Rice (*Oryza sativa* L.) serves as a primary food source for over half of the world's population. It is cultivated worldwide on approximately 158 million hectares, yielding a total production of 700 million tons and an average productivity of 4.43 tons per hectare, according to (1). India has the largest rice cultivation area, covering 44 million hectares, with a production of around 141 million tons and an average yield of 3.21 tons per hectare. As reported (2), India's growing population is projected to stabilize at about 1.4 to 1.6 billion by the years 2025 and 2050, respectively, requiring 380 to 450 million tons of food grains annually. Rice yields have either decelerated, stagnated, or declined following the Green Revolution, primarily due to excessive use of fertilizers and pesticides, soil degradation, intensive cropping systems, insufficient high-yielding rice varieties and declining groundwater levels (3). Silicon, constituting about 27.7% of the total soil weight, is the second most abundant element in the Earth's crust after oxygen, which makes up 47% (3-6). The silicon content in clay soils ranges from 200 to 300 g Si/kg, while sandy soils contain about 450 g Si/kg, with soil silicon content varying from 1 to 45 percent by dry weight (6). Although not essential, silicon is considered beneficial for crop growth, especially for those in the *Poaceae* family. For rice plants, silicon enhances cell wall strength and rigidity by accumulating in the epidermis and vascular tissue cell walls. This deposition helps rice plants maintain an erect growth habit when nitrogen fertilizers are applied, thereby increasing photosynthesis levels and overall rice production.

Silicon in plants

In plants, silicon (Si) is primarily absorbed by roots but tends to accumulate more in aerial parts, although its capacity for tissue accumulation varies. Its content in plants ranges from 0.1 to 10 percent on a dry weight basis, comparable to or even exceeding several macronutrients . Application of silicon also influences plant growth in highly weathered soils (8-10). Despite its ubiquitous presence in the biosphere, silicon is often not considered a crucial element for plant production. However, its application improves agricultural crop quality and yield by enhancing plant growth (11).

Various types of silicon have been studied and documented in soils, plants and ecosystems. Based on tissue silicon levels, three plant classes have been identified (13): dicotyledons with less than 0.1 percent dry weight content, dry region grasses (e.g., rye and oats) and grasses and paddy grown in wetlands with a silicon content of 5 percent or more.

Several transporters and genes that are involved in Si uptake and accumulation have been studied so far. Although the study of Si transporters focuses on rice and other grasses (as is commonly the case in plant Si research (14), the first plant gene to regulate Si accumulation was discovered in the gourd *Cucurbita* (Cucurbitaceae), regulating Si and phytolith formation in the fruit rind (15). Shortly after, a surge of discoveries of the physiology and genetics of Si uptake in grasses has arisen, revolving around the four Lsi transporters, all belonging to the NIP aquaporin family. The first transporter to be discovered was the influx transporter Lsi1, located in the distal plasma membrane of root exodermis and endodermis cells (16). An efflux transporter on the proximal plasma membrane of the same cells, Lsi2, transports Si from the exodermis to the cortex and further loads it from the endodermis onto the xylem (17-19). A third transporter, Lsi6, exists in the shoots and is responsible for xylem offloading (20). In grass shoot nodes, Lsi6 and Lsi3 (previously thought to be Lsi2 due to structural similarities) are involved in distributing Si among branches (19). Together, these transporters constitute an elaborate cooperative system of Si uptake and distribution in grasses, with some variations in the details of where exactly each transporter is localized within each species (Fig. 1).

The multi-functionality of soil Si and its uptake and cycling by rice plants, as well as their many benefits for humans, imply that we should consider plant and herbivorous Si cycles as providers of some ecosystem services (Fig. 2).

Silicon in soil

Soil formation is a complex process influenced by the interaction of parent material, climate, living organisms, topography and time. These interactions result in soils that are the outcome of various processes categorized into addition, transformation, removal and translocation. The chemical processes occurring within soils often involve minerals derived from silicates, which are particularly rich in silicon. Silicate minerals exhibit varying degrees of resistance to weathering and transformation, depending on the environmental conditions and the factors that shape the soil. Under conditions of high rainfall and intense weathering, less resistant silicates release silica, which is subsequently leached into surrounding streams and water bodies. This leaching process is more pronounced in regions with significant rainfall and active weathering, contributing to the dynamic nature of silicon distribution in soils. Managing heavily weathered soils effectively requires a deep understanding of their intrinsic properties and the processes that govern their behaviour.

One critical aspect of soil management is recognizing the impact of soil moisture content changes, which result from alternating wetting and drying cycles. These cycles can influence the concentration of silicon in the soil solution more readily than any other process. Silicon in soil exists primarily in the form of monosilicic acid (H_4SiO_4) and polysilicic acids. These forms of silicon interact with both organic and inorganic compounds within the soil matrix. For instance, silicon can form complexes with aluminum oxides and hydroxides, contributing to the overall soil chemistry and influencing nutrient availability. Moreover, the presence of silicon in soil plays a crucial role in plant growth and development. Silicon aids in strengthening plant cell walls, enhancing resistance to pests and diseases and improving overall crop resilience, particularly in grasses and cereals like rice.

