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REVIEW ARTICLE

A review on silicon nutrition for sustainable rice production

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Abstract

Increasing food demand with ever-increasing world population, declining water availability and imbalanced fertilizer application to agriculture have impacted global food security. A substantial disparity exists between the potential and actual yield of rice in farmer's fields, which is primarily attributed to improper nutrient management practices. Silicon (Si) is one of the essential nutrients that play a vital role in rice growth and development. It is the second most abundant element in the earth's crust, which is assimilated solely as monosilicic acid. Rice is a high Si accumulator plant and absorbs on an average 150-300 kg of Si ha^{-1}. Absorption and accumulation of Si in rice plants vary from 0.1-10 per cent on dry weight basis. It is probably the only element which can enhance the resistance to multiple stresses. Silicon fertilization has emerged as a promising approach to enhance the sustainability of rice cultivation. Silicon plays a multifaceted role in rice plants, influencing growth, yield and resistance to biotic and abiotic stresses. It enhances plant resilience against various pests and diseases and inducing the accumulation of antifungal compounds. Moreover, silicon mitigates abiotic stresses such as salinity, drought and metal toxicity, thereby improving yield stability and resilience to environmental fluctuations. Furthermore, silicon application contributes to sustainable water management by reducing transpiration and enhancing water use efficiency.

Keywords

biotic stress; diatomaceous earth; mono silicic acid; metal toxicity; silicon

Introduction

Rice (*Oryza sativa* L.) is the principal and staple food crop, providing sustenance to approximately two-thirds of the global population (1). As one of the most widely cultivated cereals, rice holds immense socio-economic significance, particularly in Asia, which contributes over 90 % of the world's rice production and consumption (2). In India, rice occupies a prominent position as the primary and extensively cultivated crop, spanning an area of 46.27 million hectares, with a total production of 129.47 million tonnes and an average productivity of 2.79 t ha^{-1}. In Tamil Nadu, rice cultivation covers 2.21 million hectares, producing 7.90 million tonnes with a productivity of 3566 kg ha^{-1} (3).

The Green Revolution marked a significant milestone in agricultural productivity, leading to notable increases in rice yields. However, its long-term consequences, including the overuse of fertilizers and pesticides, soil degradation, intensive cropping systems, stagnation of groundwater levels and inadequate availability of improved rice varieties, have negatively impacted the sustainability of rice production systems (4). Addressing these challenges is critical to meeting the demands of an ever-growing global population. According to the Food and Agriculture Organization (5), the global population reached 8.1 billion in 2025 and is projected to rise to 9.2 billion by 2050. To feed this expanding population, food grain production must increase from the current 300 million tonnes to 400 million tonnes, emphasizing the need for sustainable agricultural practices.

In this context, silicon (Si) emerges as a crucial element for enhancing the resilience and productivity of rice plants. Although not classified as an essential nutrient, silicon has been recognized as a beneficial element due to its significant role in plant growth, development and stress tolerance. Silicon improves structural integrity by strengthening cell walls, thereby enhancing upright growth and light capture for photosynthesis (6). Furthermore, it helps rice plants mitigate biotic stresses such as pest and disease attacks and abiotic stresses, including drought, salinity and heavy metal toxicity, thereby contributing to sustainable productivity (7). This review focuses on the role of silicon fertilization in rice production, emphasizing its effects on growth, yield and stress tolerance. By exploring the mechanisms underlying silicon's beneficial effects, this review aims to provide insights into how silicon can contribute to sustainable rice cultivation.

1.Sources, uptake and distribution of silicon in rice

Rice plants absorb silicon from the soil primarily in the form of monosilicic acid (H_4SiO_4), which is readily available in the soil solution. The uptake of silicon is mediated by two specific transporters located in the root cells: Lsi1, a passive transporter and Lsi2, an active transporter (8). Once absorbed, silicon is translocated through the xylem and deposited as amorphous silica ($SiO_2{\cdot}nH_2O$) in various plant parts, such as the epidermal cells, leaf blades and hulls. This deposition forms a silica cuticle that strengthens the structural integrity of the plant and acts as a protective barrier against both biotic and abiotic stresses (9).

