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Revolutionizing Agriculture: Nano Fertilizers for Sustainable Crop Improvement

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Abstract

The abundant metalloid element silicon (Si) is present in the crust of the Earth and is important for improving many aspects of plant characteristics. The potential of silicon in agriculture is examined in this article with particular attention to how it affects crop improvement, stress management, and plant growth. Under certain pH circumstances, plant roots absorb orthosilicic acid, the form of silicon that is accessible to plants in soil. The benefits of Si application, including improved vegetative growth, development, and resistance to biotic and abiotic stress, have been demonstrated by numerous studies. Additionally, silica plays a role in decreased transpiration, enhanced photosynthesis, and UV-B radiation protection. Agricultural crops encounter a multitude of difficulties, such as pathogens, pests, drought, flooding, salinity, and metal toxicity, which are frequently intensified by inadequate silicon availability in soils. To remedy this deficiency, si fertilizers are used, which improves plant function. It is further important to fertilize with Si because certain crops actively accumulate Si in their tissues. Applications of Si take into account the fertility of the soil, the amount of moisture present, and the uptake of nutrients, resulting in enhanced growth, productivity, and resilience to stress. Si increases stem strength, stress tolerance, and lodging resistance, for instance, in rice. Moreover, silica boosts water use efficiency in drought-stricken maize and modifies proline levels in upland rice in response to water restrictions. Eventually, Si-based compounds have a great deal of promise to improve crop yield and solve the problems facing contemporary agriculture. The numerous advantages of applying Si in supporting resilient and sustainable agriculture are highlighted in this review.

Keywords: *Silicon Agriculture, Nanotechnology Innovation, Sustainable Crop Enhancement, Eco-Friendly Fertilizers, Food Security Solution*

1. Introduction

Once oxygen is found in the earth's crust, silicon (Si) is the most frequently occurring metalloid element [1]. The form of silicon that is available to plants and found in small amounts in the soil is called orthosilicic acid. Its concentration ranges from 0.1 to 0.6 nM and is absorbed by plant roots at pH values below < 9. Research has demonstrated that Si application has numerous positive effects on various plant attributes, such as vegetative growth, development, production, and reduction of biotic and abiotic stress [3,4,5,6]. The effects of Si application on a number of plant species have been demonstrated for several decades. Increased photosynthetic rate, decreased transpiration rate, and resistance to UV-B radiation are some additional Si-driven advantages [7].

Insect pest damage, drought, flooding, salinity, metal toxicity, and other biotic and abiotic stressors are just a few of the issues that destroy plants. Most agricultural soils lack sufficient silicon (Si) for plant uptake [2,8,9]. Thus, in order to measure the effect on plants, silicon is frequently provided as fertilizer. High levels of silicon can be actively absorbed and accumulated in the plant tissues of some monocotyledonous plants, some dicotyledonous plants, and vegetable and fruit crops [1, 10]. Applying silicon fertilizer considers soil fertility, crop requirements, soil moisture patterns, and crop uptake of nutrients from the soil; it also aids in controlling the amount of nutrients withdrawn by crops [4]. Plants that use silicon fertilizers have grown more productively, grown resistant to a variety of pathogen invasions, and become more acclimated to adverse environmental conditions [2,5,6]. Si fertilization, for instance, increased the culm wall thickness, vascular bundle size, and peroxidase activity in rice (Oryza sativa), improving stress tolerance, stem strength, and preventing lodging [11,12]. Similar to this, during water stress in the vegetative and reproductive stages, upland rice cultivars that receive Si fertilizer tend to have different levels of proline; this effect may be suggestive of stress tolerance [13].

