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Silicon in agriculture: A review of its roles, mechanisms, and applications in crop production

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ABSTRACT

Silicon (Si) is an abundant constituent of soils and also occurs widely in plants. However, the importance of silicon in crop productivity has been overlooked due to the fact that most plants do not require Si for their life cycles. Nevertheless, there are increasing numbers of reports that suggest that silicon acts as a beneficial or even a quasi-essential element, especially by enhancing plant growth in response to stress conditions. This article compiles the current data about the behavior of silicon in the soil, the processes of plant silicon absorption via *Lsi1*, *Lsi2*, and *Lsi6* transporters, and the distribution of silicon in different plants. In addition, it addresses the effects of silicon on alleviation of abiotic stresses like drought, salt, temperature extremes, lodging, and heavy metal toxicity, as well as biotic stresses caused by fungi, bacteria, and arthropods, through its two modes of actions: physical by strengthening the plant cell wall and forming barriers, and biochemical by regulating the antioxidant system, hormones, and defense genes. The review article also assesses methods of fertilizer application that could enhance crop yields through better utilization of silicon nanomaterials (Si-NPs). The importance of Si-NPs in enhancing agricultural practices using the concept of precision agriculture is also looked at in this review. The decreasing amounts of available soil silicon due to intensive cultivation practices and artificial fertilizers indicate that silicon management is one avenue that could be exploited economically to improve crop yield and resilience.

Keywords: Silicon, Crop productivity, Availability of silicon, Silicon nanoparticles

1. Introduction

Approximately 28% of the Earth's crust consists of silicon (Si) by weight, and silicon is found in almost all agricultural soils, though it has been neglected in plant nutrition because it is not essential to the completion of the life cycle of the majority of plants (Epstein, 1999; Datnoff *et al.*, 2001) [2, 1]. Consequently, silicon has always been considered a "beneficial" or "quasi-essential" element rather than an essential one (Elsokkary, 2018) [3], since while the lack of silicon in soils does not affect the process of growth, its presence increases the performance of plants especially when they are exposed to various stresses (Richmond *et al.*, 2003; Guntzer *et al.*, 2012; Coskun *et al.*, 2019) [5, 6, 4]. At the same time, the interest towards silicon has been rising since, owing to intensive cropping practices, harvesting cycles, and the usage of synthetic fertilizers poor in silicon, the availability of silicon for plants has been declining (Savant *et al.*, 1996; Sommer *et al.*, 2006) [7, 8], which has occurred during a period marked by climatic changes, soil salinity, and pests. Interest in this element was not generated recently. Japanese plant pathologists observed the relationship between the level of silicon in the soil and rice blast disease at the beginning of the twentieth century (Pooja *et al.*, 2014) [9]. Over many years of soil fertility and plant physiology studies, researchers have shown the need to pay attention to silicon because of its importance for agronomy (Fox *et al.*, 1978; Marschner, 1995; Ma, 2004) [10, 11, 12]. Identification of the special gene that encodes silicon transporters at the beginning of the 2000s (Ma *et al.*, 2006; Ma *et al.*, 2007) [13, 14] provided the molecular base to this research field. Since then, there has been a rapid increase in the number of publications related to soil science, plant physiology, molecular biology, entomology, plant pathology, and nanotechnology (Frew *et al.*, 2018; Coskun *et al.*, 2019) [15, 4].

This review highlights current research studies and reviews involving soil silicon chemistry, silicon absorption and transportation by plants, the effect of silicon on alleviation of abiotic and biotic stresses, its impact on crop productivity and quality in various plant species, and the novel field of silicon nanoparticles along with their effects on rhizospheric microbiome. All these pieces of evidence together help establish a clear trend regarding the fact that silicon needs to be incorporated more systematically into soil fertility management practices (Guntzer *et al.*, 2012; Meharg *et al.*, 2015; Debona *et al.*, 2017) [6, 17, 16].

2. Silicon in soil: Forms, sources, and availability

Silicon in soil is found in three forms—liquid, adsorbed, and solid (Sommer *et al.*, 2006) [8]. Silicon in its plant-available form, monosilicic acid (H_4SiO_4), is soluble in soil under pH conditions less than 9, and its concentration in soil solution is usually comparable to other elements, like potassium and sulfate (Epstein, 1999; Ma *et al.*, 2006) [2, 18]. Mineral soils have a high total amount of silicon in the form of quartz sand and primary silicates (olivine, feldspar, mica) and also secondary clay silicates (illite, kaolinite, montmorillonite), but since the total amount is insoluble and biogeochemically inactive, it is not possible to use total soil silicon to predict the amount available to plants (Sommer *et al.*, 2006; Cornelis *et al.*, 2016) [8, 19].

The availability of silicon is low in highly weathered and leached soils, like Oxisols and Ultisols, in organic Histosols that have little mineral content, and in soils that have high quartz sand content or a long history of intense cropping in the absence of silicon supply (Savant *et al.*, 1996; Klotzbücher *et al.*, 2015) [21, 20, 7]. Soil pH, soil redox potential, soil organic matter, and soil oxides of iron and aluminum all affect the amount of silicic acid left in soil solution as opposed to the amount of silicic acid adsorbed onto the mineral surface (Sommer *et al.*, 2006; Gérard *et al.*, 2008) [8, 22]. Soil waterlogging increases solubility of silicon, while adsorption on iron and aluminum hydroxides decreases the solubility of silicic acid in the soil solution as the soil pH increases (Cornelis *et al.*, 2016) [19]. This information is important for agriculture since the actual threshold for silicon fertilizer application is not the total silicon content of the soil but rather its plant-available content, measured with extractants like citric acid, acetic acid, or sodium acetate (Savant *et al.*, 1996; Klotzbücher *et al.*, 2015 [7]; Heckman, 2021).

There is a biological cycling mechanism whereby silicon moves back to the soil in large part due to plants themselves. In a mechanism whereby plants that accumulate silicon take in monosilicic acid, the process of polymerization in the plants leads to silica bodies known as phytoliths, which are amorphous and hydrated (Currie *et al.*, 2007; Trembath-Reichert *et al.*, 2015) [23, 24]. When the plant dies and its tissues decay, the phytoliths get dissolved and hence contribute to the pool of available silicon in the soil (Strömberg *et al.*, 2018) [25]. It follows that residue management such as recycling rice straw and husk would influence the soil's availability of silicon in the long term (de Tombeur *et al.*, 2021; Cornelis *et al.*, 2016) [26, 19].