Soil types vary in their natural silicon availability. Alluvial and volcanic ash soils are rich in silicon, whereas highly weathered tropical soils often exhibit deficiencies. The continuous cultivation of rice without replenishing silicon leads to its depletion in paddy soils, necessitating the use of silicon fertilizers (10-14). Commonly used silicon fertilizers include calcium silicate, sodium silicate and fine silica. While potassium silicate, although expensive, is highly soluble and preferred for hydroponic systems and foliar applications (15). Organic sources of silicon, such as rice husk, rice husk ash and straw, also serve as viable alternatives. Rice straw, often removed from fields for uses like animal feed, biogas generation and mushroom cultivation, retains significant silicon content, ranging from 4 % to 20 %, while rice husk contains 9 % to 26 % silicon (16-18) Different sources of silicon fertilizers along with their total Si content and chemical composition is given in Table 1.

Table 1. Different sources of silicon fertilizers along with their total Si content and chemical composition

Source	Chemical composition	Silicon contents (%)	References
Diatomaceous earth	Not known	80 -90	[19]
Silicic acid	H_4SiO_4	36.0	[20]
Rice hull fresh	SiO_2	7–9.2	[21]
Rich hull ash	SiO_2	> 28.0	[22]
Fly ash	Not known	29.1	[23]
Potassium silicate	K_2SiO_3	18	[24]
Sodium silicate	Na_2SiO_3	23	[25]
Calcium silicate	Ca_2SiO_3	24	[26]
Quartz sand	SiO_2	46	[27]
Silica gel	Not known	46.7	[28]

The total silicon content in soils depends on the parent material, climatic conditions, topography, living organisms and time, which collectively influence soil formation processes like additions, transformations, removals and translocations (29, 30). Silicate minerals play a crucial role in soil chemistry and silicon ranks as the second most abundant element in soils, accounting for approximately 28 % of the total soil weight, following oxygen at 47 % (31). In the soil solution, silicon exists as monosilicic acid, polysilicic acid and complexes with organic and inorganic compounds, such as aluminium oxides and hydroxides (32). Silicon content varies significantly across soil types, with clay soils containing approximately 200-300 g Si kg^{-1} and sandy soils having up to 450 g Si kg^{-1}. On a dry weight basis, silicon content ranges from 1 % to 45 % in soils (6).

Plant-available silicon (PAS) directly influences crop growth and improves soil's physical, chemical, and biological properties. The solubility of silicon in soils is affected by factors such as particle size of silicon fertilizers, soil pH, organic matter and the presence of ions like aluminium, iron and phosphate (33). Additionally, soil moisture and dissolution reactions play significant roles in its availability. Since silicon has limited mobility in the soil, maintaining an adequate supply throughout the crop's growth stages is essential to support healthy and productive plant development (34).

2. Role of silicon in rice

The percentage of silica present in the rice plant can vary across its different parts (35). Rice joints at the base of the grain contains highest silicon content, making up 46 % of the total, highlighting silicon's role in structural support (36). The role of silicon in rice was depicted in (Fig. 1). It is followed by rice hull with 30 %, where silicon likely enhances toughness and protection. Rice straw has 17 % silicon, contributing to the plant's rigidity and disease resistance (37). Finally, rice bran has the least silicon at 7 %, indicating lower structural needs in this part (Fig. 2). Rice, being a high silicon accumulator, greatly benefits from silicon supplementation (38). It absorbs silicon at a higher rate compared to other mineral nutrients, with uptake levels ranging from 230 to 470 kg ha^{-1} (39). The rice plant utilizes silicon in quantities surpassing most macronutrients (40). Typically, to produce 5 t ha^{-1} grain yield, around 230 to 470 kg of silicon per crop is drawn from the soil (41). Without silicon fertilization, intensive rice cultivation has led to yield declines in numerous countries (42). Silicon plays a crucial role in enhancing plant growth and is indispensable for optimizing and sustaining rice productivity (43). Beyond increasing rice yield, silicon offers numerous benefits such as enhancing nutrient availability (44) including nitrogen, phosphorus, potassium, calcium, magnesium, sulfur and zinc, mitigating nutrient toxicity (45) (such as iron, phosphorus and aluminium) and both biotic and abiotic stresses in rice plants (46). Therefore, the application of silicon to soil or plants proves

