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Review

Growth, Nutrient Accumulation, and Drought Tolerance in Crop Plants with Silicon Application: A Review

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Abstract: Plants take up silicon (Si) from the soil which impacts their growth and nutrient accumulation. It increases plant resistance to abiotic and biotic stresses such as drought, salinity, and heavy metal, diseases, and pest infestation. However, until recently, research of Si application on the crop is limited. This article reviews the recent progress of research on Si application on crop growth and yield, nutrient availability in soil and accumulation, and drought tolerance of crop plants. The review's findings show that Si improves crop development and output under stressful environmental conditions. Silicon increases the availability and accumulation of both macronutrients (nitrogen, potassium, calcium, and sulphur) and micronutrients (iron and manganese). It improves drought resistance by increasing plant water usage efficiency and reducing water loss during transportation. Silicon application is a crucial aspect of crop productivity because of all of these favorable attributes. The gaps in current understandings are identified. Based on the outcome of the present research, future scopes of research on this field are proposed.

Keywords: growth; nutrients; drought; silicon; plants

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Citation: Rea, R.S.; Islam, M.R.; Rahman, M.M.; Nath, B.; Mix, K. Growth, Nutrient Accumulation, and Drought Tolerance in Crop Plants with Silicon Application: A Review. *Sustainability* **2022**, *14*, 4525. https://doi.org/10.3390/su14084525

Academic Editor: Teodor Rusu

Received: 4 March 2022
Accepted: 8 April 2022
Published: 11 April 2022

1. Introduction

Most of the major crops accumulate a significant amount of Si though it is considered non-essential for plant growth and development [1]. While Si does not directly contribute to plant metabolism [2,3], there is evidence that Si improves: crop productivity [4–7], nutrient accumulation in plants [8–11], heavy metal resistance in grain crops [12–14], and increases drought tolerance of plants [15–17]. Since these benefits for crop production have been recognized, the global use of Si as a soil amendment is increasing.

The Earth's pedosphere of Si is estimated to be 28.2% by weight [3]. Si, along with oxygen and metals, forms silicon dioxide (Si_2O) and water-soluble silicates. Si minerals go through various physical and chemical weathering and release Si in solution under suitable pH condition. The source of silica and silicates in soil and clays is from the weathered Si minerals such as quartz and feldspar present in the pedosphere [18,19]. Si is present in soil mainly in three different phases such as solid, liquid, and adsorbed. Solid phases can be either amorphous or crystalline. Amorphous silica contributes significantly more to dissolve Si in soil solution because of its higher solubility than the crystalline form [3]. However, the plant does not uptake any Si as amorphous silica; rather it is taken up by plants in the form of monosilicic acid (H_4SiO_4) [20].

The addition of Si as a soil amendment in the crop field is a recent phenomenon, and few reports have been published on the impact of Si on plants. The recent publications report that Si affects growth, yield [21–23], and disease resistance [24–27] among other plant conditions.

Figure 1 shows the number of publications vs. year for the time period 1950–2021. The research on the plant silicon relationship began after 1935. Until 1980, research on this field was minimal. However, between 1980–2000, the overall number of publications started to increase gradually. After 2010, a dramatic increase in publication indicates that this field is getting more research attention [28].