3. Uptake and transport of silicon in plants

Silicon uptake by plants takes place via the roots in the form of monosilicic acid and moves acropetally through the xylem to deposit as amorphous silica gel ($\text{SiO}_2 \cdot n\text{H}_2\text{O}$) in the cell wall, intracellular space, and trichomes, particularly in the leaf epidermis (Ma *et al.*, 2006; Currie *et al.*, 2007) [18, 23]. Silicon once deposited is immobile and cannot be translocated to younger parts (Ma *et al.*, 2008) [27]; thus, its frequent application gives better results than once-off application.

There are three ways of silicon uptake: active silicon uptake where the roots absorb silicon at a higher rate compared to water, hence creating low concentrations of silicon around them; passive uptake, whereby uptake takes place in proportion to the transpiration flow; and rejective uptake where plants exclude silicon. There is great variation among species as far as the uptake of silicon goes and the amounts of silicon accumulated. From the concentrations of silicon in the shoots and their ratios to calcium, plants can be categorized into accumulators (silicon content above 1%), intermediate accumulators, and excluders (less than 0.5%). Accumulators include rice, sugarcane, and many members of the Poaceae and Cyperaceae families.

The molecular basis for this variation became clear with the discovery of dedicated silicon transporter genes. Transporter genes for influx (type *Lsi1*, low-silicon genes which belong to the nodulin26-like intrinsic proteins group) transport silicic acid from the soil solution to root cells, whereas efflux transporter genes (type *Lsi2*) transport it from root cells to the xylem for delivery to the shoots; there is an ad-

ditional transporter gene (type *Lsi6*) involved in silicon unloading from the xylem to leaf tissue (Ma *et al.*, 2006; Ma *et al.*, 2007; Yamaji *et al.*, 2007; Yamaji *et al.*, 2011) [13, 14, 28, 29]. The transporters were initially identified in rice but have later been found in barley (Chiba *et al.*, 2009) [30], maize (Mitani *et al.*, 2009) [31], wheat (Montpetit *et al.*, 2012) [32], soybean (Deshmukh *et al.*, 2013) [33], cucumber, and other plants, giving an insight into the genetic basis behind the different amounts of silicon accumulated by various crops growing in the same soils (Ma *et al.*, 2015; Kaur *et al.*, 2019) [35, 34].

4. Silicon and abiotic stress tolerance

4.1 Drought and water-deficit stress

The application of silicon, either as soil application, foliar spray or nanosilicon, has time and again proven effective on improving growth and development in crops such as wheat, sugarcane, sugar beet, maize, soybean and other crops, under water stress conditions (Wang *et al.*, 2021; Zhu *et al.*, 2014) [36, 37]. Mechanisms reported include improved cell membrane integrity and relative water content, higher leaf chlorophyll content and photosynthesis rate, higher root hydraulic conductivity and radial water transport, reduced water loss by transpiration due to formation of silica in leaves, and greater antioxidant enzyme activities including superoxide dismutase, catalase, ascorbate peroxidase which prevent oxidation stress due to the generation of reactive oxygen species due to drought stress (Kim *et al.*, 2017; Wang *et al.*, 2021; Biju *et al.*, 2017) [39, 36, 38]. In lentils, foliar and root-applied silicon regulates osmolyte and hydrolytic enzymes activity and reprogramming gene expression pathways for drought stress tolerance (Biju *et al.*, 2017; Biju *et al.*, 2021; Biju *et al.*, 2023) [38, 40, 41]. In rice, silicon fertilization enhanced plant water balance, photosynthesis rate, and uptake of minerals under water deficit condition (Chen *et al.*, 2011) [42], while the combination of water management practices and silicon treatments resulted in decreased accumulation of arsenic as well as in improved germination and growth (Zia *et al.*, 2017) [43]. For the sugarcane crop, silicon fertilization increased photosynthetic efficiency and activity of antioxidant enzymes under conditions of drought (Li, 2019) [44]. In a number of field and pot experiments, silicon-fertilized plants subjected to water deficit exhibited higher yields, biomass, and grain quality compared to non-treated plants, and especially under the conditions of more intense drought (Zhu *et al.*, 2014; Debona *et al.*, 2017) [37, 16].

4.2 Salinity stress

Silicon acts against salinity stress using a variety of strategies: lowering the uptake and transport of sodium into shoots, increasing the absorption of potassium, thereby raising the K^+/Na^+ ratio, ion compartmentalization into the vacuoles, lowering membrane permeability and electrolyte leakage, and increasing the activities of antioxidative enzymes (Liang, 1999; Dhiman *et al.*, 2021; Zhu *et al.*, 2014) [46, 45, 37]. Silicon treatment in barley plants led to changes in the ultrastructure of leaves, chlorophyll concentration and photosynthesis in salt-stressed plants (Liang, 1998) [47], and hydroponic silicon application in soybean caused enhanced growth under salinity stress (Lee *et al.*, 2010) [48]. The same has been reported for cucumber, tomato, sweet pepper, spinach, and cereal crops under saline conditions, leading to better germination, growth, and biomass production (Abdelaal *et al.*, 2020; Dhiman *et al.*, 2021) [49, 45].

4.3 Heavy-metal and mineral toxicity

Another common feature of the reviewed literature is that silicon can decrease the uptake, translocation, and toxicity of aluminum, cadmium, arsenic, manganese, lead, zinc, and many more harmful elements (Neumann & zur Nieden, 2001; Wu *et al.*, 2013) [50, 51]. The following mechanisms have been suggested to account for these effects: precipitation of metals outside the cells along with silica precipitation in the growth medium, changes in the rhizosphere pH, increased by silicon, reducing the solubility of the metals, metal binding to the cell walls and their limitation in entering the cytoplasm, hydroxy-aluminosilicate complexation as a mechanism of aluminum

detoxification, and enhanced activities of antioxidative defense systems against metal-induced oxidative stress (Hou *et al.*, 2023; Liang *et al.*, 2007) [52, 53]. For example, it was found that silicon nutrition decreased cadmium uptake and reprogramming of leaf proteome during cadmium stress in rice (Nwugo *et al.*, 2008; Nwugo *et al.*, 2011) [54, 55] and that silicon nutrition decreased metal accumulation and translocation but increased plant biomass and chlorophyll concentration in the hyperaccumulator of arsenic/cadmium *Isatis cappadocica* (Azam *et al.*, 2021) [56]. Zinc toxicity reduction due to zinc transport regulation and antioxidant activity has also been reported in rice (Song *et al.*, 2011; Gu *et al.*, 2012) [58, 57]. Such effects have great significance in crop production in acidic, metal-polluted, or heavily weathered soils in which aluminum or manganese toxicity is an obstacle for growth (Wu *et al.*, 2013; Zargar *et al.*, 2019) [51, 59].