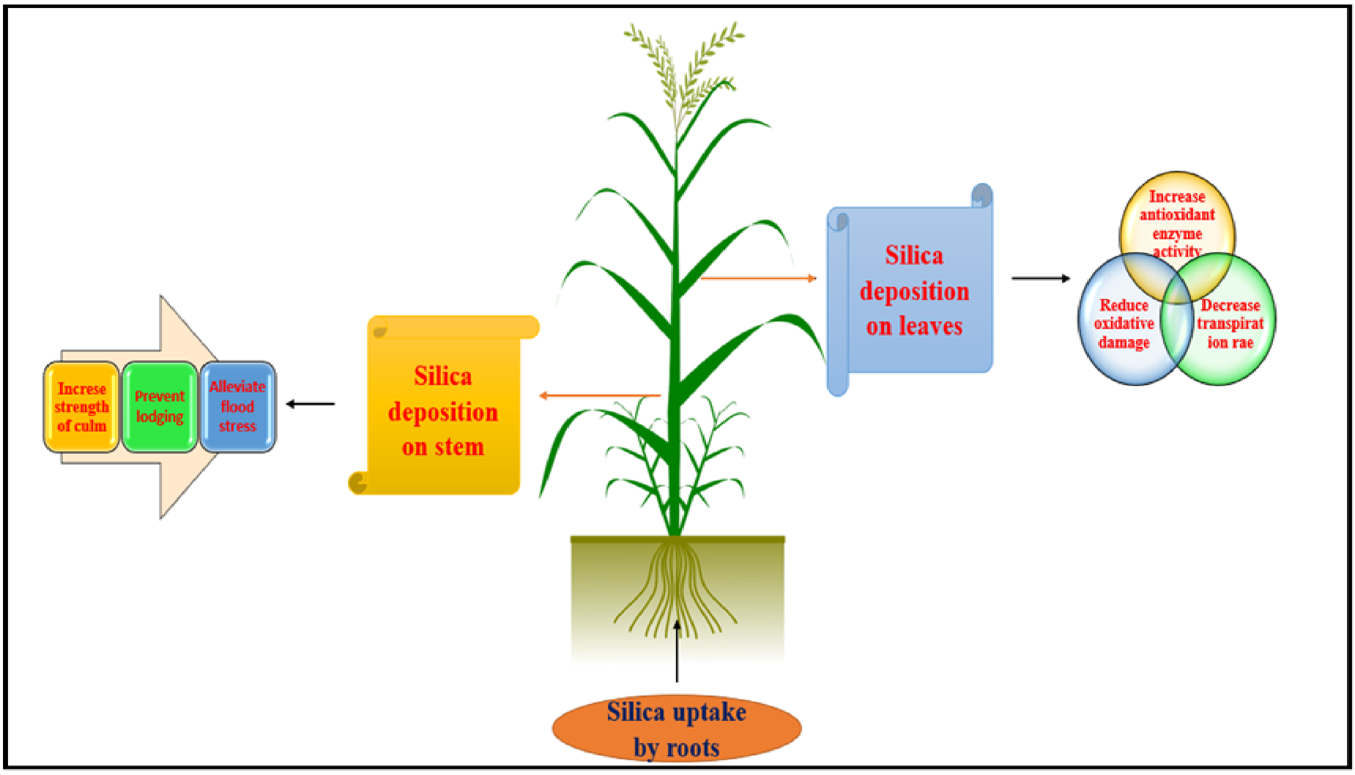

Fig. 1. Role of silicon in rice.