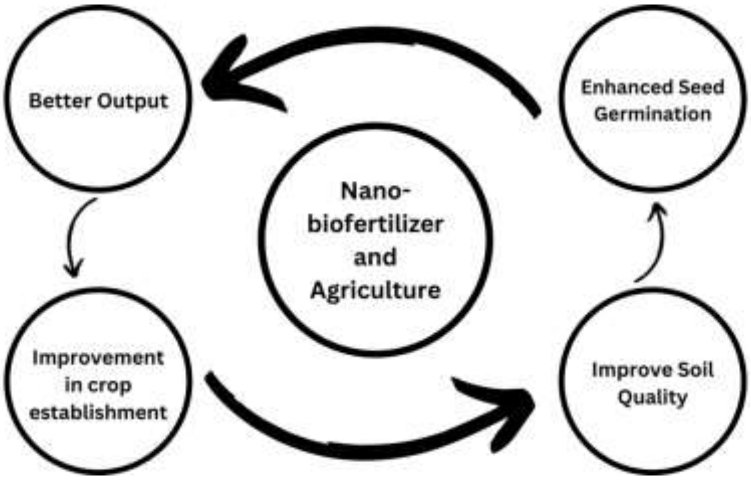
Figure 1: Silicone Fertilizer

Furthermore, by decreasing water loss through transpiration in plants experiencing drought stress in maize (Zea mays), supplementing with Si is hypothesized to raise the water flow rate in the xylem vessels and enhance water use efficiency [14,15,16]. According to Murillo-Amador et al. (2007) [17], kidney beans (Phaseolus vulgaris L.) and cowpeas (Vigna unguiculata) under sodium chloride (NaCl) stress experienced significant reductions in plant growth; however, silica supplementation significantly increased the plants' growth by increasing net photosynthesis, chlorophyll content, stomatal conductance, transpiration, and intercellular carbon dioxide [14]. Si supplementation increased the crops' ability to withstand flooding by strengthening their oxidative defense system. Additionally, Si creates a defense against a variety of pests and insects, such as mites, brown plant hoppers, green leafhoppers, sugarcane stalk borers, leaf spiders, and stem borers [18, 19, 20]. In conclusion, the agricultural sector uses Si-based compounds for a variety of purposes in crop production.

Enhancing Crop Productivity and Sustainability: The Role of Silicon Fertilizers in Agriculture

Climate change poses a threat to crop species worldwide, and both biotic and abiotic stressors significantly lower crop yields. By 2050, crop production will not be able to keep up with the increasing demand brought on by population growth [21]. Thus, in order to increase crop productivity, a variety of management technologies are needed. It is important to remember that sustainability is essential to both the planet's future and agriculture. Under these conditions, fertilizer advancements, like the application of Si fertilizer, can significantly affect plant characteristics and contribute to increased plant yield and health.

Si fertilizer's effects on crop growth, yield, and quality are widely acknowledged. Since silica fertilizers are noncorrosive and pollution-free, they are high-quality fertilizers that are regarded as sustainable and eco-friendly for agriculture. They can also be inexpensive, making them smart fertilizers. Moreover, silicate fertilizers are applied to soil to adjust its pH and to acquire macro- and micronutrients; this is especially true when silicate fertilizer sources such as slag or mineral ores containing Si are used [22].



The various smart fertilizers that are available, how they are applied to monocotyledonous and dicotyledonous plants in agriculture, the availability of these fertilizers, the results of experiments carried out in open fields, growth chambers, and greenhouses, and the opportunities for farmers and the research community to support Si as a smart fertilizer for sustainable agriculture and yield improvement are all covered in this review.

Silicon Fertilizers and Amendments for Enhanced Plant Growth and Environmental Resilience

Potential silica fertilizers include industrial wastes like bottom ash, fly ash, steel slag, and slag from furnaces [23, 24]. The material known as steel slag, which makes up 15–20% of the total amount of steel produced, is specifically a by-product that is created during the process of manufacturing steel from iron [25]. Different manufacturing, cooling, and value-adding processes result in different basic properties for slag [26]. The nutritional components of steel slag include iron Fe (17–28%), silicon dioxide SiO2 (10–28%), calcium oxide CaO (40–50%), and traces of magnesium oxide MgO (2.5–10%) and manganese oxide MnO (1.5–6%) [27].