4.4 Other abiotic stresses

Silicon has been found to reduce the impact of extreme temperatures, UV-B exposure, nutritional stress, and lodging (Etesami *et al.*, 2018; Bakhat *et al.*, 2018) [61, 60]. In various studies involving cereals, the presence of silicon within stem tissues resulted in structural hardness and lignification, thus preventing lodging and preserving canopy photosynthesis and productivity during wind and rain (Detmann *et al.*, 2012) [62]. Silicon has also been shown to enhance phosphorus uptake and utilization efficiency, possibly because of its influence on the secretion of organic acids and phosphate transporters from root tissues (de Tombeur *et al.*, 2021) [26].

5. Silicon and biotic stress management

5.1 Plant pathogens

Silicon is arguably one of the most reliable methods of decreasing the impact of both fungi and bacterial diseases on various crops (Fauteux *et al.*, 2005; Wang *et al.*, 2017; Rodrigues, 2015) [63, 64, 65]. There are two basic mechanisms that are thought to be involved. The first one is physical. Silicon polymerization under the leaf cuticle results in formation of a physical barrier—the so-called double cuticular layer, which prevents fungi from penetrating into plant tissues and also silica deposition at the infection points (papillae) creates a physical barrier against pathogens (Rodrigues *et al.*, 2003; Guerriero *et al.*, 2016) [67, 66]. The second mechanism is biochemical or molecular. It has been shown that silicon application enhances the activity of certain defense enzymes such as peroxidase, polyphenol oxidase, phenylalanine ammonia-lyase, and chitinase (Cai *et al.*, 2008; Mohammadi *et al.*, 2002) [68, 69], increases the concentration of antimicrobial phenols and phytoalexins (Fawe *et al.*, 1998; Rodrigues *et al.*, 2004; Remus-Borel *et al.*, 2005) [70, 71, 72], and primes plants for enhanced reaction to pathogens by promoting gene expression (priming effect) (Vivancos *et al.*, 2015; Van Bockhaven *et al.*, 2013) [74, 73].

Numerous studies have shown that the use of silicon is highly effective in inhibiting the intensity of pathogens affecting crop species. Silicon applications on cereals inhibit the effect of the major fungal diseases such as blast, brown spot, and sheath blight in rice (Rodrigues *et al.*, 2003; Cacique *et al.*, 2013; Abed-Ashtiani *et al.*, 2012) [67, 76, 75], while on wheat and barley it prevents the development of powdery mildew and spot blotch (Carver *et al.*, 1987; Bélanger *et al.*, 2003; Perez *et al.*, 2014) [78, 77, 79]. The same effects are recorded in perennial and horticulture crops such as rust and ring spot on sugarcane, Panama wilt and black Sigatoka on banana, leaf rust in coffee (Carré-Missio *et al.*, 2009) [80], powdery mildew in cucurbits (Fawe *et al.*, 1998) [70] and grapevine (Bowen *et al.*, 1992) [81], bacterial wilt and speck in solanaceous crops such as tomato and potato (Andrade *et al.*, 2013) [82]. Despite the fact that silicon applications do not inhibit the initial penetration of pathogens into the plants, they significantly reduce the development of the disease leading to the smaller lesions.

5.2 Arthropod pests and herbivores

The use of silicon causes plants to gain resistance against different insect herbivores and mites using a combination of physical and biochemical processes (Reynolds *et al.*, 2016; Alhousari *et al.*, 2018) [84, 83]. Physically, deposition of silicon makes the leaves more abrasive and rigid; as a result, palatability, digestibility, and mechanical wear of herbivore mouthparts are reduced in some cases (Massey *et al.*, 2006; Massey *et al.*, 2009; Keeping *et al.*, 2008) [85, 86, 87]. Biochemically, silicon plays an active role in jasmonic acid signaling process that is involved in inducible defenses against chewing herbivores. Some studies demonstrate the presence of positive feedback between jasmonate signaling and silicon accumulation (Ye *et al.*, 2013; Reynolds *et al.*, 2016) [88, 84]. Silicon has similarly been implicated in alterations in the volatile emissions of the HIPVs which could enhance the attraction of their enemies such as predators and parasitoids towards the stressed plants. This is yet another type of indirect defense mechanism of the third trophic level aside from the direct one exhibited by the herbivores (Reynolds *et al.*, 2016; Golubkina *et al.*, 2022) [84, 89]. Its effects have been reported for leaf-folder insect pest of the rice (Ye *et al.*, 2013) [88] and diverse chewing and piercing-sucking pests on both grasses and legumes, as well as the vertebrate herbivores in some grass and cereals (Massey *et al.*, 2006; Alhousari *et al.*, 2018) [87, 83].

6. Silicon fertilization: Effects on crop yield and quality

Trials on cereals, legumes, root and tuber crops, vegetables, fruit and ornamental plants consistently show that application of silicon fertilizers results in increased yields or improvement in quality, either via soil application or through foliar spraying (Artyszak, 2018; Sarma *et al.*, 2024) [90, 91]. Since silicon is not retranslocated once it is absorbed, any positive effects can be observed only under some form of stress, whether drought, salinity, disease or pest attack, and foliar application of nutrients has been found relatively inexpensive and easy compared to soil applications (Artyszak, 2018; Munir *et al.*, 2023) [90, 92].