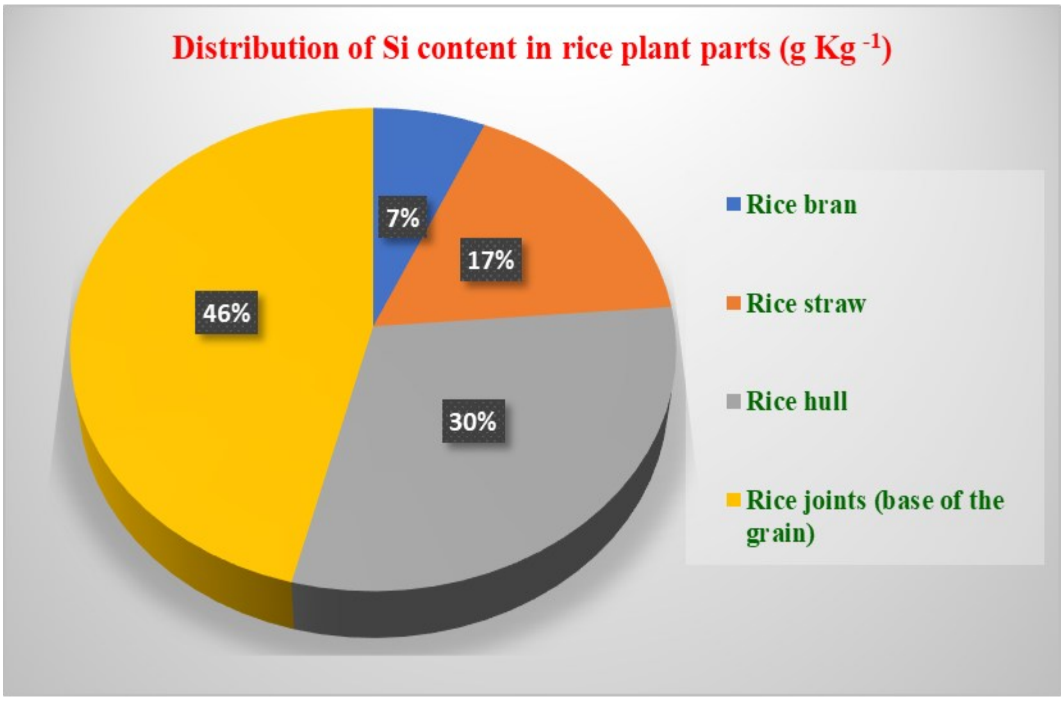

Fig. 2. Distribution of Si content in rice plant (g kg $^{-1}$).

highly beneficial for paddy soils, not only boosting yields but also addressing iron toxicity issues (47). Silicon soil amendments are essential for promoting vegetative growth and ensuring healthy development, especially in stress-prone grasses like rice (48). Silicon is essential for the robust development and yield of rice plants (49). Supplementing rice plants with silicon increases the levels of carbohydrates and proteins (50). This suggests that silicon can serve as a significant factor contributing to rice yield. Therefore, the application of silicon fertilizer may prove beneficial for enhancing and sustaining rice production systems (51) Silicon uptake by rice shoots contributes to thickening the culm wall and enlarging vascular bundles, thereby reducing the risk of lodging (52). Increased silicon content in the lower internodes provides mechanical reinforcement, enabling the plant to withstand lodging (53). Silicon fosters growth, fortifies culms, promotes early panicle formation, enhances the number of spikelets per panicle and boosts the percentage of matured rice grains (54). It also aids in maintaining upright leaves, crucial for maximizing photosynthesis rates. Silicon's role in hull formation in rice is significant, influencing grain quality (24). It was found that silicon fertilizer application not only enhances growth parameters, yield, yield attributes and rice quality but also improves the availability of applied nutrients (38).