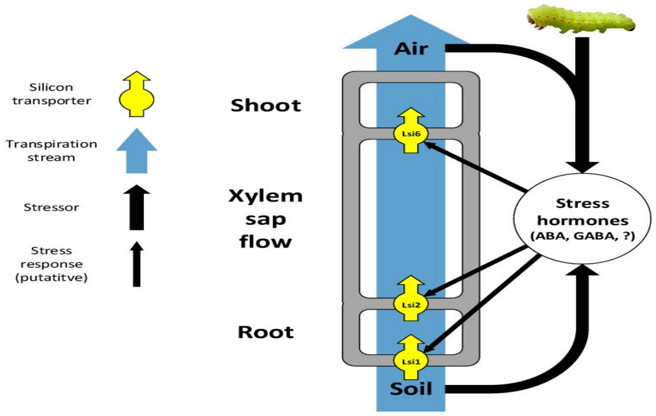


Fig. 1. Silicon uptake metabolic process

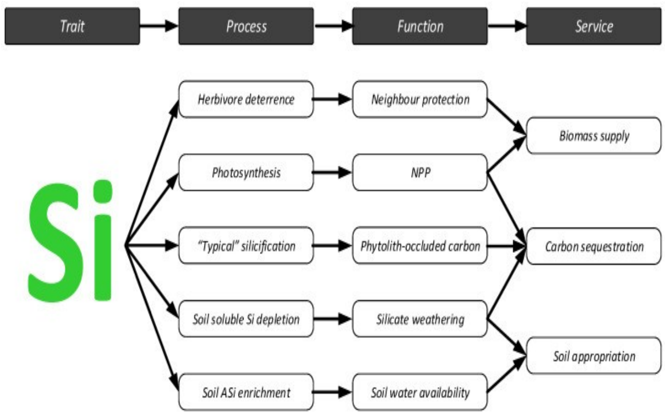


Fig. 2.Silicon and their functions in ecosystem

Understanding the role of silicon in soil and plant systems is essential for developing strategies to enhance crop productivity and maintain soil health. (21) documented that as soil silicate minerals undergo weathering, silicon (Si) is released in the form of silicic acid (H_4SiO_4) into the soil solution, where it is subsequently absorbed by plants. Despite advancements, the precise silicon status across various paddy ecosystems remains undefined, highlighting the need to establish a comprehensive Si management strategy to optimize the yield potential of improved paddy cultivars.

Given the correlation between rice yield response and silicon application, it is crucial to develop efficient and rapid extraction methods to assess silicon availability in soil, which directly impacts crop uptake. Several dynamic processes influence silicon solubility in the soil solution, including soil pH, acidity, presence of organic complexes, aluminum, iron, phosphate ions and soil moisture. Furthermore, silicon contributes to enhancing the physical, chemical and biological properties of the soil.

Mineral weathering acts as the primary Si source in terrestrial ecosystems, dictating Si concentrations in soils. Weathering within soil-plant systems is governed by climate (precipitation, temperature), soil conditions (mineral composition, quantity and properties of biogenic silica, soil pH) and vegetation (Si uptake, recycling) (Fig. 3). Mineral dissolution is slower than amorphous silica (e.g., phytoliths) dissolution, with phytoliths being 10^2 to 10^4 times more reactive than clay minerals and primary silicates at common soil pH (about 4 to 8). Organism (especially plant) Si recycling gains attention for accelerating Si turnover rates and exporting Si to riverine and marine systems.

Silicon nutrition in rice

Rice is recognized as a significant accumulator of silicon (16). Depletion of silicon is a major concern correlated with higher rice yields per unit area (22). Silicon has recently been acknowledged as a quasi-essential factor for enhanced plant growth (23). Typically, around 230 to 470 kg of silicon per crop is extracted from the soil to produce a grain yield of 5 t/ha and without silicon fertilization, intensive rice cultivation can result in yield decline in various countries (22). However, there remains a limited understanding of the significance of silicon in the Indian farming system (3). The silicon content in paddy surpasses that of major elements such as nitrogen, phosphorus and potassium (22).

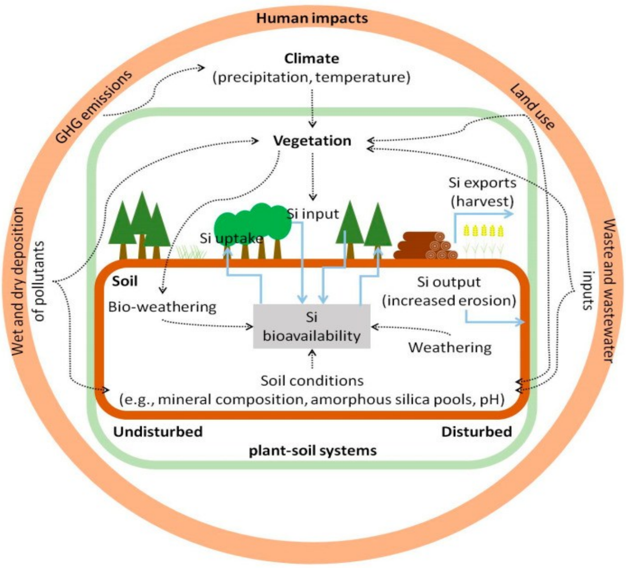


Fig. 3. Schematic overview of silicon cycle

The concept of essentiality doesn't apply to silicon, as it neither complements nor substitutes any plant component nor shows deficiency symptoms. However, due to its numerous positive effects on crop health, production, and productivity, particularly in crops like wheat, rice, sugarcane and barley, silicon is categorized as a 'beneficial element' (23). Approximately 20 kg/hm^2 of SiO_2 is depleted from the soil to produce every 100 kg of brown rice (19). Decreased silicon levels in plants result in necrosis, reduced leaf photosynthetic capacity, growth retardation and lower grain yields, particularly in rice crops (24).