6.1 Cereals

In wheat, silicon fertilization—via sodium silicate, silicate slag, potassium metasilicate, or proprietary silicic acid formulations—has increased grain yield primarily by improving spike density, number of grains per spike, and thousand-grain weight, with particularly strong effects reported under drought and salinity stress and in soils with low native silicon availability (Artyszak, 2018; Dhiman *et al.*, 2021) [90, 45]. Similarly in maize, increased yield was achieved due to increased number of grains per ear and grain weight, as well as better drought tolerance (Sarma *et al.*, 2024; Munir *et al.*, 2023) [91, 92]. In rice, silicon fertilization has increased grain yield through improved spikelet formation, fertilization, and grain filling (Detmann *et al.*, 2012; Klotzbücher *et al.*, 2015) [62, 20], alongside its well-established role in disease suppression (Rodrigues *et al.*, 2003; Datnoff *et al.*, 2001) [67, 1].

6.2 Legumes and oilseeds

In soybean, foliar silicic acid has increased the number of pods per plant, seeds per pod, and thousand-seed weight, with benefits most evident under drought and salinity stress (Lee *et al.*, 2010; Artyszak, 2018) [48, 90]. In lentil, silicon supplementation improved seed germination, osmotic regulation, and antioxidant defense under water-limited conditions (Biju *et al.*, 2017; Biju *et al.*, 2021) [38, 40]. In winter oilseed rape, silicon-containing foliar products have improved winter survival via more compact, cold-hardy rosette growth, root system development, and seed weight (Artyszak, 2018) [90].

6.3 Root and tuber crops

Sugar beet trials, particularly from European field studies, report consistent increases in root yield, biological and commercial sugar yield, and in some cases a reduction in impurities such as alpha-amino nitro

gen that lower processing quality, following silicon fertilization delivered as marine calcite, potassium or sodium silicate solutions, or nano-silica formulations (Artyszak *et al.*, 2021; Artyszak *et al.*, 2024; Artyszak *et al.*, 2026 [93]; Artyszak & Gozdowski, 2021; Vicedo *et al.*, 2019) [94]. In potato, silicon fertilization has increased average tuber weight and total tuber yield, altered tuber skin anatomy in ways associated with delayed maturation and improved storage, reduced nitrate accumulation, and in some studies reduced the incidence of specific tuber diseases, although effects on overall disease pressure have been inconsistent across studies (Trawczyński, 2018; Artyszak, 2018) [95, 90].

6.4 Vegetables, berries, and orchard crops

Across lettuce, tomato, cucumber, pepper, onion, and strawberry, silicon fertilization—soil or foliar—has generally increased yield, fruit or head weight, firmness, and postharvest quality, while in several cases reducing fruit cracking, nitrate accumulation, and susceptibility to specific pathogens (Peris-Felipo *et al.*, 2020; Hajiboland *et al.*, 2018; Abdelaal *et al.*, 2020) [96, 97, 49]. In orchard and vine crops, silicon applications have reduced grapevine powdery mildew severity (Bowen *et al.*, 1992) [81], increased grape yield, and improved seedling establishment in ornamental bedding and pot plants through firmer, better-formed growth (Artyszak, 2018) [90].

6.5 Commercial silicon fertilizer sources

Silicon fertilizers used in practice include solid mineral sources such as calcium silicate, potassium silicate, sodium silicate, and calcium-magnesium silicate—often applied to soil and, in the case of calcium silicate, valued additionally as a liming material; liquid stabilized silicic acid formulations used mainly for foliar application; and industrial by-products such as iron and steel slag, blast-furnace slag, and fly ash, which supply silicon while also recycling waste material (Datnoff *et al.*, 2001; Artyszak, 2018; Munir *et al.*, 2023) [1, 90, 92]. Plant-derived silica sources, including rice hull and rice hull ash, offer an additional, renewable route to replenishing plant-available soil silicon in intensively cropped systems such as rice paddies (Klotzbücher *et al.*, 2015; Savant *et al.*, 1996; Pereira *et al.*, 2004) [20, 7, 98], and silicon is now recognized in several countries as an officially designated plant-beneficial substance eligible for fertilizer labeling (Heckman, 2013) [99].

7. Silicon-based nanoparticles in agriculture

A growing body of work examines silicon dioxide nanoparticles (SiO₂-NPs or Si-NPs) as a higher-bioavailability alternative to conventional silicate fertilizers, which are often poorly soluble (Rajput *et al.*, 2021) [100]. It has been observed that Si-NPs can help enhance germination and vigor of plants including wheat, peas, mustard, sunflowers, tomatoes, lentils, and maize, increase the content of photosynthetic pigments and gas exchange capacity, and improve resistance against salinity, drought, low temperatures, and UV-B through a mechanism very much like that in bulk silicon but with higher efficiency at smaller quantities due to the large surface-to-volume ratio and activity of nanoparticles (Sharf-Eldin *et al.*, 2023; Rajput *et al.*, 2021) [101, 100].

Si-NPs have also shown antimicrobial activity against a range of plant pathogens and can reduce the uptake and phytotoxicity of heavy metals such as cadmium, lead, arsenic, and mercury by limiting their translocation from root to shoot and by supporting antioxidant defense systems (Rajput *et al.*, 2021; Hou *et al.*, 2023) [100, 52]. Mesoporous silica nanoparticles have additionally been explored as carriers for macronutrients and pesticides in controlled-release fertilizer and nanopesticide formulations, exploiting their large surface area, tunable pore size, and stimulus-responsive release behavior to improve the efficiency and photostability of agrochemicals while reducing environmental losses. As with conventional silicon, the magnitude and direction of Si-NP effects depend heavily on particle size, shape, concentration, and method of application (soil drench, seed priming, or foliar spray), and soil-applied Si-NPs are generally re-

ported to be more effective than foliar applications for producing measurable increases in plant tissue silicon content (Rajput *et al.*, 2021) [100].

8. Silicon, soil properties, and the rhizosphere microbiome

In addition to their direct impacts on the growth of plants, silicon and Si-NPs affect the soil-plant-microbe ecosystem. It has been demonstrated that amendments of silicon have an effect on the metabolic composition of the rhizosphere—the presence of organic acids, sugars, and fatty acids related to carbon and nitrogen metabolism, altering the ratio of certain genera of bacteria and fungi in the rhizosphere, increasing the growth-promoting genera of bacteria, such as *Paenibacillus*, as well as interacting with phosphate-solubilizing and nitrogen-fixing microorganisms, thus positively affecting nutrient cycling and soil fertility (Rajput *et al.*, 2021; Cornelis *et al.*, 2016) [100, 19]. In turn, silicate-solubilizing bacteria, which are found in the soil, are capable of transforming insoluble mineral silicates into soluble forms that can be assimilated by the plants. This process provides a biological alternative to silicon fertilization (Rajput *et al.*, 2021; Etesami *et al.*, 2018) [100, 61]. However, there have been some reports on the negative impact of excessive amounts of Si-NPs on the activity of soil enzymes and microbial gene abundance (Rajput *et al.*, 2021; Wu *et al.*, 2013) [100, 51].