2.1 Effect of silicon on growth attributes

At Banaras Hindu University in Varanasi, an experiment examining the impact of silica on rice growth and yield revealed that the addition of 180 kg of silicon as calcium silicate notably increased plant height, tiller count and dry matter production in rice (55). Similarly, it was found that the maximum plant height, tiller count and dry matter production were achieved with the application of 2 t ha^{-1} of calcium silicate (27). Previous research demonstrated that foliar application of silicic acid at a concentration of 4 mL per litter resulted in the tallest plants (99 cm) and maximal dry matter production in rice (56). Additionally, experiment conducted at the University of Agriculture in Faisalabad showed that the application of 0.5 % silicon led to the highest plant height (107.17 cm) and maximum tillers per plant (259.58) in Super Basmati rice (57). In a study, it was observed that foliar spraying of silicic acid at a concentration of 3 mL per litter along with 50 % of the recommended pesticide achieved the highest plant height (105.2 cm) and number of tillers per plant (28.88) in rice (25). A pot culture experiment has found that applying the recommended dose of fertilizers together with calcium silicate resulted in the tallest plants (63.08 cm) and a higher number of active tillers per pot (18.7) (58). Additionally, it was reported that the inclusion of silicon improved growth attributes such as plant height (95.50 cm) and the number of tillers (325.5 m^{-2}) in rice plants (59). In a field experiment conducted at the Indian Agricultural Research Institute (IARI) in New Delhi, it was observed that applying silicon at a rate of 120 kg ha^{-1} resulted in the highest dry matter accumulation at 60 DAS (415.7 and 428.8 g m^{-2}), 90 DAS (1156.7 and 1201.1 g m^{-2}) and at harvest (1406.7 and 1362.1 g m^{-2}) which was comparable to applying silicon at a rate of 80 kg ha^{-1} (60). Similarly, in a pot experiment conducted at Cairo University, Dokki, it was noted that silicon played a significant role in the accumulation of plant dry matter, with the addition of silicon leading to increased dry matter in both roots (29.48 g per pot) and shoots (48.86 g per pot) (52).

2.2 Effect of silicon on yield attributes

Foliar application of silicon on rice led to a 36.4 % increase in the number of panicles per square meter compared to untreated plants, as reported (61-63). A field experiment conducted in Varanasi and confirmed that the addition of 180 kg of silicon in the form of calcium silicate significantly boosted the number of panicles per square meter, filled grains per panicle and test weight in rice (55). It was observed that the highest panicle length, increased number of productive tillers and thousand grain weight were associated with the application of calcium silicate at a rate of 2 t ha^{-1}, resulting in a 25 to 30 % greater grain yield (35). In a field experiment conducted in the hilly zone of Karnataka, it was found that foliar spraying of silicic acid at a concentration of 4 mL L^{-1} resulted in the highest panicle length (23.0 cm) and number of tillers per plant (9.0) in rice (56). In a study conducted at the University of Agriculture, Faisalabad, it was found that applying 0.5 per cent silica resulted in the maximum panicle length (26.83 cm) and 1000-seed weight (19.65g) in Super Basmati rice (64). It is reported that the foliar spray of silicic acid at a concentration of 3 mL L^{-1} achieved the highest panicle length (28.65 cm) and the maximum number of grains per panicle (267.91) in rice (44). It is observed that the application of silicon at a rate of 120 kg ha^{-1} as calcium silicate led to superior numbers of productive tillers, panicles per square meter and test weight in rice, which was comparable to applying silicon at a rate of 80 kg ha^{-1}(65).

2.3 Effect of silicon on yield

A field experiment conducted at Santa Rosa Agricultural University in Colombia demonstrated that the addition of silica improved the grain yield of both rice and wheat (66). It was found that applying 180 kg of silicon as calcium silicate significantly increased the grain yield of rice to 6588 kg per hectare (55). Previous study observed that the maximum grain yield (6380 kg ha^{-1}) and straw yield (8929 kg ha^{-1}) were achieved by spraying silicic acid at a concentration of 4 mL per liter, possibly due to reduced pest and disease occurrence and decreased spikelet sterility during the crop period (56). However, it was noted that the yield decreased when the application rate was increased to 8 mL per liter (67). Previous research found that spraying 1.0 % silica resulted in the maximum grain yield (4.88 t ha^{-1}) and straw yield (12.61 t ha^{-1}) in rice, which was comparable to spraying 0.25 % and 0.50 % silicon (68). A study has determined that adding silica to upland rice at a rate of 240 kg ha^{-1} through calcium silicate was optimal for achieving maximum grain and straw yield (69). The yield increases ranged from 12 % to 25 %, depending on the method and source of silica applied. Similarly, it is reported that applying calcium silicate at a rate of 2 t ha^{-1} in wetland rice resulted in the highest grain yield (70). They also found that higher grain and straw yields were obtained by applying calcium silicate at 2 t ha^{-1} along with 100 kg ha^{-1} of nitrogen (71). A previous study has demonstrated that the application of silicon in the form of calcium silicate at a rate of 200 mg per kg significantly increased grain and straw yield compared to the control (72). Another study noted that the application of 80 and 120 kg of silica as calcium silicate resulted in the maximum grain yield of 5.53 and 5.65 t ha^{-1}, respectively, along with straw yields of 8.09 and 8.57 t ha^{-1}, respectively (61). This increase in yield could be attributed to factors such as an increase in the number of tillers per square meter and increase in panicle length and a decrease in lodging due to silicon application (68).