Various plant physical characteristics, such as culm diameter, peak wall thickness, and basal internode dry matter weight, are significantly correlated with rice plant strength (25), indicating that silicon can contribute to yield in rice production. Therefore, the application of silicon fertilizer may be beneficial for enhancing and sustaining rice production systems (26).

The silicon uptake, transport and deposition pathways in plants have been illustrated (27).Silicon in the form of silicic acid (H_4SiO_4) is taken up from the soil solution by the root epidermal cells via the silicon influx transporter Lsi1 (orange). It is then radially transported across the root cortex towards the stele by the silicon efflux transporter Lsi2 (teal). An unknown transporter (purple) loads silicon into the xylem vessels of the stele for long-distance translocation to the shoots and leaves through the root xylem. In the leaves, silicon is deposited as silica gel ($SiO_2{\cdot}nH_2O$) in specialized cells called phytoliths, facilitated by the silicon influx transporter (Fig. 4) Lsi6 (brown). The Casparian strips in the root endodermis regulate the radial movement of water and solutes, while the aerenchyma (air-filled spaces) in the root cortex facilitate gas exchange. This silicon uptake and deposition process is crucial for enhancing mechanical strength, stress tolerance, water balance and photosynthetic efficiency in plants.

Potential benefits of silicon fertilization

Decreases lodging

Lodging, a common occurrence in rice crops, typically manifests after the ear or panicle stage, occurring approximately 1 month prior to harvest. This phenomenon leads to the permanent leaning or horizontal placement of shoots on the soil surface. The consequences include significant yield reductions of up to 80 %, along with diminished grain quality, increased drying costs and prolonged harvesting time (27). The decline in yield primarily results from compromised water and nutrient translocation, reduced light interception, alterations in microclimatic conditions and decreased photosynthetic activity of the leaves (28).

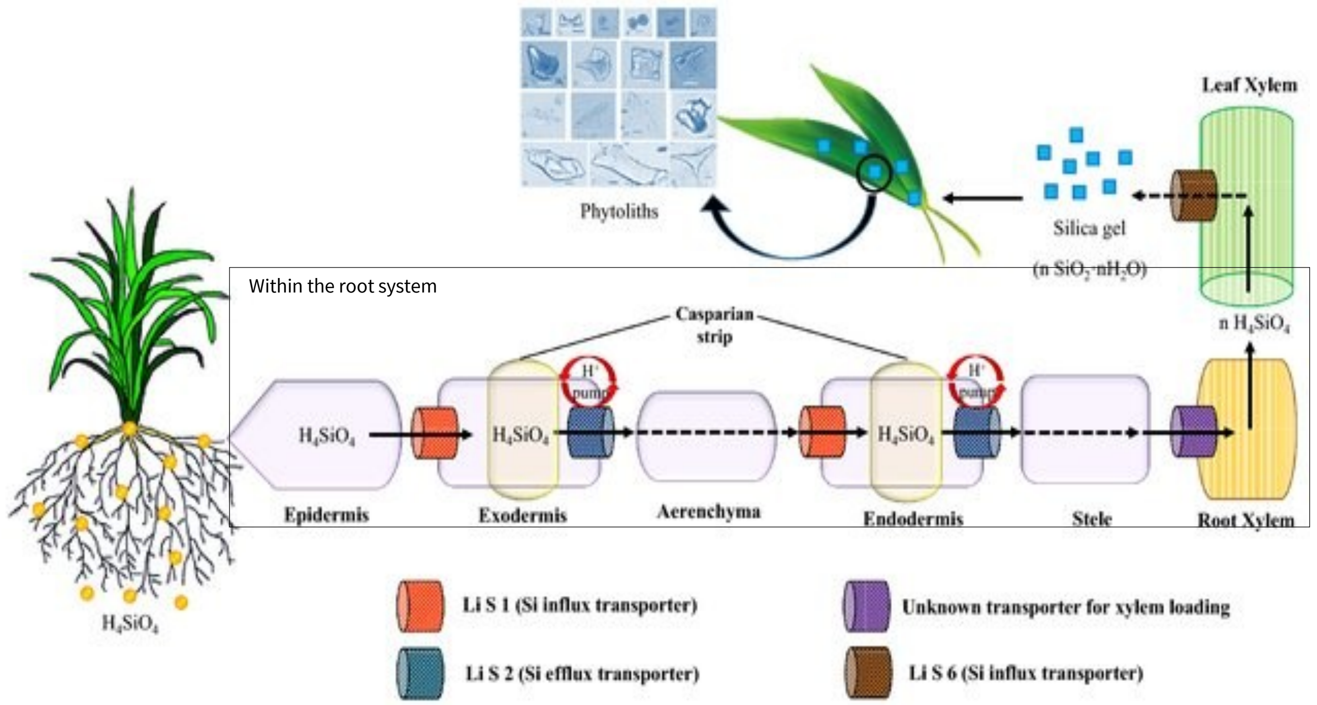
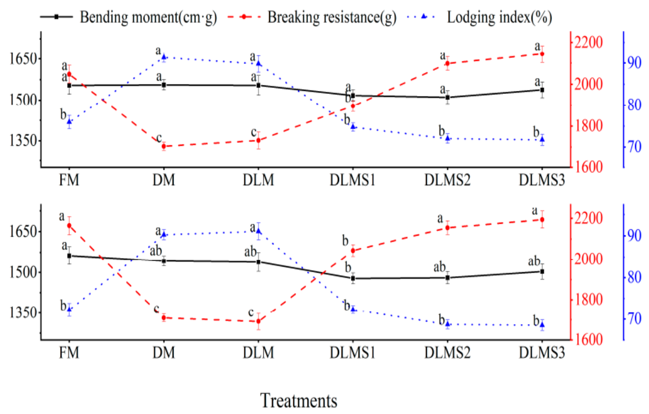