These slags, produced as byproducts, have been used in agricultural fields as Si supplements. These byproduct slags have been applied as Si supplements to fields of agriculture. The effects of various slag-based fertilizers on plant growth and disease incidence, however, have not been thoroughly studied. The effects of Si fertilizers based on steel and iron slag, for instance, on rice yield parameters and disease incidence were studied [28]. According to the authors, steel slag outperformed iron slag in raising rice yield and reducing brown-spot disease incidence.

Worldwide, about 3.2 million tons of silicon are produced from rice husks and hulls, primarily as opaline silica, out of about 80 million tons total production [29]. This nutrient-rich rice husk is beneficial as a soil ameliorant when it is partially oxygenated and converted into biochar [30].

The amount of insect infestation was reduced by rice husk biochar (RHB), but the amount of Si in the brinjal plant's leaves increased concurrently. Si-rich rice husk ash (RHA) and rice bran (RBB) also reduced the amount of inorganic arsenic accumulation in rice grains when combined [31]. The research findings indicate that silicon (Si) derived from RHB and RHA sources is likely to be more soluble than silicate minerals. Applications of K2SiO3 suppressed tomato plant mildew [33] and powdery mildew [32] and were also reported to have developed resistance to disease incidence. Furthermore, the application of sodium silicate (Na2SiO3), a different source of silicon, topically on maize enhanced the plant's absorption of potassium and calcium as well as the contents of chlorophyll and carotenoid under drought stress [34].

Na2SiO3 was found to reduce Fusarium wilt in cucumbers by altering the microbial characteristics of the soil and promoting plant seedling growth in another study assessing the effects of the substance in response to disease occurrence [35].

When monosilicic acid was applied to barley plantation soil with high concentrations of heavy metals, it was observed that resistance to these heavy metals increased in plants and that the mobility of the metals in the plants decreased as the acid concentration increased from 5–20 mg kg^{-1} to ≥50 mg kg^{-1} [36]. The apoplast pathway of cadmium transportation also resulted in a 50–90% reduction in toxicity levels in the roots, leaves, and stems of rice when monosilicic acid was applied to prevent cadmium toxicity [37].

Implementing NanoSi in Agricultural Applications"

Particularly in the context of yield improvement and plant disease management, nanotechnology is a cutting-edge field with significant potential in the agricultural sector [38]. Applications of nanotechnology have created a new area of study in agricultural and biotechnological science and are a new platform for increasing global food production, which has become a hot research topic for all agri-food production sectors [39]. According to reports, NanoSi (NSi) helps plants grow and yield under a variety of biotic and abiotic stress conditions while also maximizing the use of applied fertilizers [40].

In a field study of black rice, the application of 1 N of NSi in conjunction with N, P, and K resulted in a notable increase in harvested and milled dry grains [41]. A similar outcome was noted in two Iranian rice varieties, where NSi and nitroxin were combined to yield the maximum harvest index [42]. In field experiments conducted in two different years under deficit irrigation conditions, the application of NSi (containing 2% chelated Si) consistently increased wheat yields by 28% and 32% [43]. Under both full and deficit irrigation conditions, the same experiment demonstrated that foliar application of NSi resulted in the highest water use efficiency. In a field experiment utilizing NSi fertilizer at a rate of 60 mg/L under salt stress conditions, more growth parameters and yield were seen in cucumbers [44].

3. Results and Discussion

It is impossible to exaggerate the importance of silicon to agriculture. Enhancing plant characteristics is essential, as it is the second most abundant element in the Earth's crust after oxygen. The silicon form that is available to plants is called orthosilicic acid, and it plays a role in improving plant growth, development, and stress tolerance. Because of its beneficial effects on photosynthesis and lower transpiration rates, it is an important tool for crop production. In addition to being sustainable and eco-friendly, silicon plays a critical role in ensuring environmental sustainability and food security by reducing biotic and abiotic challenges. Silicon undoubtedly has the power to completely transform contemporary agriculture [45].