2.4 Biotic stress tolerance

Pest tolerance: Silicon enhances the resistance of rice plants to various insects such as stem borers, leaf folders and brown plant hoppers (69). The deposition of silica on epidermal layers creates a physical barrier that prevents insects from penetrating the plant tissue. Sucking and leaf-eating caterpillars show a lower preference for silicified tissues compared to low-silica succulent parts (70). Moreover, soluble silicic acid present in the sap of rice plants, even at low concentrations (as low as 0.01 mg/mL), acts as an inhibitor of the sucking activity of the brown plant hopper (71). Various Insect-pests of rice suppressed by Si nutrition was given in Table 2.

Disease tolerance : Silicon has been observed to reduce the incidence of several diseases in rice, including sheath blight, brown spot and grain discoloration (72). Silicon may form complexes with the organic compounds present in the cell walls of epidermal cells, thereby enhancing their resistance to enzymes produced by pathogens (73). Additionally, antifungal compounds such as momilactones have been found to accumulate in rice plants treated with silicon. These compounds act against blast pathogens, contributing to the plant's defence mechanism against fungal infections (74). Various disease of rice suppressed by Si nutrition was given in Table 3.

2.5 Abiotic stress tolerance

Silicon plays a critical role in enhancing rice plants' tolerance to various abiotic stresses, including drought, salinity, heat and heavy metal toxicity. Under drought conditions, silicon deposition in leaf epidermal cells reduces transpiration by forming a silica cuticle, which helps retain moisture and maintain plant water status (14). In saline environments, silicon mitigates ion toxicity by reducing the uptake of sodium (Na^+) and chloride (Cl^-) ions, thus maintaining ionic balance and improving plant growth (19). Heat stress tolerance is improved as silicon enhances chlorophyll stability, photosynthetic efficiency and antioxidant enzyme activity, reducing oxidative damage caused by reactive oxygen species (26). Additionally, silicon alleviates heavy metal toxicity by forming stable complexes with metals like aluminium (Al), cadmium (Cd) and arsenic (As), thereby preventing their accumulation in plant tissues (33). These mechanisms collectively enhance the resilience of rice plants to abiotic stresses, making silicon an essential element for sustainable rice cultivation (11).

3. Silicon deficiency and its implication

Silicon deficiency in rice plants leads to weakened structural integrity, resulting in poor growth and reduced yield potential (6). A lack of silicon decreases the formation of the silica cuticle, leaving plants vulnerable to lodging and damage from wind and rain. Additionally, silicon-deficient plants exhibit higher susceptibility to biotic stresses, including pests like stem borers and diseases such as blast and sheath blight (13). The absence of silicon also reduces tolerance to abiotic stresses like drought, salinity and heavy metal toxicity, further hampering growth and productivity (22). Poor silicon availability in soils, often due to intensive cropping, depletes its reserves, especially in tropical regions where weathered soils dominate (17). Plants grown in silicon-deficient soils show delayed growth, reduced photosynthetic efficiency and lower nutrient-use efficiency (15). Furthermore, silicon deficiency impairs the ability of plants to resist oxidative stress by limiting the formation of antioxidants (36). To address these challenges, external silicon supplementation is essential for maintaining crop health and ensuring sustainable productivity (41).