Fig. 4. Silicon Influx and Transport Pathway in Rice.

The extent of yield loss tends to be greater in crops that lodge during heading or early ripening stages compared to those that lodge later in the ripening phase. Additionally, lodging is often associated with favourable growth conditions, particularly ample nutrient availability, notably nitrogen. Enhancing the physical or mechanical strength of rice plants can effectively mitigate lodging issues.

Silicon contributes to the robustness and rigidity of rice plants. Additionally, the quality of lignin, cellulose, or hemicellulose in the culm determines its physical strength, with lower quality leading to brittleness. Disrupted accumulation of cellulose, hemicellulose and lignin in culms reduces secondary wall thickness and stability, as observed in the rice mutant brittle culm1 (bc1) (29).

The cumulative carbohydrate content in rice stems is closely related to lodging resistance, with increased starch accumulation improving bending strength and stability, as demonstrated by (30). Similarly, higher silicon content is linked to greater physical strength, as highlighted by (31). Additionally, (32) reported that the prl5 locus, which controls stem thickness in the lower part of rice crops, increases the weight of the lower stem, possibly due to higher carbohydrate content at maturity, thereby enhancing lodging resistance in rice. Fig. 5 illustrates the bending moment, bending resistance and lodging index of the fourth internode (N4) of rice stems across various treatments over two years (33). The farming mode (FM) showed the highest bending moment due to lower planting density, while the increased density treatments (DM and DLM) exhibited the lowest bending resistance. Notably, the application of silicon fertilizer, especially at the highest rate (DLMS3), significantly enhanced bending resistance and reduced the lodging index compared to other treatments. In the DLMS3 treatment, bending resistance increased by 440.1 g and

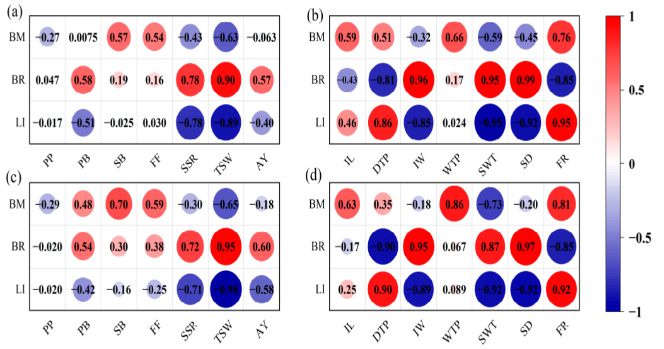


*Local farming modes (FMs) were used as a control and a conventional densification treatment (DM), a densification with reduced N (-20%) treatment (DLM) and three densifications with reduced N (-20%) and base silicon fertilizer treatments (low fertilizer: DLMS1, medium fertilizer: DLMS2, high fertilizer: DLMS3).

Fig. 5. Stem lodging traits in the fourth internode (N4) of rice (33).

503.8 g and the lodging index decreased by 19.6% and 22.5% in 2020 and 2021, respectively, compared to the DM and DLM treatments. This indicates improved lodging resistance with the application of silicon fertilizer under reduced nitrogen and increased density conditions.

A similar trend can be seen in the correlation between the rice lodging index and various indices of the stem, which is shown in Fig. 6. The bending resistance was positively correlated with the setting rate, thousand grain weight and actual yield and the 2-year correlation coefficients were 0.78 and 0.72, 0.90 and 0.95 and 0.57 and 0.60, respectively. This indicates that an increase in stem strength is beneficial for the single spike yield (32). The trend in the lodging coefficient was the opposite of the trend in the bending resistance and as the lodging coefficient increased, both the yield and its constituent factors decreased.



*Lodging traits: Plant height (PH), Plant center of gravity (PCG), Panicle weight (PW), Plant length (PL), Internode length (IL), Distance to the top of the plant (DTP), Internode weight (IW), Weight to the top of the plant (WTP), Stem wall thickness (SWT), Stem diameter (SD), Flattening rate (FR)

Fig. 6. Correlation analysis between the lodging traits of rice stems and yield, its constituent factors and internode morphology in 2022 and 2021.

Enhanced crop growth and yield

In India's warm, sub-humid tropical climate, rice cultivation demands substantial quantities of silicon for optimal plant growth and development. A significant increase was noted a significant increase in various growth parameters with silicon application, including plant height, dry matter production, number of panicles per square meter, filled grains per panicle, test weight and overall rice yield (34). The maximum grain yield of 6588 kg/ha was achieved with silicon application at a level of 180 kg/ha.