Conclusion

Silicon is increasingly recognized as an important beneficial element in modern crop production, particularly under conditions of environmental and biological stress. While silicon is not classified as one of the elements that are essential for the entire life cycle of the plant, the information that has been provided above clearly indicates that silicon can bring a lot of benefit to plant growth, productivity and resistance through its impact on soil-plant interactions. The benefits that silicon offers to plants come through the complex dual interaction that is composed of two aspects - the physical and the biochemical aspects. This combination enables plants to cope up with various stressful situations including droughts, salinity, heavy metal toxicity, fungi attacks, pests and others.

Despite the advances that have been made in this area, many knowledge gaps still exist. There is the possibility that plant-available silicon could be reduced as a result of intensive farming practices, continuous removal of residue, and the use of silicon-deficient synthetic fertilizers; but silicon management has received limited attention within soil testing and fertilizer recommendations. The recent developments in silicon fertilization and crop residue management, as well as the novel techniques of using silicon nanoparticles (Si-NPs) and silicate-solubilizing bacteria, hold great promise in this regard. However, there is a lack of knowledge regarding the efficiency of these methods on the farm-scale, optimal application rates, and environmental fate of silicon-based nanomaterials.

In general, the scientific literature reviewed in this paper shows that the use of silicon as a fertilizer input can be included within broader frameworks of soil fertility and crop climate resilience management, especially for high-input and stress-prone agroecosystems. Silicon should not be seen as another fertilizer input but rather as an integral part of integrated soil-plant-microbe management system.

References

1. Datnoff LE, Snyder GH, Korndörfer GH, editors. *Silicon in Agriculture*. Elsevier; 2001.
2. Epstein E. SILICON. *Annual Review of Plant Physiology and Plant Molecular Biology*. 1999;50(1):641–664.
3. Elsokkary IH. Silicon as a beneficial element and as an essential plant nutrient: An outlook (review). *Alexandria Science Exchange Journal An International Quarterly Journal of Science Agricultural Environments*. 2018;39(3):534–550.

