www.ThePharmaJournal.com
The Pharma Innovation

ISSN (E): 2277-7695
ISSN (P): 2349-8242
NAAS Rating: 5.23
TPI 2023; SP-12(10): 652-656

www.thepharmajournal.com
Received: 19-07-2023
Accepted: 26-08-2023

Role of silicon in increasing crop production: A review

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Abstract

Silicon is the second most prevalent element in the universe and the second most prevalent element on Earth after oxygen. Silicon makes up around 25% of the Earth's crust. Since it is found in the crust of the Earth, many plants can acquire it in large quantities comparable to macronutrients. Despite its many advantages in agriculture, silicon is not typically regarded as a crucial component of plants. In nature, silicon is found as silicates and as the oxide (silica), both of which are utilized to make fertilizers. Through its roots, a plant assimilates silicon as silicic acid. It moves to the active growth regions of the plant, where it combines with an organic component to fortify the cell walls. Several studies conducted on hydroponics, pot, and field experiments shows that silicon has positive benefits on plants. In addition to promoting upright growth (stronger, thicker stems, shorter internodes), preventing lodging, promoting favourable leaf exposure to light, providing resistance to bacterial and fungal diseases, and reducing some abiotic stress like temperatures, salinity, heavy metal and aluminium toxicity, silicon increases the growth and yield of all annual and vegetable crops. According to the studies, silicon makes plants more resistant to a variety of plant diseases, including powdery mildew, as well as a variety of insect pests. Under deficit irrigation condition, silicon increases biomass yield. Plants exposed to drought performs well on application of silicon and maintained increased water potential, relative water content, and stomatal conductivity. It encourages the growth of larger, thicker leaves, which limits water loss through transpiration and lowers water use. The development of plant roots is greatly influenced by silicon, which allows for faster root growth and improved root resistance in dry soils.

Keywords: Silicon, crop production, toxicity

Introduction

Silicon typically ranges from 5 to 40% in soils. Usually, soil silicates take the form of different aluminosilicates and silicon dioxide. In the soil, Si is typically present in large amounts and in a variety of forms, particularly quartz, silicates, biogenic SiO$_2$ (found in organisms like diatoms and phytoliths), and silica gel (Liang *et al*., 2007; Sommer *et al*., 2006) [26, 41]. The extractable forms of Si in the soil consists of amorphous, active, and water soluble forms of silicon. Plants can readily access the water soluble forms of silicon while the rest of the silicon must first be transformed to a water soluble form under favorable conditions before being used by plants. Minerals have an impact on a wide variety of physical-chemical soil parameters. Soil fertility is the result of both inorganic and organic soil components. Silicon plays a crucial role in higher plants as their inorganic constituent and various evidences shown that silicon improves crop productivity very well. (Keeping *et al*., 2009; Meyer and Keeping, 2005; Snyder *et al*., 2007) [23, 32, 30]. Silicon exhibits broad spectrum functioning in plant metabolism, particularly in graminaceous and cyperaceous species, and plays a significant role in growth and developmental processes (Epstein, 1999) [13]. Si can change the characteristics of the soil by enhancing its nutrient (nitrogen, phosphorus, and potassium) contents, raising the pH of the soil, reducing the toxicity of heavy metals by enhancing the physical and chemical properties of the soil, and forming new silicate complexes (Adrees *et al*., 2015) [1].

Silicon affects the binding properties of other elements hence making them more or less available for uptake. It is well known that silicon improves the amount of phosphorus (P) that is available to plants in the soil by reducing soil sorption of P, particularly at low pH levels. Because of monomeric or monosilicic (H$_4$SiO$_4$) character of silicon, it is readily absorbed by roots and accumulates to areal parts of the plants. (Hodson *et al*., 2005) [20]. High rainfall, which causes Si to leach from the soil and low pH levels, have a detrimental impact on the biological Si pools in the soil and reduce the amount of Si that is accessible to plants. This reduces the amount of Si that is available to the plants. Si is the only known element that, when accumulated in excess, does not harm plants.

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It has been shown that a high Si content in rice is essential for healthy growth and high, stable production. For this reason, silicate fertilizers have been used to paddy soils and Si has been designated in Japan as an "Agronomically Essential Element" (Ma *et al*., 2001) [27]. Si has gained recognition as a nearly essential element in recent years (Epstein, 1999) [13].