The treatment that showed the best grain yield of rice was RDF + 400 kg/hm^2 SiO_2, providing a yield of 3705 kg/hm^2 (35). This was attributed to the exogenous application of silicon fertilizer along with the recommended NPK fertilizers, which significantly improved yield components like the number of grains per panicle, seed setting rate and 1000-grain weight. Moreover, silicon application enhanced the uptake of not only silicon but also nitrogen, phosphorus and potassium by the rice plants, with a strong positive linear relationship between silicon uptake and uptake of these major nutrients. This improved nutrient uptake likely promoted better plant growth and development. Additionally, the increased silicon nutrition may have helped the rice plants better cope with abiotic and biotic stresses. The quadratic regression analysis identified 329 kg/hm^2 SiO_2 as the optimum silicon level to maximize yield and the treatment with 400 kg/hm2 SiO_2 was very close to this optimum level. Thus, the synergistic effects of silicon fertilization along with NPK fertilizers on improving yield components, nutrient uptake and potential stress tolerance appeared to be the main factors contributing to the highest grain yield in the RDF + 400 kg/hm^2 SiO_2 treatment (Fig. 7).

(36) found that the application of nitrogen and potassium at 2 t/ha, along with furnace slag as a silicon source, resulted in higher yield attributes such as the number of effective tillers per square meter, panicles per area, filled grains per panicle and test weight. Substantial increase in rice yield when NPK fertilizer was supplemented with silica at different rates, with maximum yield enhancements observed at higher silicon levels (37). Similarly, treatments supplemented with rice hull also led to significant yield improvements.

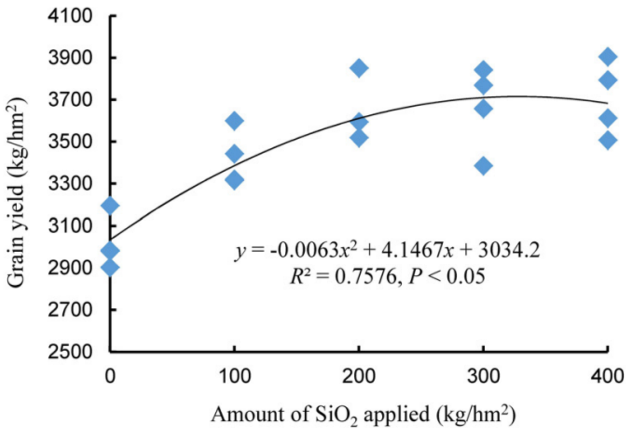


Fig. 7. Effects of Si fertilizer applied on grain yield of rice

(38) emphasized the importance of optimal silicon content in straw for achieving higher rice yields. They categorized straw silicon content as high (>34 g/kg), medium (17-34 g/kg) and low (<17 g/kg) based on relative yield percentages, highlighting the significance of silicon levels in maximizing rice production.

Enhanced nutrient availability

Nitrogen: Nitrogen fertilization often leads to drooping of leaves, a condition mitigated by silicon, which helps maintain leaf erectness. 10 percent improvement in photosynthetic activity can be achieved through proper silicon fertilizer application and management practices, resulting in similar yield increases (38). When silicon is applied alongside nitrogen, it enhances the optimal nitrogen dose, synergistically impacting plant growth. Additionally, nitrogen supplementation contributes to lodging, while plants treated with both nitrogen and silicon exhibit increased resistance to lodging (39). Silicon-fertilized plants may derive maximum benefits from nitrogen availability, as silicon mitigates its harmful effects and boosts photosynthetic activity (39).

Phosphorus: Reports on the interaction between silicon and phosphorus availability to plants show promise, albeit with varying explanations for this effect. Silicon application has been shown to reduce the phosphorus requirement of crops under low phosphorus-absorbing conditions. However, research findings on phosphorus are complex and less promising. It was observed that silicon's overall beneficial impact on phosphorus utilization is indirect, attributed to its influence on the phosphorus to manganese ratio in shoots, thereby reducing iron and manganese uptake and indirectly aiding phosphorus utilization in rice crops (40). Consequently, the relationship between phosphorus and silicon in phosphorus-deficient soil is indirect.

Potassium: The interaction between applied potassium (K) and silicon (Si) in soil appears to have beneficial effects on rice yield. Cell wall silicification is correlated with potassium nutrition and deficiency in potassium reduces silicon accumulation in leaf blade epidermal cells, consequently increasing the plant's susceptibility to rice blast (40). Therefore, potassium-integrated silicon management may hold greater significance in upland areas compared to lowland areas for sustaining rice yield.

Silicon application enhanced the uptake of not only silicon but also nitrogen, phosphorus and potassium by the rice plants, with a strong positive linear relationship between silicon uptake and uptake of these major nutrients (41). This improved nutrient uptake likely promoted better plant growth and development. Additionally, the increased silicon nutrition may have helped the rice plants better cope with abiotic and biotic stresses. The quadratic regression analysis identified 329 kg/hm^2 SiO_2 as the optimum silicon level to maximize yield and the treatment with 400 kg/hm2 SiO_2 was very close to this optimum level. Thus, the synergistic effects of silicon fertilization along with NPK fertilizers on improving yield components, nutrient uptake and potential stress tolerance appeared to be the main factors contributing to the highest grain yield in the RDF + 400 kg/hm^2 SiO_2 treatment (Fig. 8).