4. Coskun D, Deshmukh R, Sonah H, Menzies JG, Reynolds O, Ma JF, Kronzucker HJ, Bélanger RR. The controversies of silicon's role in plant biology. *The New Phytologist*. 2019;221(1):67–85.
5. Richmond KE, Sussman M. Got silicon? The non-essential beneficial plant nutrient. *Current Opinion in Plant Biology*. 2003;6(3):268–272.
6. Guntzer F, Keller C, Meunier JD. Benefits of plant silicon for crops: a review. *Agronomy for Sustainable Development*. 2012;32(1):201–213.
7. Savant NK, Snyder GH, Datnoff LE. Silicon management and sustainable rice production. *Advances in Agronomy*. 1996:151–199.
8. Sommer M, Kaczorek D, Kuzyakov Y, Breuer J. Silicon pools and fluxes in soils and landscapes—a review. *Zeitschrift Für Pflanzenernährung Und Bodenkunde [Journal of Plant Nutrition and Soil Science]*. 2006;169(3):310–329.
9. Pooja K, Katoch A. Past, present and future of rice blast management. *Plant Science Today*. 2014;1(3):165–173.
10. Fox RL, Silva JA. Symptoms of plant malnutrition—Silicon, an agronomically essential nutrient for sugarcane. University of Hawaii, College of Tropical Agriculture. 1978.
11. Ma JF. Role of silicon in enhancing the resistance of plants to biotic and abiotic stresses. *Soil Science and Plant Nutrition*. 2004;50(1):11–18.
12. Marschner H. Mineral nutrition of higher plants (2nd ed.). Academic Press; 1995.
13. Ma JF, Tamai K, Yamaji N, Mitani N, Konishi S, Katsuhara M, Ishiguro M, Murata Y, Yano M. A silicon transporter in rice. *Nature*. 2006;440(7084):688–691.
14. Ma JF, Yamaji N, Mitani N, Tamai K, Konishi S, Fujiwara T, Katsuhara M, Yano M. An efflux transporter of silicon in rice. *Nature*. 2007;448(7150):209–212.
15. Frew A, Weston LA, Reynolds OL, Gurr GM. The role of silicon in plant biology: a paradigm shift in research approach. *Annals of Botany*. 2018;121(7):1265–1273.
16. Debona D, Rodrigues FA, Datnoff LE. Silicon's role in abiotic and biotic plant stresses. *Annual Review of Phytopathology*. 2017;55:85–107.
17. Meharg C, Meharg AA. Silicon, the silver bullet for mitigating biotic and abiotic stress, and improving grain quality, in rice? *Environmental and Experimental Botany*. 2015;120:8–17.
18. Ma JF, Yamaji N. Silicon uptake and accumulation in higher plants. *Trends in Plant Science*. 2006;11(8):392–397.
19. Cornelis JT, Delvaux B. Soil processes drive the biological silicon feedback loop. *Functional Ecology*. 2016;30(8):1298–1310.
20. Klotzbücher T, Marxen A, Vetterlein D, Schneiker J, Türke M, van Sinh N, Manh NH, van Chien H, Marquez L, Villareal S, Bustamante JV, Jahn R. Plant-available silicon in paddy soils as a key factor for sustainable rice production in Southeast Asia. *Basic and Applied Ecology*. 2015;16(8):665–673.
21. Heckman JR. Silicon needs of soils and crops (FS1278). Rutgers Cooperative Extension, Rutgers University. 2021.
22. Gérard F, Mayer KU, Hodson MJ, Ranger J. Modelling the biogeochemical cycle of silicon in soils: Application to a temperate forest ecosystem. *Geochimica et Cosmochimica Acta*. 2008;72(3):741–758.
23. Currie HA, Perry CC. Silica in plants: biological, biochemical and chemical studies. *Annals of Botany*. 2007;100(7):1383–1389.
24. Trembath-Reichert E, Wilson JP, McGlynn SE, Fischer WW. Four hundred million years of silica biomineralization in land plants. *Proceedings of the National Academy of Sciences of the United States of America*. 2015;112(17):5449–5454.
25. Strömberg CAE, Dunn RE, Crifò C, Harris EB. Phytoliths in paleoecology: Analytical considerations, current use, and future directions. *Vertebrate Paleobiology and Paleoanthropology*. 2018:235–287.
26. de Tombeur F, Cornelis JT, Lambers H. Silicon mobilisation by root-released carboxylates. *Trends in Plant Science*. 2021;26(11):1116–1125.
27. Ma JF, Yamaji N. Functions and transport of silicon in plants. *Cellular and Molecular Life Sciences*. 2008;65(19):3049–3057.
28. Yamaji N, Ma JF. Spatial distribution and temporal variation of the rice silicon transporter Lsi1. *Plant Physiology*. 2007;143(3):1306–1313.
29. Yamaji N, Ma JF. Further characterization of a rice silicon efflux transporter, Lsi2. *Soil Science and Plant Nutrition*. 2011;57(2):259–264.
30. Chiba Y, Mitani N, Yamaji N, Ma JF. HvLsi1 is a silicon influx transporter in barley. *The Plant Journal: For Cell and Molecular Biology*. 2009;57(5):810–818.
31. Mitani N, Chiba Y, Yamaji N, Ma JF. Identification and characterization of maize and barley Lsi2-like silicon efflux transporters reveals a distinct silicon uptake system from that in rice. *The Plant Cell*. 2009;21(7):2133–2142.
32. Montpetit J, Vivancos J, Mitani-Ueno N, Yamaji N, Rémus-Borel W, Belzile F, Feng MR, Bélanger RR. Cloning, functional characterization and heterologous expression of TaLsi1, a wheat silicon transporter gene. *Plant Molecular Biology*. 2012;79(1–2):35–46.
33. Deshmukh RK, Vivancos J, Guérin V, Sonah H, Labbé C, Belzile F, Bélanger RR. Identification and functional characterization of silicon transporters in soybean using comparative genomics of major intrinsic proteins in *Arabidopsis* and rice. *Plant Molecular Biology*. 2013;83(4–5):303–315.
34. Kaur H, Greger M. A review on Si uptake and transport system. *Plants*. 2019;8(4):E81.
35. Ma JF, Yamaji N. A cooperative system of silicon transport in plants. *Trends in Plant Science*. 2015;20(7):435–442.
36. Wang M, Wang R, Mur LAJ, Ruan J, Shen Q, Guo S. Functions of silicon in plant drought stress responses. *Horticulture Research*. 2021;8(1):254.
37. Zhu Y, Gong H. Beneficial effects of silicon on salt and drought tolerance in plants. *Agronomy for Sustainable Development*. 2014;34(2):455–472.
38. Biju S, Fuentes S, Gupta D. Silicon improves seed germination and alleviates drought stress in lentil crops by regulating osmolytes, hydrolytic enzymes and antioxidant defense system. *Plant Physiology and Biochemistry*. 2017;119:250–264.
39. Kim YH, Khan AL, Waqas M, Lee IJ. Silicon regulates antioxidant activities of crop plants under abiotic-induced oxidative stress: A review. *Frontiers in Plant Science*. 2017;8:510.
40. Biju S, Fuentes S, Gupta D. Silicon modulates nitro-oxidative homeostasis along with the antioxidant metabolism to promote drought stress tolerance in lentil plants. *Physiologia Plantarum*. 2021;172(2):1382–1398.
41. Biju S, Fuentes S, Gupta D. Novel insights into the mechanism(s) of silicon-induced drought stress tolerance in lentil plants revealed by RNA sequencing analysis. *BMC Plant Biology*. 2023;23:498.
42. Chen W, Yao X, Cai K, Chen J. Silicon alleviates drought stress of rice plants by improving plant water status, photosynthesis and mineral nutrient absorption. *Biological Trace Element Research*. 2011;142(1):67–76.
43. Zia Z, Bakhat HF, Saqib ZA, Shah GM, Fahad S, Ashraf MR, Hammad HM, Naseem W, Shahid M. Effect of water management and silicon on germination, growth, phosphorus and arsenic uptake in rice. *Ecotoxicology and Environmental Safety*. 2017;144:11–18.

