Ecofarming (e-Magazine)
Agriculture

Ecofarming
e-Magazine for Agriculture and Allied Sciences
http://www.ecofarming.rdagriculture.in
e-ISSN: 2583-0791

Silicon: The Hidden Ally in Our Soils

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Received: December, 2025; Accepted: December, 2025; Published: January, 2026

Introduction

Silicon (Si) is one of the most widespread elements in nature, ranking second only to oxygen in abundance, and makes up nearly 28% of the Earth's crust. In soils, however, most of the silicon is present in solid forms, either bound within primary silicate minerals, secondary clay minerals, or as adsorbed complexes that plants can not directly use. The only form that plants can absorb is monosilicic acid (H_4SiO_4), which occurs in soil solution at very low concentrations, ranging from 0.09 to 23.4 mg L^{-1}. This small yet crucial pool of dissolved silicon plays an important role in plant nutrition and resilience. Silicon fertilization has been shown to increase yield in a wide array of crops, including rice, sugarcane, wheat, barley, maize, sorghum, and rye. Besides boosting productivity, it enhances plant tolerance to both biotic (such as pathogens and insect pests) and abiotic (such as drought, salinity, alkalinity, freezing, and heavy metal toxicity) stresses.

Although silicon is not classified as an essential element, it is recognized as a beneficial element, particularly for certain crops. Plants may not show obvious visible symptoms of either deficiency or toxicity, and excess Si accumulation is not generally harmful. Based on the ability to absorb and accumulate Si, plants can broadly be categorized into three groups (Liang et al. 2007). *Silicon accumulators*, e.g., rice, barley, sugarcane, which can accumulate 1.0-10% Si in their dry matter. Uptake of nitrogen (N) is generally the largest among the essential elements, but uptake of Si may be twice the amount of N in rice. *Intermediate accumulators*, e.g., cucumber, sunflower, tomato, which accumulate 0.5-1.0% Si in their dry matter. *Silica rejecters*, most of the dicotyledons absorbs less than 0.5% Si in their dry matter.

Silicon sources, dynamics, and bioavailability

Silicon used in agriculture comes from many sources: naturally occurring minerals, by-products of the steel and iron industry, crop residues, etc. Manures and composts also add Si to soils, while the breakdown of Si-rich organic inputs gradually increases the amount of plant-available Si. Silicon exists in different forms in soil (Fig. 1). The only form that plants and soil microbes can absorb is monosilicic acid (H_4SiO_4). Once taken up, it moves to the shoots and is deposited in the leaf epidermis as tiny amorphous silica bodies called phytoliths ($SiO_2 \cdot nH_2O$). When plant residues return to the soil, these phytoliths contribute to the biogenic

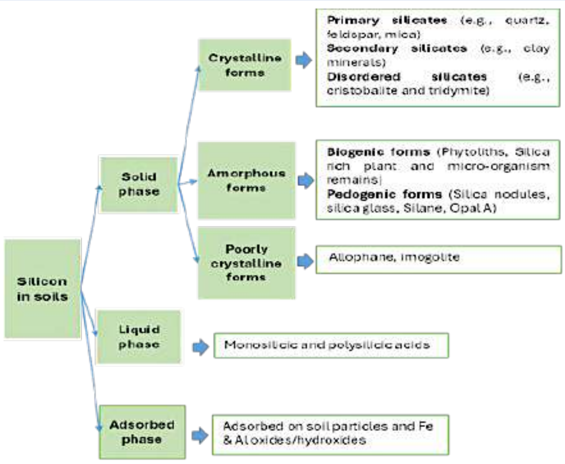

Fig. 1. Forms of silicon in soil (Modified from Matichenkov and Bocharnikova, 2001)

silica pool, which is far more soluble than most mineral silicates. In fact, biogenic silica is 100 to 10,000 times more soluble than mineral silicates, making it a critical source of soluble Si in soils.

At the same time, Si in soils is constantly moving through different processes. It can adsorb onto Fe/Al oxides, hydroxides, and clay minerals; dissolve into solution; precipitate as amorphous silica; or leach out of the soil profile. These transformations regulate the balance between soluble, adsorbed, and solid-phase Si. Typically, the concentration of Si in soil solution ranges from 0.01 to 1.99 mM. When added Si raises this concentration above about 2 mM, silicic acid slowly polymerizes into polysilicic acid, which is less mobile, not bioavailable, and may eventually settle as amorphous silica. Conversely, when the level of soluble Si drops, amorphous silica dissolves back into solution until a new equilibrium is reached.

Determination of Si in soil

Estimating Si in soil is essential to know different forms of Si available in soil and, more importantly, to know the plant available form of Si. The molybdenum blue colorimetry is commonly used to quantify Si concentration in the extracts. Si concentration can also be measured by using inductively coupled plasma-optical emission spectrometry (ICP-OES). To quantify differences in Si fraction available in the soil, different extractants are used. For achieving sustainable soil and crop management accurate assessment of Si availability is required, which can be effectively evaluated through a combination of soil testing and plant tissue analysis.

Silicon sources for agriculture

Silicon used as a fertilizer in agriculture comes from a variety of sources. Slag-based fertilizers, such as calcium silicate derived from industrial slags, are widely applied. Fused magnesium phosphate, which contains phosphorus, magnesium, calcium, and about 16–20% soluble SiO_2, also serves as a significant source**.** Soluble silicate fertilizers (sodium silicate and potassium silicate) provide readily available forms of Si. In addition**,** Si-containing minerals such as wollastonite and olivine are utilized after being finely pulverized to improve their solubility. Recently, Si-rich agri-wastes, e.g., rice straw, sugarcane leaf, rice husk ash, sugarcane bagasse ash, corn cob ash, etc. have been evaluated by researchers for their potential to supply Si in order to increase phosphate mobilization in soil.