Decrease metal toxicities of Iron (Fe) and Aluminum (Al): Iron (Fe) toxicity poses a significant challenge in lowland rice production, primarily due to the accumulation of excess ferrous iron (Fe^{+2}) in reduced soil conditions (41). Silicon plays a crucial role in increasing the oxidizing strength of roots, facilitating the conversion of Fe^{+2} iron to Fe^{+3} iron. This transformation helps prevent excessive iron uptake and reduces its toxicity (16). Additionally, silicon effectively mitigates excess toxicity in rice by enhancing the oxidative capacity of rice roots, leading to increased oxidation of Fe^{+2} iron to insoluble Fe^{+3} iron. As a result, silicon application indirectly prevents the excessive absorption of iron by the plant (41).

Aluminum (Al) poses a significant threat to plant growth, particularly in acidic conditions and remains a major factor affecting agricultural productivity. Its detrimental effects include inhibiting root cell division, impairing cell elongation, and reducing the elasticity and plasticity of cell walls (42-44). Silicon plays a crucial role in mitigating Al toxicity through processes occurring in the soil solution and within the plant's internal mechanisms. The antagonistic effect of silicon on Al toxicity involves reducing aluminum levels by forming Al-Si complexes in the soil solution.

Moreover, silicon alleviates Al toxicity in plants as silicon and aluminium accumulations in the plant are mutually exclusive, with silicon being preferentially taken up over aluminum (44-47). Additionally, the application of silicon reduces Al toxicity by producing inert alumino-silicates, inducing root-based phenolic exudates, or sequestering aluminum in phytoliths (45). Consequently, the tolerance of certain plant species to aluminum may be associated with high silicon uptake and accumulation in plant tissues, particularly in upland rice, despite the effectiveness of silicon uptake and translocation (48).

Enhanced biotic stress tolerance

Research by (49) indicates that plants deficient in silicon are more susceptible to insect pest attacks, fungal diseases and various abiotic and biotic stresses that impede plant growth and development. Plants with low silicon content are particularly vulnerable to diseases such as stem rot (*Magnaporthe salvinii*), brown spot (*Cochliobolus miyabeanus*), leaf blight (*Xanthomonas oryzae* pv. oryzae), scald (*Monographella albescens*), blast (*Magnaporthe grisea*) and grain discoloration.

Soluble silicon has been found to effectively mitigate the impact of plant diseases such as powdery mildew and rice blast (*Magnaporthe grisea*) (50,51). Additionally, third-instar larvae of rice stem borers penetrate more deeply into susceptible rice cultivars, which benefit more from silicon supplementation compared to resistant varieties in deterring larvae (52). Moreover, insect pests like *Sitophilus granarius, Sitophilus oryzae, Rhyzopertha dominica* and *Cryptolestes ferrugineus* have been reported to be effectively controlled by silicon, often in the form of diatomaceous spray or dusted onto plants (53).

Adequate silicon uptake also reduces plant susceptibility to chewing insects such as stem borers (*Chilo suppressalis Walker*), potentially by rendering plant tissue less digestible and causing greater damage to the mandibles of feeding insects (53).

The bioavailable Si absorbed by plants generally strengthens direct and indirect plant resistance to insect pests via the deposition of SiO_2 as biogenic opals (phytoliths), primarily in the epidermal cells of leaves, stems and roots (54). Silicon is deposited as a 2.5-µm-thick layer just beneath the cuticle layer (0.1 µm thick), forming a silicon-cuticle double layer in rice leaf blades (56) (Fig. 2). Consequently, phytoliths promote cell wall strengthening. The abrasiveness of silicified leaves and other plant tissues associated with protection, storage, support and strengthening leads to the increased irreversible wear of mouthparts when insects are

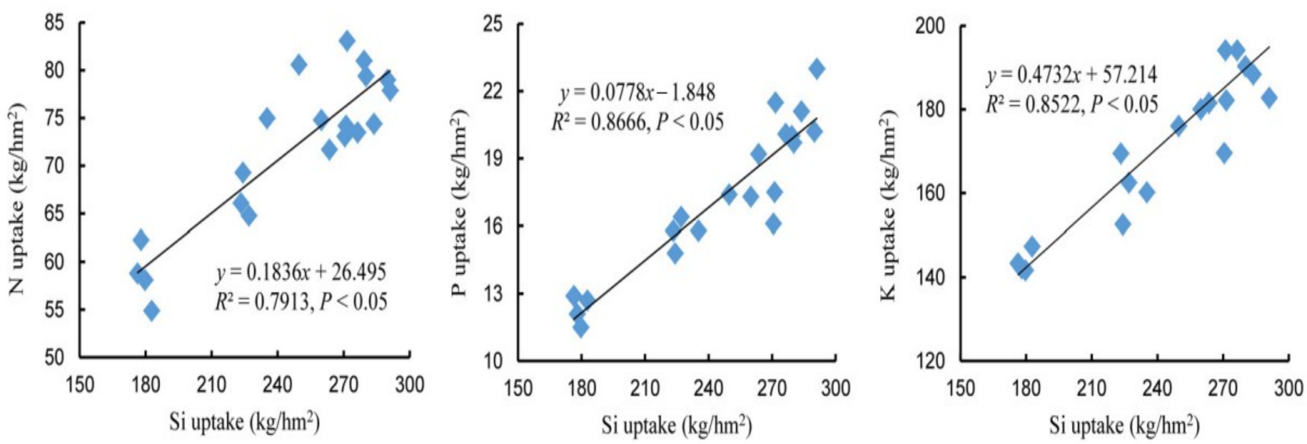


Fig. 8. Linear regression between silicon (Si) uptake and N, P and K uptakes in above-ground biomass of rice.