44. Li YR. The protective role of silicon in sugarcane under water stress: Photosynthesis and antioxidant enzymes. *Biomedical Journal of Scientific & Technical Research*. 2019;15(2).
45. Dhiman P, Rajora N, Bhardwaj S, Sudhakaran SS, Kumar A, Raturi G, Chakraborty K, Gupta SS, Devanna BN, Tripathi DK, Deshmukh R. Fascinating role of silicon to combat salinity stress in plants: An updated overview. *Plant Physiology and Biochemistry*. 2021;162:110-123.
46. Liang Y. Effects of silicon on enzyme activity and sodium, potassium and calcium concentration in barley under salt stress. *Plant and Soil*. 1999;209(2):217-224.
47. Liang YC. Effects of Si on leaf ultrastructure, chlorophyll content and photosynthetic activity in barley under salt stress. *Pedosphere*. 1998;8:289-296.
48. Lee SK, Sohn EY, Hamayun M, Yoon JY, Lee IJ. Effect of silicon on growth and salinity stress of soybean plant grown under hydroponic system. *Agroforestry Systems*. 2010;80(3):333-340.
49. Abdelaal KAA, Mazrou YSA, Hafez YM. Silicon foliar application mitigates salt stress in sweet pepper plants by enhancing water status, photosynthesis, antioxidant enzyme activity and fruit yield. *Plants*. 2020;9(6):733.
50. Neumann D, zur Nieden U. Silicon and heavy metal tolerance of higher plants. *Phytochemistry*. 2001;56(7):685-692.
51. Wu JW, Shi Y, Zhu YX, Wang YC, Gong HJ. Mechanisms of enhanced heavy metal tolerance in plants by silicon: A review. *Pedosphere*. 2013;23(6):815-825.
52. Hou L, Ji S, Zhang Y, Wu X, Zhang L, Liu P. The mechanism of silicon on alleviating cadmium toxicity in plants: A review. *Frontiers in Plant Science*. 2023;14:1141138.
53. Liang Y, Sun W, Zhu YG, Christie P. Mechanisms of silicon-mediated alleviation of abiotic stresses in higher plants: A review. *Environmental Pollution*. 2007;147(2):422-428.
54. Nwugo CC, Huerta AJ. Effects of silicon nutrition on cadmium uptake, growth and photosynthesis of rice plants exposed to low-level cadmium. *Plant and Soil*. 2008;311(1-2):73-86.
55. Nwugo CC, Huerta AJ. The effect of silicon on the leaf proteome of rice (*Oryza sativa* L.) plants under cadmium-stress. *Journal of Proteome Research*. 2011;10(2):518-528.
56. Azam SK, Karimi N, Souri Z, Vaculik M. Multiple effects of silicon on alleviation of arsenic and cadmium toxicity in hyperaccumulator *Isatis cappadocica* Desv. *Plant Physiology and Biochemistry*. 2021;168:177-187.
57. Gu HH, Zhan SS, Wang SZ *et al.* Silicon-mediated amelioration of zinc toxicity in rice (*Oryza sativa* L.) seedlings. *Plant Soil*. 2012;350:193-204.
58. Song A, Li P, Li Z, Fan F, Nikolic M, Liang Y. The alleviation of zinc toxicity by silicon is related to zinc transport and antioxidative reactions in rice. *Plant and Soil*. 2011;344(1-2):319-333.
59. Zargar SM, Mahajan R, Bhat JA, Nazir M, Deshmukh R. Role of silicon in plant stress tolerance: opportunities to achieve a sustainable cropping system. *3 Biotech*. 2019;9(3):73.
60. Bakhat HF, Bibi N, Zia Z, Abbas S, Hammad HM, Fahad S, Ashraf MR, Shah GM, Rabbani F, Saeed S. Silicon mitigates biotic stresses in crop plants: A review. *Crop Protection (Guildford, Surrey)*. 2018;104:21-34.
61. Etesami H, Jeong BR. Silicon (Si): Review and future prospects on the action mechanisms in alleviating biotic and abiotic stresses in plants. *Ecotoxicology and Environmental Safety*. 2018;147:881-896.
62. Detmann KC, Araújo WL, Martins SCV, Sanglard LMVP, Reis JV, Detmann E, Rodrigues FA, Nunes-Nesi A, Fernie AR, DaMatta FM. Silicon nutrition increases grain yield, which, in turn, exerts a feed-forward stimulation of photosynthetic rates via enhanced mesophyll conductance and alters primary metabolism in rice. *New Phytologist*. 2012;196(3):752-762.
63. Fauteux F, Rémus-Borel W, Menzies JG, Bélanger RR. Silicon and plant disease resistance against pathogenic fungi. *FEMS Microbiology Letters*. 2005;249(1):1-6.
64. Wang M, Gao L, Dong S, Sun Y, Shen Q, Guo S. Role of silicon on plant-pathogen interactions. *Frontiers in Plant Science*. 2017;8:701.
65. Rodrigues F. Silicon and Plant Diseases (F. A. Rodrigues & L. E. Datnoff, Eds). 2015.
66. Guerriero G, Hausman JF, Legay S. Silicon and the plant extracellular matrix. *Frontiers in Plant Science*. 2016;7:463.
67. Rodrigues FA, Benhamou N, Datnoff LE, Jones JB, Bélanger RR. Ultrastructural and cytochemical aspects of silicon-mediated rice blast resistance. *Phytopathology*. 2003;93(5):535-546.
68. Cai K, Gao D, Luo S, Zeng R, Yang J, Zhu X. Physiological and cytological mechanisms of silicon-induced resistance in rice against blast disease. *Physiologia Plantarum*. 2008;134(2):324-333.
69. Mohammadi M, Kazemi H. Changes in peroxidase and polyphenol oxidase activities in susceptible and resistant wheat heads inoculated with *Fusarium graminearum* and induced resistance. *Plant Science*. 2002;162(4):491-498.
70. Fawe A, Abou-Zaid M, Menzies JG, Bélanger RR. Silicon-mediated accumulation of flavonoid phytoalexins in cucumber. *Phytopathology*. 1998;88(5):396-401.
71. Rodrigues FA, McNally DJ, Datnoff LE, Jones JB, Labbé C, Benhamou N, Menzies JG, Bélanger RR. Silicon enhances the accumulation of diterpenoid phytoalexins in rice: a potential mechanism for blast resistance. *Phytopathology*. 2004;94(2):177-183.
72. Remus-Borel W, Menzies JG, Belanger RR. Silicon induced antifungal compounds in powdery mildew-infected wheat. *Physiological and Molecular Plant Pathology*. 2005;66(3):108-115.
73. Van Bockhaven J, De Vleeschauwer D, Höfte M. Towards establishing broad-spectrum disease resistance in plants: silicon leads the way. *Journal of Experimental Botany*. 2013;64(5):1281-1293.
74. Vivancos J, Labbé C, Menzies JG, Bélanger RR. Silicon-mediated resistance of *Arabidopsis* against powdery mildew involves mechanisms other than the salicylic acid (SA)-dependent defence pathway. *Molecular Plant Pathology*. 2015;16(6):572-582.
75. Abed-Ashtiani F, Kadir JB, Selamat AB, Hanif AHM, Nasehi A. Effect of foliar and root application of silicon against rice blast fungus in MR219 rice variety. *Plant Pathology Journal*. 2012;28(2):164-171.
76. Cacique IS, Domiciano GP, Moreira WR, Rodrigues FA, Cruz MFA, Serra NS, Català AB. Effect of root and leaf applications of soluble silicon on blast development in rice. *Bragantia: Boletim Técnico Do Instituto Agronômico Do Estado de São Paulo*. 2013;72(3):304-309.
77. Bélanger RR, Benhamou N, Menzies JG. Cytological Evidence of an Active Role of Silicon in Wheat Resistance to Powdery Mildew (*Blumeria graminis* f. sp. tritici). *Phytopathology*. 2003;93(4):402-412.
78. Carver TLW, Zeyen RJ, Ahlstrand GG. The relationship between insoluble silicon and success or failure of attempted primary penetration by powdery mildew (*Erysiphe graminis*) germlings on barley. *Physiological and Molecular Plant Pathology*. 1987;31(1):133-148.
79. Perez CEA, Rodrigues FA, Moreira WR, DaMatta FM. Leaf gas exchange and chlorophyll a fluorescence in wheat plants supplied with silicon and infected with *Piricularia oryzae*. *Phytopathology*. 2014;104(2):143-149.
80. Carré-Missio V, Rodrigues FA, Schurt DA, Pereira SC, Oliveira MGA, Zambolim L. Ineficiência do silício no controle da ferrugem do caféiro em solução nutritiva. *Trabalhos Em Lingüística Aplicada*. 2009;34(6).