4. Economic benefits of silicon nutrition

In a field experiment conducted at Varanasi, various levels of rice husk ash (RHA) were evaluated in rice and it was documented that the maximum benefit-cost ratio was achieved under the application of 9 tons of RHA ha^{-1} (0.65), which was comparable to the application of 6 tons of RHA ha^{-1} (0.61) (75). It was reported that a higher cost was incurred with the application of 120 kg of calcium silicate ha^{-1} (Rs. 14666), which was comparable to the cost of applying 80 kg of calcium silicate ha^{-1} (Rs. 14205) (76). The maximum benefit-cost ratio was achieved with the application of 120 kg of calcium silicate ha^{-1} (2.38), which was equivalent to applying 80 kg ha^{-1} (2.36). A previous study assessed that the use of rice husk ash at a rate of 750 kg ha^{-1} which resulted in the highest cost of cultivation (Rs. 24010) and a benefit-cost ratio of 1.48, which was like using rice husk ash at a rate of 500 kg ha^{-1}, where the highest cost of cultivation was Rs. 23985, with a benefit-cost ratio of 1.46 (77). It is reported that a higher cost of cultivation was observed with the application of 120 kg of calcium silicate ha^{-1} (Rs. 4882), which was comparable to applying 80 kg of silicon ha^{-1} (Rs. 4820) (78). The maximum benefit-cost ratio was achieved with the application of 120 kg of silicon ha^{-1}, equivalent to applying silicon at the quantity of 80 kg ha^{-1}. This could be attributed to the higher grain yield and lower cultivation expenses associated with silicon application (79).

Table 2. Insect-pests of rice suppressed by Si nutrition

Insect Pest	Scientific Name	Reference(s)
Asiatic Rice Borer	*Chilo suppressalis*	[79]
Rice Stink Bug	*Oebalus pugnax*	[80]
Green Leafhopper	*Nephotettix virescens*	[81]
Brown Planthopper	*Nilaparvata lugens*	[82]
Rice Leaf Folder	*Cnaphalocrocis medinalis*	[83]
Gall Midge	*Orseolia oryzae*	[84]
White Leafhopper	*Cicadulina spp.*	[85]
Rice Mealybug	*Brevennia rehi*	[86]
Rice Root Aphid	*Rhopalosiphum rufiabdominalis*	[87]
Armyworm	*Spodoptera Mauritia*	[88]
Rice Water Weevil	*Lissorhoptrus oryzophilus*	[89]

Table 3. Diseases suppressed by silicon nutrition

Disease	Pathogen	References
Leaf and Neck Blast	*Magnaporthe oryzae*	[90]
Brown Spot	*Bipolaris oryzae*	[91]
Sheath Blight	*Rhizoctonia solani*	[92]
False Smut	*Ustilaginoidea virens*	[93]
Leaf Scald	*Monographella albescens*	[94]
Stem Rot	*Magnaporthe salvinii*	[95]
Grain Discoloration	*Fusarium spp.*	[96]
Bacterial Leaf Streak	*Xanthomonas oryzae pv. Oryzicola*	[96]
Brown Leaf Spot	*Cercospora oryzae*	[97]

Conclusion

Integration of silicon in rice production offers a holistic approach to achieving sustainability in rice cultivation. Through its multifaceted benefits, silicon enhances plant resilience to biotic and abiotic stresses, improves soil health and fertility and promotes efficient resource utilization. By strengthening plant defences, mitigating environmental stresses and fostering ecosystem health, silicon plays a pivotal role in ensuring food security, environmental sustainability and economic viability in rice production. Moving forward, further research and adoption of silicon utilization in rice cultivation are essential to maximize its potential and realize its benefits on a broader scale. Collaboration among researchers, farmers, policymakers and industry stakeholders is crucial to develop tailored silicon management strategies that suit diverse agroecological contexts and farming systems. Additionally, education and extension efforts are necessary to raise awareness about the importance of silicon in sustainable rice production and to facilitate its adoption among farmers. Incorporating silicon into sustainable rice production practices represents a promising pathway towards achieving resilient, productive and environmentally friendly agricultural systems that can meet the challenges of feeding a growing global population while safeguarding our natural resources for future generations.

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Authors' contributions

DSK contributed to the conceptualization, data curation and drafting of the original manuscript. JS played a key role in conceptualization, supervision, funding acquisition and reviewing and editing the manuscript. GA was responsible for drafting the original manuscript, developing the methodology and validation. RT contributed to the original draft and editing. PJ provided resources and contributed to visualization. ST was involved in methodology development and manuscript review and editing. RS focused on reviewing and editing, while VK contributed to methodology and editing. All authors read and approved the manuscript.

Compliance with ethical standards

Conflict of interest: On behalf of all authors, the corresponding author states that there is no conflict of interest.

Ethical issues: None

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