Silicon in soil

The silicon content of the crust of the earth is roughly 28.8%. The total silicon concentration of soil typically ranges from 25 to 35 percent, with an average of 30 percent, depending considerably on the types of soil and weathering. According to Sommer *et al*. (2006) [41], soil types and the amount of silicon (Si) they contain are highly influenced by the processes that create the soil. Primary minerals, secondary minerals produced from primary minerals, and secondary microcrystalline as soil strata are some of the processes that lead to the creation of Si pools in soils. A significant silicon source that results from the weathering of volcanic rocks is cristobalite. Secondary Si-mineral production is influenced by a variety of environmental conditions, including temperature, pH, acidity, and organic anions and cations. Water primarily mediates Si fluxes in terrestrial areas and soil ecosystems. The main ingredient in soil solution is silicic acid, which is present as monomeric silicic acid. Under certain circumstances, this monomeric form of silicic acid transforms into a polymeric form. This polymeric form has two or more Si atoms placed inside the designed structure in various arrangements. Si pools can be found in soil in solid, liquid, and adsorbed phases. According to Knight and Kinrade (2001) [24], monomeric silicic acid (H_4SiO_4) separates into $H^{+}\ ^{+}\ H_3SiO_4$ and $2H^{+\ +}\ H_2SiO_4^{2}$ above pH 9. Only at high concentrations of silicic acid and pH values more than 9 is polymeric silicic acid stable. According to Daniela *et al*. (2006) [9], the silicate compounds in soils can be broken down into amorphous (phytoliths and silica nodules), poorly crystalline and microcrystalline (allophane, immogolite, and secondary quartz), and crystalline forms (primary silicates: quartz, feldspars, and secondary silicates: clay minerals).

Silicon in Plants

In general, silicon is not regarded as a necessary nutrient. In nature, silicon is found as silica oxide and silicates, both of which are employed as fertilizers. Epstein and Bloom (2003) [14]. Through its roots, a plant assimilates silicon as silicic acid. In nature, silicon is found as silica oxide and silicates, both of which are employed as fertilizers Epstein and Bloom (2003) [14]. Through its roots, a plant assimilates silicon as silicic acid. In the soil solution, the concentration of H_4SiO_4 varies from 0.1 to 0.6 mM, which is absorb by the plants (Knight and Kinrade, 2001) [24]. It moves to the active growth regions of the plant, where it combines with an organic component to fortify the cell walls. According to Cornelis *et al*. (2011) [8], three main mechanisms-active, passive, and rejective-are involved in the uptake of silicon by plants. According to Ma *et al*. (2001) [27], the passive mechanism and transpiration bypass flow are how most dicot plants absorb Si. Many plants, including rice, wheat, maize, and sugarcane, absorb Si by an active mechanism (Casey *et al*., 2004; Rains *et al*., 2006) [7, 35]. Plants with Si concentrations above 1% are known as accumulators, while those with concentrations below 0.5% are known as excluders. Plants with concentrations in the middle are known as intermediates. Seven important crops are categorized as accumulators: maize, wheat, sugarcane, rice, soybean, barley, and sugar beet. Due to the Si accumulation in their leaves, which ranges from 1 to 5%, a number of forage grasses are also known as accumulators. One of the instructive elements, silicon, does not have a negative effect on plants when it is present in excess. In a natural ecosystem, Si was recycled into the soil by the breakdown of plant litter into biogenic Si pools, where it once more became a component of the soil's Si cycle. By reducing plant transpiration and boosting a plant's ability to withstand drought, silicon plays a significant part in reducing the impact that drought has on many crops.

Silica Solubilizing Bacteria

Silica is solubilized and made available to plants by silica-solubilizing bacteria (SSB), which are found in soil and the rhizosphere. *Bacillus sp., Rhizobia sp., Pseudomonas sp., Burkholderia sp., Proteus sp., and Enterobacter sp.* are examples of bacteria that have been identified as very effective for silicon solubilization. These bacteria breakdown silicates, particularly primary and secondary silicates like calcium silicate and aluminum silicate, and convert it into available silicon. The effectiveness and activity of silicon mobilizing and other helpful rhizobacteria improved when these bacteria solubilized the silicon. These rhizo-bacteria begin to recycle the various chemicals generated during these weathering and solubilization processes. The fact that silica-solubilizing bacteria are found in the rhizosphere makes them commonly used in agriculture. These bacteria have a close, potentially symbiotic association with the crop that helps to promote fruit development and yield. This balance creates a strong relationship that helps plants thrive and resist pests. As a result, bacteria that solubilize silica are classified as Yield Increasing Bacteria (YIB). There is evidence that several Pseudomonas and Bacillus species promote maize fruit development, canola oil content, wheat pest resistance, pulse drought resilience, and insect resistance in various legumes. The growth, chlorophyll content, thousand grain weight, matured grains, biomass, and yield of rice were found to be improved by inoculating SSB with organosiliceous rice straw, husk, and husk ash (black char/ash). Silica-solubilizing bacteria, according to Avakyan *et al*. (1986) [48], boost rice plant growth, chlorophyll content, grain weight, full grains, biomass, and yield.