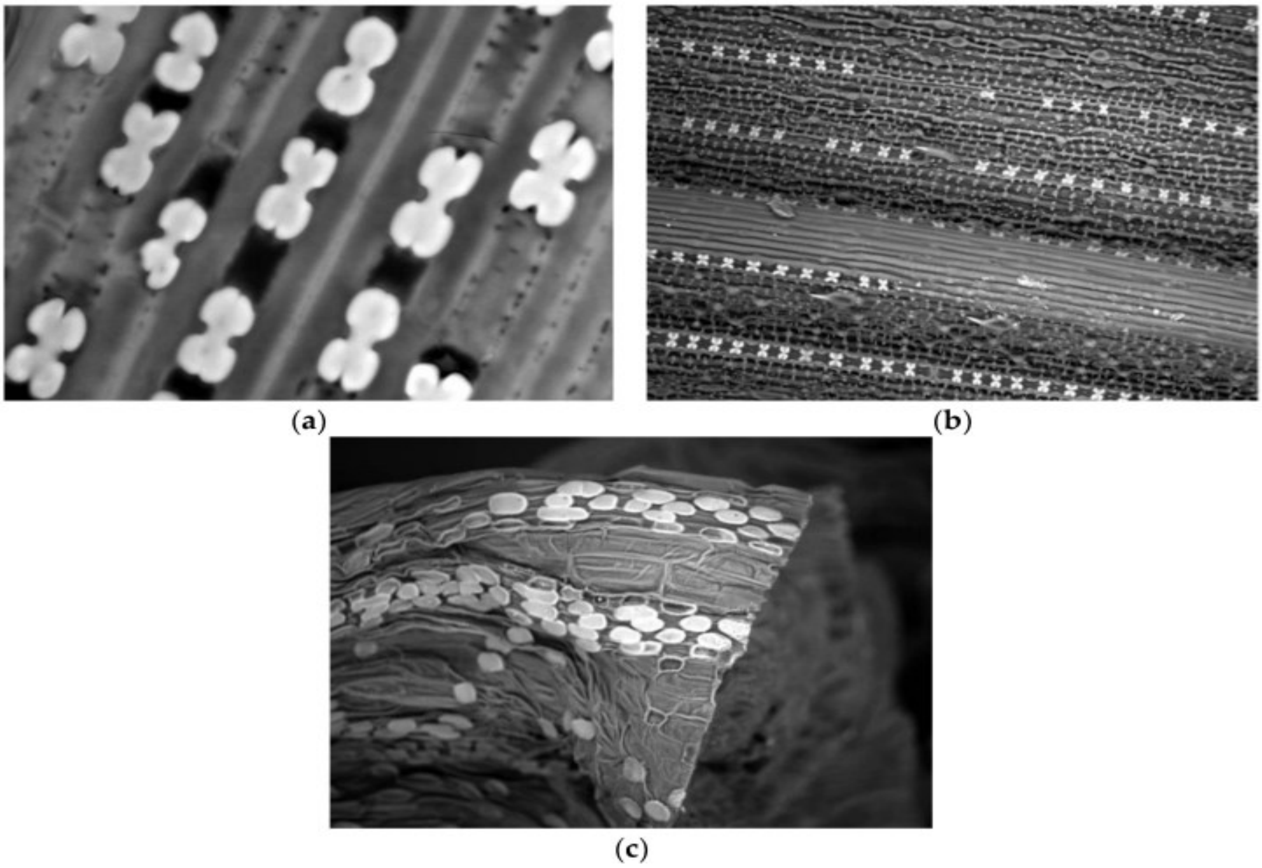


Fig. 9. Silicon-cuticle double layer in rice leaf blades

feeding, therefore deterring chewing insects. Mouthpart wear due to Si treatment can vary according to feeding habits. For instance, *Spodoptera exempta* larvae fed a silica-rich diet displayed increased mandible wear.

Increases abiotic stress tolerance

The rise in the water table poses a significant global challenge, leading to excessive salinity in the soil. Silicon (Si) plays a crucial role in mitigating salt stress in plants through various mechanisms. Studies have shown that Si enhances photosynthetic activity, increases the potassium (K) to sodium (Na) selectivity ratio, boosts enzyme activity and elevates the concentration of soluble substances in the xylem (57). Additionally, the application of Si fertilizer can minimize the toxic effects of salt stress on plants by enhancing the consistency and stability of cell membranes, thus stimulating the antioxidant function of the plant (54).

Deposition of Si in culms, leaves and hulls reduces transpiration from the cuticle, enhancing resistance to drought stress. Under drought conditions, plants treated with silicon fertilizer exhibit greater stomatal conductivity, relative water content and water-holding capacity compared to untreated plants. Furthermore, silicon increases resistance to heavy winds generated by typhoons by improving shoot rigidity through silicification (45).