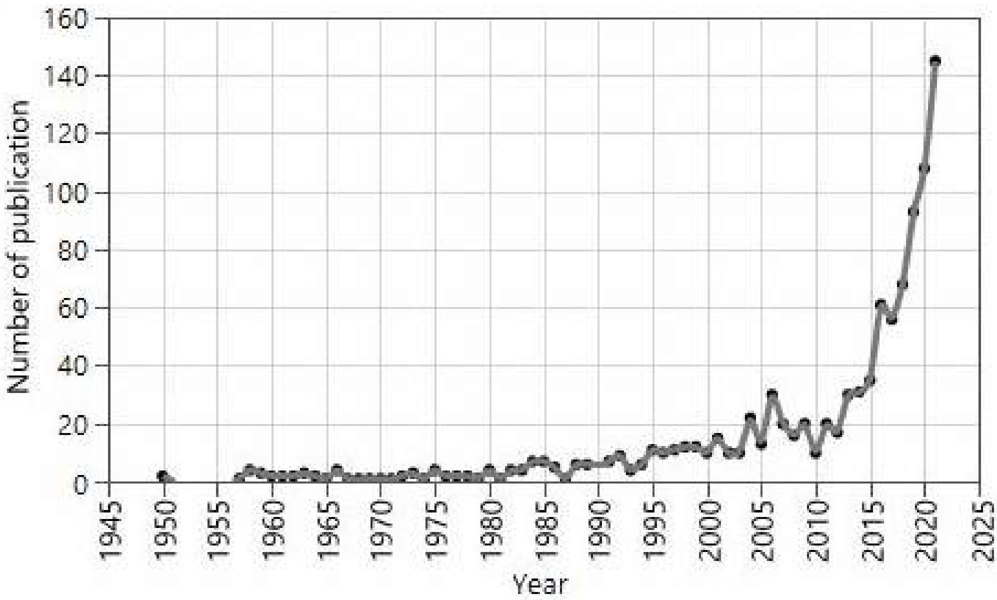

Figure 1. Number of Si-related publications in the plant sciences from 1950 to 2021 [28].

It is noteworthy, that among the ten major produced crops in the world, seven crops (rice, wheat, sugarcane, sugar beet, soybean, tomato, and barley) are Si accumulators and their biomasses consist of more than 1% Si in dry matter [29]. Though the ability of Si accumulation in these plants highly varies [30], production of these crops takes away large amounts of Si from the soil. For instance, rice and sugarcane individually can remove approximately 500 kg and 300 kg of Si per ha, respectively, while harvesting [20,31]. After several years of continuous cropping and harvesting of plants, available Si declines in the soil. This fact necessitates the application of Si from external sources. In different parts of the world, such as India, Vietnam, China, researchers used rice [32], wheat [17], and sugarcane [20] for experiments on Si applications related to crop production. It has been observed that Si has a beneficial effect, including increasing crop yield, limiting abiotic stresses from salinity, increasing drought tolerance [33], and reducing the toxic effects [34,35] of heavy metals. [36]. The presence of higher Si in the plants' roots, shoots, and leaves makes the plants more resistant to pest attack and enhances drought tolerance as it forms a thick layer under the cuticle. This Si layer reduces leaf digestibility for pests as well as water transpiration loss from plants [37]. Silicate application sharply decreased transpirational flow in rice about 4.2% to 0.8% [38]. It was reported that applications of amorphous silica minimize the cadmium stress in the plants by inhibiting root to shoot transfer of cadmium along with other metals [39,40]. When amorphous silica was applied at a rate of 1000 kg/ha, it increased the availability and accumulation of mineral nutrients: P (10–40%), Ca (up to 33%), S (up to 51%), Mo (up to 54%), and Cu (10–40%) [41]. Si helps make the nutrients available to plant root systems by impeding soil particles from bonding with mineral nutrients. It is known that the content of Si in agricultural soils is declining, both due to natural weathering and continuous agricultural and activities [42]. This work reviews the contemporary research on the application of Si to soils to in-crease crop production. The scope of this review includes the impact of Si fertilization on growth and yield, soil nutrient availability in uptake form, and drought stress tolerance of crop plants, with a general summary of Si application in crop fields from different sources following different methods of use. The gap between current understandings and the experimental results is identified throughout.

2. Role of Si on Plant Growth and Yield

Application of Si-based fertilizer has been reported to be effective for plant growth and yield. To determine the effect of Si fertilizer on growth, yield, and nutrient accumulation of the rice plant, four different dosages of SiO_2 were applied with identical recommended dosages of N, P, and K fertilizers. It was observed that yield components (number of tillers, number of panicles per plant, and number of grains per panicle) and yield were significantly affected by Si fertilizer doses. About 3716 kg/ha maximum grain yield was obtained when they applied SiO_2 at a rate of 329 kg/ha. There was about a 23% increase in grain yield compared to the control [8]. Whereas in a similar study with different Si fertilizer (Na_2SiO_3) dosages, up to 17.4% yield increase along with increased panicle numbers were recorded from a field trial in China. The increased growth and yield recorded from this experiment are given in Table 1.

Table 1. Effect of Si fertilization on rice growth and yield in China [4].