In order to increase crop resilience and productivity, silicon fertilizers are essential. These fertilizers cover a vital need because many agricultural soils don't contain enough silicon. Applications of silicon promote higher yields and increased plant growth by carefully taking into account variables such as crop requirements, soil fertility, and moisture cycle. Plants that are strengthened against various stressors are better able to withstand unfavorable circumstances. Examples that demonstrate silicon's potential to improve crop performance include the fortification of rice culm walls and the modification of proline levels during water stress in rice. Fertilizers made of silicon are sustainable and eco-friendly, making agriculture more robust and fruitful [46].

One of the key components of sustainable agriculture is silicon's resistance to pests and diseases. The need for chemical pesticides is decreased when plants are supplemented with silicon, which strengthens their defenses against a range of insects and diseases. This is consistent with environmentally friendly agricultural practices and protects crops as well. For plants, silicon increases the strength of cell walls and activates defense mechanisms, making it more difficult for pests to enter and grow established. It also enhances overall disease resistance and improves the health of the plants. Hence, silicon acts as a crop's natural defense system, reducing the need for dangerous chemicals and fostering a stronger and healthier farming ecosystem [47].

A major threat to food security is the effects of climate change and growing population, which make agriculture a complex global issue. It is not possible to meet the increasing demand by 2050 with current trends in crop production. To solve these issues, sustainability is essential. Organic and inorganic silicon fertilizers are becoming environmentally friendly, sustainable, and "smart" solutions that improve crop resilience, productivity, and attributes. They play a crucial role in sustainable agriculture thanks to their adaptability in nutrient uptake and soil pH changes. We can increase food production, lessen our impact on the environment, and guarantee a more secure future for the planet and agriculture by sticking with our current course of research and application [48].

In order to meet the changing demands of a growing world population while reducing environmental impact, sustainable agriculture must be promoted. Creative fertilizers and silicon-based solutions are becoming vital resources in this endeavor. They support eco-friendly practices, increase crop productivity, and strengthen disease resistance. Nanotechnology applications, silicate-based soil amendments, and silicon fertilizers are a few examples of these innovations that have several advantages. They increase yields while simultaneously lowering the need for chemical inputs and promoting a more resilient and ecologically conscious agriculture industry. In order to achieve a sustainable future for agriculture and the planet, we must embrace these technologies as we navigate the challenges posed by climate change and rising food demand [49]

A novel avenue for agricultural innovation is presented by nanotechnology. The utilization of it in agriculture has the capacity to transform crop yield and tackle urgent worldwide food security issues. Enhancing the effectiveness of pesticides, fertilizers, and nutrient delivery systems is possible with nanotechnology since it can engineer and manipulate materials at the nanoscale. To further optimize resource use and reduce environmental impact, real-time monitoring and tailored interventions are made possible by precision agriculture techniques and nano sensors [50]. Using nanotechnology to its full potential will transform food production, boost yields, and help us adapt to changing climates. In the end, this will ensure a more resilient and fruitful agricultural future.

4. Conclusion

In conclusion, it is impossible to exaggerate the significant influence that silicon and nanotechnology have on agriculture. The second most abundant element in the Earth's crust, silicon, is essential for improving plant characteristics, reducing stress, and promoting disease resistance. By increasing productivity and lessening environmental impact, its use as fertilizer supports sustainable agriculture. Due to its adaptability and eco-friendliness, silicon is an essential resource for tackling the problems caused by climate change and an expanding global population. Simultaneously, the agricultural landscape is being transformed by nanotechnology. It provides creative ways to increase nutrient delivery, monitor crops in real time, and maximize resource use. Crop production could be revolutionized and food security concerns could be addressed with the help of precision agriculture methods and Nano scale materials. With the help of nanotechnology, we can meet the growing demand for food while preserving the health of our planet by moving toward more environmentally friendly, efficient, and sustainable agriculture. Using silicon and nanotechnology to its full potential will be essential for agriculture in the future, and a more resilient and fruitful agricultural ecosystem depends on these technologies being developed and applied.

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