Moreover, silicon helps relieve water tension by reducing transpiration. Water stress typically results in stomatal closure, reducing the rate of photosynthesis. However, silicon stimulates plant growth more effectively under water-stressed conditions than under non-stressed conditions (16). Pre-treatment of rice plants with silicon under salinity stress has been found to increase stomatal conductivity, leading to an increase in the net assimilation rate (NAR) (55). Additionally, upland rice varieties grown under high silicon culture solutions exhibit increased relative water content and reduced leaf stomatal resistance compared to non-silicon culture solutions (56). Stomatal resistance shows a strongly negative correlation with silicon concentration in the leaf blade, while silicon concentration in the leaf blade positively correlates with relative water content.

Silicon fertilizers

Various sources of silicon fertilizers are available, with calcium silicate, fine silica and sodium silicate being among the most common. Potassium silicate, although highly soluble and suitable for hydroponic systems, is relatively expensive and can also be applied foliarly. Inorganic materials like quartz, clays, micas and feldspars, while silicon-rich, are not ideal sources due to their low solubility.

The efficacy of silicon (Si) as a spray, particularly in the form of potassium silicate or similar soluble compounds, has been shown to be beneficial for improving plant health and resilience (57).

Strengthen plant tissues: Si is deposited in cell walls, enhancing mechanical strength and making plants more resistant to physical damage, pests and diseases.

Improve stress tolerance: It helps plants cope with abiotic stresses like drought, salinity and extreme temperatures by regulating water uptake and improving photosynthesis efficiency.

Provide rapid absorption: Foliar application allows silicon to be quickly absorbed by leaves, bypassing soil limitations and ensuring more immediate effects, especially in plants with poor root absorption of silicon.

Enhance pest and disease resistance: It forms a protective layer on leaf surfaces, reducing insect feeding and fungal infections.

Calcium silicate, often derived as a by-product from industrial processes, is widely used as a silicon fertilizer. Organic sources such as rice ash, straw and husk also contain silicon and can serve as valuable fertilizers (57). Rice straw and husk, with silicon contents ranging from 4-20 percent and 9-26 percent, respectively, can retain their nutrient values and be recycled for various purposes like biogas processing, mushroom cultivation and animal feed.

Silicon-solubilizing bacteria (SSB) represent another microbial fertilizer derived from specified strains of the Bacillus genus, typically extracted from granite quarries. It functions as a crucial field inoculant, absorbing silicon and fortifying plants against both biotic and abiotic stresses. Thickening cell walls enhances plant resilience, underscoring the importance of silica in maintaining and enhancing crop sustainability.

Silicon solubilizers play a crucial role in enhancing the availability of silicon (Si) to plants by converting insoluble forms of silicon into plant-accessible forms (58). Many natural sources of silicon, such as quartz, feldspars, clays and micas, are not readily available to plants due to their low solubility in soil. Silicon solubilizers help overcome this challenge in several ways (59).

Microbial action: Certain microbes, such as bacteria and fungi, are capable of breaking down insoluble silicate minerals in the soil. These microorganisms produce organic acids or enzymes that solubilize silicon, making it available for plant uptake. For example, *Bacillus* and *Pseudomonas* species are known silicon-solubilizing bacteria.

Enhanced plant growth: By increasing the bioavailability of silicon, these solubilizers improve silicon uptake, leading to enhanced plant growth, strengthened cell walls and greater resistance to lodging, diseases and pests.

Improved stress tolerance: Silicon solubilizers indirectly contribute to better drought, salinity and heat tolerance in plants by providing a steady supply of soluble silicon, which supports water-use efficiency and improves plant metabolism under stress conditions.

Soil health improvement: Silicon solubilizers also contribute to long-term soil fertility by breaking down silicate minerals, gradually releasing essential nutrients in addition to silicon.

Conclusion and future prospects

Rice is a major accumulator of silicon (Si), making it vulnerable to both biotic and abiotic stress when soil silicon levels are insufficient. Particularly in tropical and subtropical regions, highly weathered soils often lack silicon due to leaching processes. Ensuring sufficient silicon supply in the soil is crucial for the healthy growth and optimal development of rice production. The application of silicon enhances the availability of essential nutrients such as nitrogen (N), phosphorus (P) and potassium (K), thereby improving agronomic performance and yield response efficiency. Moreover, rice plants treated with silicon exhibit varying degrees of resilience to biotic stresses like insect pest infestations and fungal diseases, as well as abiotic stresses such as aluminum (Al), iron (Fe) and manganese (Mn) toxicity, excessive salinity and drought. In summary, the effective management of silicon is pivotal for the development and enhancement of rice productivity across tropical, subtropical and temperate soils. By bolstering nutrient availability, augmenting stress resistance and optimizing agronomic performance, silicon holds significant promise for advancing rice cultivation and ensuring food security in diverse agricultural landscapes (58-61).

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Authors' contributions

JSM carried out the research part of the review and drafted the review paper. NS carried out the corrections. RK participated in the sequence alignment. CL participated in the modification and the diagram arrangements. ND helped in the rearrangement of the subheadings and finishing. FF helped in arranging the sub topics and searching relevant data. SM helped in the final assessment and fact checking. All authors read and approved the final manuscript.

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

During the preparation of this word, the author(s) used Quillbot and Claude AI/Google collab in order to paraphrase/correct grammatical mistakes and heat map's python code generation, respectively. After using this tool/ service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the published article.

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