Role of silicon in alleviating abiotic stress

The growth and production of crop plants are negatively impacted by abiotic factors such as drought, salinity, cold, heat, and UV-B radiation (Pareek *et al*., 2010) [34]. From the earliest stages of seed germination to flowering, abiotic stressors have the capacity to affect nearly all of a plant's physiological, biochemical, and molecular processes and ultimately result in significant losses to crop output (Pareek *et al*., 2010) [34]. Drought, salt, heat, cold, metals, and mechanical stress are just a few of the harmful abiotic stresses that silicon, a beneficial macronutrient, has been proven to lessen. It is the only known element that can increase resistance to a variety of stresses. The addition of silicon has aided in overcoming the negative impacts of abiotic stresses and enhanced plants ability to adapt to challenging conditions. Several studies (Tuna *et al*., 2008) [43] found that Si has the ability to decrease the salt ions uptake and their transport in plant parts under salinity in diverse plant species such soybean, wheat, rice, and barley. Due to its negative effects on crop growth, drought stress is a growing source of concern.

It happens for a variety of reasons, including less rainfall, salt stress, scarcity of water, extreme fluctuations in temperature, etc. Increases in water uptake and transport, accumulation of compatible solutes, an increase in osmoprotectants, an improvement in stomatal conductance, and the activation of defensive genes involved in stress mitigants are the main mechanisms underlying the processes, all of which are fueled by the addition of Si to plants under water-deficit conditions.

The release of toxic pollutants into the atmosphere, particularly in agricultural soils, has been caused by the modern era's population explosion, which also leads to mining, smelting, plastic manufacturing, e-waste processing, excessive fertilizer and pesticide use, and waste water irrigation (Bi *et al*., 2018; Ma *et al*., 2019) [6, 28]. Heavy metals and metalloids, such as arsenic (As), lead (Pb), cadmium (Cd), chromium (Cr), mercury (Hg), copper (Cu), and antimony (Sb), make up the majority of these harmful contaminants (Feng *et al*., 2021) [15]. The substantial risks to the health of people living in contaminated areas are caused by the uptake of these toxins by plants, especially through the food chain (Feng *et al*., 2021) [15]. The oxidation states of metals affect their toxicity and reactivity. The effects of heavy metal toxicity in plants can be seen at the morpho-anatomical, physiological, biochemical, and even genetic levels. Because silicon improved the metal binding ability to the cell walls, which restricts the concentration of the heavy metals in the cytoplasm, the toxicity of heavy metals like cadmium, copper, zinc, and manganese was reduced in plants fertilized with silicon (Liang *et al*. 2007) [26]. The idea that Si can reduce the harmful effects of heavy metals in higher plants is generally acknowledged. For example, *Hordeum vulgare, Oryza sativa, Cucurbita pepo, Vicia feba, Vigna unguiculata, and Cucumis sativus* can all reduce the toxicity of Mn by containing very small amounts of Si (Liang *et al*., 2007) [26]. Horst *et al.* (1999) [21] also discovered that Si might change the binding capacity to cell wall by reducing the apoplastic mobility of Mn. Hodge (2004) [19] discovered that silicon can alter root flexibility, increasing the capacity of the plants to withstand stress.

Role of silicon in alleviating biotic stress

Throughout their life cycle, plants are also subjected to a variety of biotic stress factors such fungi, bacteria, viruses, and herbivores. Several factors, including the causal organism, ambient and soil conditions, plant genotype, and crop development stage, influence the degree of biotic stress and the ensuing damage or loss of plant yield. Increase in the number of low molecular weight metabolites and modification of epidermal layer of leaves and fruits silicon gets diffused by transpiration flow and checks the dissemination of disease (Gillman *et al*. 2003) [17]. There are two primary pathways for Si-mediated defense against biotic stress in plants: mechanical and biochemical or molecular. The physical defense provided by Si deposition in plant tissues in the form of phytoliths (SiO_2) is the mechanical barrier mechanism linked to plant resistance to pathogens. According to Alhousari and Greger (2018) [3], Si deposition in the form of phytoliths increases plant cell wall rigidity and tissue hardness and serves as a physical barrier to pathogen penetration, chewing, and digestion. For a very long time, it was believed that Si-derived resistance to diseases and insects resulted from a mechanical barrier that Si deposition along the cell wall created that prevented their growth.