81. Bowen P, Menzies J, Ehret D, Samuels L, Glass ADM. Soluble silicon sprays inhibit powdery mildew development on grape leaves. *Journal of the American Society for Horticultural Science*. 1992;117(6):906–912.
82. Andrade CCL, Resende RS, Rodrigues FA, Pereira RB, Oliveira JR, Mariano RLR. Silicon reduces bacterial speck development on tomato leaves. *Tropical Plant Pathology*. 2013;38:436–442.
83. Alhousari F, Greger M. Silicon and mechanisms of plant resistance to insect pests. *Plants*. 2018;7(2):33.
84. Reynolds OL, Padula MP, Zeng R, Gurr GM. Silicon: Potential to promote direct and indirect effects on plant defense against arthropod pests in agriculture. *Frontiers in Plant Science*. 2016;7:744.
85. Keeping MG, Kvedaras OL. Silicon as a plant defence against insect herbivory: response to Massey, Ennos and Hartley. *The Journal of Animal Ecology*. 2008;77(3):631–633.
86. Massey FP, Hartley SE. Physical defences wear you down: progressive and irreversible impacts of silica on insect herbivores. *The Journal of Animal Ecology*. 2009;78(1):281–291.
87. Massey FP, Ennos AR, Hartley SE. Silica in grasses as a defence against insect herbivores: contrasting effects on folivores and a phloem feeder. *The Journal of Animal Ecology*. 2006;75(2):595–603.
88. Ye M, Song Y, Long J, Wang R, Baerson SR, Pan Z, Zhu-Salzman K, Xie J, Cai K, Luo S, Zeng R. Priming of jasmonate-mediated antiherbivore defense responses in rice by silicon. *Proceedings of the National Academy of Sciences of the United States of America*. 2013;110(38):E3631–9.
89. Golubkina N, Zayachkovsky V, Sheshnitsan S, Skrypnik L, Antoshkina M, Smirnova A, Fedotov M, Caruso G. Prospects of the application of garlic extracts and selenium and silicon compounds for plant protection against herbivorous pests: A review. *Agriculture*. 2022;12(1):64.
90. Artyszak A. Effect of silicon fertilization on crop yield quantity and quality-A literature review in Europe. *Plants*. 2018;7(3):E54.
91. Sarma HH, Borah SK, Dutta N, Kashyap R, Chintey R. Impact of silicon fertilization in crop production: Enhancing yield, stress and disease resistance in agriculture. *Journal of Advances in Biology & Biotechnology*. 2024;27(9):645–658.
92. Munir FDA, Sulaiman Z, Ahmad K, Abd Samad MY, Ariffin MR, Salisu MA. A comprehensive review on the potential effect of silicon fertilizer and its significance for agriculture. *ICRRD Journal*. 2023;4(2):149–178.
93. Artyszak A, Gozdowski D, Litwińczuk-Bis M. Do forms of silicon other than orthosilicic acid, application date and dose have a beneficial effect on sugar beet yield? *Plants*. 2026;15(10):1449.
94. Viciado DO, de Mello Prado R, Lizcano Toledo R, dos Santos LCN, Calero Hurtado A, Nedd LLT, Castellanos Gonzalez L. Silicon supplementation alleviates ammonium toxicity in sugar beet (*beta vulgaris* L.). *Journal of Soil Science and Plant Nutrition*. 2019;19(2):413–419.
95. Trawczyński C. The effect of foliar preparation with silicon on the yield and quality of potato tubers in comparison to selected biostimulators. *Ziemniak Polski*. 2018;2:29–33.
96. Peris-Felipo FJ, Benavent-Gil Y, Hernández-Apaolaza L. Silicon beneficial effects on yield, fruit quality and shelf-life of strawberries grown in different culture substrates under different iron status. *Plant Physiology and Biochemistry*. 2020;152:23–31.
97. Hajiboland R, Moradtalab N, Eshaghi Z, Feizi J. Effect of silicon supplementation on growth and metabolism of strawberry plants at three developmental stages. *New Zealand Journal of Crop and Horticultural Science*. 2018;46(2):144–161.
98. Pereira HS, Korndörfer GH, Vidal AA, Camargo MS. Silicon sources for rice crop. *Scientia Agricola*. 2004;61(5):522–528.
99. Heckman J. Silicon: A beneficial substance. *Better Crops*. 2013;97(4):14–16.
100. Rajput VD, Minkina T, Feizi M, Kumari A, Khan M, Mandzhieva S, Sushkova S, El-Ramady H, Verma KK, Singh A, van Hullebusch ED, Singh RK, Jatav HS, Choudhary R. Effects of silicon and silicon-based nanoparticles on rhizosphere microbiome, plant stress and growth. *Biology*. 2021;10(8):791.
101. Sharf-Eldin AA, Alwutayd KM, El-Yazied AA, El-Beltagi HS, Alharbi BM, Eisa MAM, Alqurashi M, Sharaf M, Al-Harbi NA, Al-Qahtani SM, Ibrahim MFM. Response of maize seedlings to silicon dioxide nanoparticles (SiO₂NPs) under drought stress. *Plants*. 2023;12(14):2592.
102. Artyszak A, Gozdowski D, Siuda A. Effect of the application date of fertilizer containing silicon and potassium on the yield and technological quality of sugar beet roots. *Plants*. 2021;10(2):370.
103. Artyszak A, Kondracka M, Gozdowski D, Siuda A, Litwińczuk-Bis M. Impact of foliar application of various forms of silicon on the chemical composition of sugar beet plants. *Sugar Tech: An International Journal of Sugar Crops & Related Industries*. 2021;23(3):546–559.

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