Effect of physicochemical properties on Si in soil *pH*

In soil solution, silicic acid (H_4SiO_4) dissociation increases with pH with a pKa_1 of 9.8. Adsorption of silicic acid generally increases between pH 7 and 10, but decreases again beyond pH 10.

Soil texture: Clay-rich soils exhibit a large capacity to adsorb Si due to their higher surface area and the presence of Fe/Al oxides and hydroxides. However, this strong adsorption limits the availability of soluble silicic acid in the soil solution.

Interaction between Si and P

In recent years, the interaction between Si and P in soil has emerged as a major focus of research. When soluble P fertilizers are applied, they often become fixed in the soil, forming insoluble complexes with Fe^{3+}, Al^{3+}, or Ca^{2+} under acidic and alkaline conditions, respectively. This fixation limits P availability to plants. Silicon, in the form of monosilicic or polysilicic acid, can compete with phosphate ions for adsorption sites in the soil, influencing nutrient availability. Phosphate tends to adsorb more strongly under acidic conditions, while Si shows maximum adsorption in alkaline soils, especially around pH 9.2. Due to this, the antagonistic interaction between Si and P is most significant in alkaline conditions and minimal in acidic environments (Sarkar 2024). Both silicate and phosphate are generally more available in neutral pH conditions, where plants can efficiently absorb them. Notably, Si remains available to plants even in slightly acidic soils.

In India and abroad, several studies have explored how this interaction can be harnessed to enhance P availability in soils. Application of Si through rice straw, sugarcane bagasse ash, or other Si-sources have been shown to improve soil P availability (Alam et al. 2022; Ghosh et al. 2023; 2024). Large-scale research in Brazil indicates that Si application can boost sugarcane yields under stress conditions (Korndorfer et al. 2004). The combined application of Si-rich agricultural wastes and phosphate-solubilizing bacteria (PSB) has been shown to enhance soil P solubilization and microbial activity without adverse effects (Alam et al. 2022). Si-rich crop residues can improve both Si and P availability in soils, allowing up to a 25–50% reduction in fertilizer P use while maintaining wheat yield (Ghosh et al. 2024). Their use also offers an eco-friendly alternative to residue burning, thereby contributing to reduced air pollution.

Importance of Si in plant growth

Alleviation of abiotic stress

Silicon plays a vital role in enhancing plant tolerance to a wide range of abiotic stresses, including salinity, drought, flooding, freezing, high temperature, and metal toxicity. Its protective functions operate through both structural and physiological mechanisms.

Lodging resistance and UV protection

Silicon strengthens plants by depositing SiO_2 in cell walls, which enhances structural rigidity and reduces lodging. The silica layer in the leaf epidermis also shields against harmful UV radiation.

Salinity stress

Under saline conditions, Si lowers the accumulation of excess salts in plant tissues. It forms a physical barrier in roots, helping to restrict excess ion uptake and improve overall plant water status.

Water relations and photosynthesis

Silicon supports better drought tolerance by influencing water relations and photosynthetic efficiency. It contributes to stomatal regulation and photochemical processes, thereby maintaining higher photosynthesis under stress.

Mitigation of heavy metal toxicity

Silicon reduces heavy metal toxicity through multiple mechanisms, including regulation of metal transporter genes, chelation and compartmentation of toxic ions, co-precipitation of metals, and structural modifications that limit damage.

Carbon sequestration and organic carbon stability

Silicon contributes to long-term carbon storage through phytolith-occluded carbon. Additionally, silica stabilizes organic carbon in soils by protecting it from microbial decomposition. Enhanced plant biomass under Si application further promotes carbon sequestration.

Role of Si in biotic stress alleviation

Silicon application has proven effective in enhancing plant defence against a range of biotic stresses, particularly diseases and insect pests. Its role is both structural and biochemical, offering a sustainable alternative to heavy reliance on chemical control measures.

Disease resistance

Silicon fertilization is increasingly recognized as an eco-friendly strategy for disease management in crops. By being deposited in cell walls, Si strengthens physical barriers and activates plant defence responses. This dual action reduces the incidence and severity of fungal and bacterial diseases. When integrated with pest and disease management practices, Si application lowers the need for fungicides and promotes more sustainable farming systems.

Pest resistance

Plants with higher Si accumulation display improved resistance to insect herbivores. Silicon deposition forms abrasive barriers that hinder insect feeding, while also inducing the production of defensive compounds such as lignin, phenolics, and phytoalexins. These biochemical responses not only reduce pest feeding and growth but also enhance overall plant resilience. As a result, Si supplementation helps limit crop damage and decreases dependence on chemical pesticides.

Epilogue

Many major crops are known to accumulate Si, and the application of Si fertilizers provides multiple agronomic benefits. These include improved soil structure, enhanced nutrient and water use efficiency, and increased resistance to both biotic and abiotic stresses. Silicon strengthens a plant's mechanical defence by promoting phytolith formation, which enhances structural rigidity and acts as a barrier against pathogens. It also reduces reliance on pesticides and herbicides, while improving P availability by competing with phosphate for soil binding sites. Despite these proven advantages, Si fertilizers are not yet widely adopted in mainstream agriculture. Their importance is especially significant in Si-accumulating crops such as rice, sugarcane, and wheat. Farmers are particularly encouraged to recycle plant residues into the soil. As these residues decompose, they steadily release Si into the soil. This gradual release ensures a continuous supply of bioavailable Si, boosting crop vigour, stress tolerance, and yield. Ultimately, integrating organic sources of Si into farming practices offers a natural and environmentally friendly pathway to enrich soil health and enhance crop productivity.

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