Role of Silicon in the Uptake of Nutrients

By enhancing the physiochemical features of the soil with regard to soil nutrients and minerals, silicon effectively boosts the growth characteristics and biomass of plants. Silicon increases the biomass yield and growth attributes of crops by increasing soil nutrients and mineral composition as a result of improved physio-chemical properties. When silicon is applied, the amount of N and P that is readily available in the soil is significantly reduced, directly causing plants to absorb more N and P. Furthermore, due to the enormous surface area of crystalline silicon, P competes with Si for an adsorption site on clay particles, leading to the release of P that can be readily supplied to plants and absorbed through physio-chemical pathways. According to reports, applying Si improves the root system's ability to absorb nitrogen, hence reducing nitrogen deficiencies in various crops. Application of silicic acid has boosted plant N uptake and accumulation in rice, maize, cowpea, rapeseed, and wheat under N availability constraints. According to experimental results, applying Si to the soil and to plants leaves reduced the need for mineral nitrogen fertilizers in a number of crops. The key determinants of P availability are biogeochemical processes and mineral compositions of the soil. Reduced P accumulation caused by phosphorus and silica deficit results in slower plant development and physiology. The addition of Si solution can boost P accumulation, which lowers electrolyte leakage brought on by stress, and increase the chlorophyll index of the leaves of the sorghum plant. Potassium (K) is a critical nutrient for plants and is also crucial for the health of the soil because it makes up a significant portion of essential soil minerals. Although crops have a high requirement for K, K uses in Indian agriculture have lagged behind those for nitrogen (N) and phosphorus (P). Numerous studies have shown that silicon (Si) eliminates K deficiency symptoms in many crops when salt stress occurs. Silicon did not entirely manage the damage induced by nitrogen deficiency in plants, but it did mitigate K and S deficiency stress. The soil quality and plant growth were also improved in the same context by the modest amounts of other elements, such as Ca, Fe, Mg, and Mn, etc. with Si as Mineral-Si (Ning *et al*., 2014) [33]. Furthermore, because different plant species have different capacity for accumulating Si and other minerals that aggregate with Si, the impact of Si on soil mineral nutrients is uncommon. Because so much study has focused on Si-accumulating plants rather than other plant species, it is still challenging to understand the integrated role of Si in all plant species.

Methods of application of silicon

Silicate mineral fertilization of crops began in Japan in the early 1950s and is now widely practiced in several nations, including the USA, Korea, Taiwan, Thailand, and Ceylon. For plants, silicon has been obtained from a wide range of sources. Crop leftovers, particularly those from plants that accumulate silicon, can be utilized as a source of silicon. However, due to silicon's limited solubility, inorganic minerals including quartz, clay, mica, and feldspars perform poorly as silicon fertilizers. One of the most popular silicon fertilizers is calcium silicate, which is produced as a by-product of the production of steel and phosphorus.

Silicon Fertilization

The majority of fertilizers made of silicon are by-products from various industrial processes. From the steel sector, important materials include steel slag, blast furnace slag, silica fumes, ferromanganous slag, and converter slag. The only pure silicon fertilizers that are employed as efficient fertilizers are calcium silicate slag and magnesium slag. The application of slags and wollastonite significantly raised the pH and soluble Si contents of the soil. According to research, soil applications of silicon are thought to be a better option for boosting plants resistance against biotic and abiotic stresses and increasing agricultural yields.

Foliar application of silicon

Silicon applied topically to many plant species, including grapes, muskmelon, cucumber, soybeans, and coriander, has been shown to promote crop development and protect against biotic stress.

Smart fertilizer

The three types of smart fertilizers are nano fertilizers, composite fertilizers, and bio-formulations. As their name implies, nano fertilizers are based on nanoparticles and come in powder or liquid forms, including manufacture, design, and application. These fertilizers can assist increase the efficiency of plant absorption and nutrient release kinetics. Bio-formulations are fertilizers containing microorganisms in active or dormant condition. Several bacteria and fungi are capable of influencing physiological growth, crop nutrition, and plant protection.

Conclusion and Future prospective

Silicon helps plants grow and develop as well as protect them from a variety of biotic and abiotic challenges. Heavy metals are taken up and accumulated less by plants due to the presence of Si, resulting in the creation of food that is safe for humans and contains little to no heavy metals. Application of inexpensive industrial waste products as a source of silicon and silicon mobilizer/solubilizer bacteria may become useful agronomic techniques for a variety of crops, particularly under biotic and abiotic challenges that may lower crop production. Recent studies in the area of nanotechnology have resulted in the production of granulated and liquid silicon fertilizer with high bio-availability. This type of silicon fertilizer can easily penetrate the leaves and can form a thick silicate layer on the leaf surface. Hence, there is a need of applied research to determine whether this method is more sustainable than conventional fertilization practices.

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