Application Rate (kg/ha)	Number of Panicles ($\times 10^4$/ha)	Number of Spikelets/Panicle	Yield (kg/ha)
0	4.84	74.7	7010
75	4.94	73.9	7870
105	5.03	74.8	8160
135	5.03	76.8	8230

In India, researchers used diatomaceous earth (DE) as a source of Si and compared its use in two different moisture regimes: saturated/submerged and field capacity. It was found that biomass yield was high with almost all of the DE treatments in acidic (300 and 600 kg/ha) and alkaline (150, 300 and 600 kg/ha) soil condition. Analysis of soil and rice yield, before and after the application of DE, provided evidence that applications of DE increase rice yield regardless of the soil condition. The increases were 150, 300, and 600 kg/ha in alkaline, acidic, and neutral soil, respectively. According to the report, DE works best in submerged condition compared to field capacity condition of the rice field [4]. Si is also responsible for grain quality in rice. Formation of the quality hull with milky sap is high when the concentration of Si in rice shoot is high [43].

Si fertilization has a positive impact on wheat production. It increases the plant height, no. of spikelets, and number of spikes per spikelet. In irrigated fields, grain yield increased by 13.4% compared to no Si application. It has been reported that the application of K_2SiO_3, at a rate of 12 kg/ha, increased plant height, the number of effective tillers per m^2 up to 515.33, spike length up to 12.25 cm, and number of spikelets per spike on an average 16.70. A maximum grain yield of 4380 kg/ha was observed when K_2SiO_3 was applied with four irrigations [17]. Exogenous application of Si or a combination of Si and Se were reported to change the physio-biochemical activity in wheat which resulted in the successful growth of wheat in saline soil [44]. Foliar application of sodium silicate salt ($Na_2Si_3O_7$), especially at the tillering stage and anthesis stage, increases the yield for various wheat cultivars [45]. In contrast to other materials, volcanic tuff (Chem comp) was applied in Idaho and showed no remarkable effect. There is also evidence that these improvements in yield are only related to stressed conditions and that no improvement in yield is observed during ideal growing conditions [46].

Notable improvements were observed when Si fertilizer was applied for maize production [47]. In Pakistan, two hybrid maize varieties, P-33H25 and FH-810, were grown under 100% and 60% field capacity of water levels. In a water deficit condition, application of Si significantly increased plant height, stem diameter, and cob length (13.96 cm and 12.83 cm, respectively) for both maize varieties. It also increases the number of grains per cob (235.05

and 215.35) and grain yield (0.46 kg and 0.39 kg) correspondingly. This increased yield was due to the increased number of cobs, grains per cob, and weight of 1000 grains [7]. A similar result in the drought stressed condition was published on the improvement of maize plant growth and yield from Turkey and Greenville, South Carolina [22,48].

Si is not only beneficial for cereal and grain crops; it also increases the production and fresh weight of vegetables. In India, studies were conducted from 2013 to 2017 on three different potato varieties. Application of additional Si (ferti-silica 50 mg/dm^3) increased tuber yield by 15–50% [21]. In a pot cultivation system, Ca and Mg silicate were used for growing potato in the absence and presence of water. According to this report, Si application enhances Si availability in soil, which increases overall tuber dry weight irrespective of water condition. Though there was no significant improvement on an increase in the number of tubers/plants [49].

Likewise, in soilless cultivation systems, the addition of Si increases Si content in green bean pods without any loss of biomass production [50]. Significant increase in shoot and root length of cowpea were observed in India when the water-soluble Si was applied at a concentration of 100 mg Si per Kg of Si fertilizer dose. In cowpea, it increased shoot yield by 128% [9]. In a legume (soybean) crop study in Brazil, the effect of Si (sodium–potassium silicate) and salicylic acid were examined. As stated by, individual application of sodium–potassium silicate and salicylic acid does not have any significant impact on legume plant growth. However, combined foliar application of these two Si materials has an adverse effect on the yield of soybean [51].

In the same way, the spraying of silicic acid increases lettuce yield quality and postharvest firmness [52]. Application of Si at a dose of 250 mg/dm^3 significantly increases the head weight and total dry matter content in lettuce. In comparison to control treatments, the yield of cucumber increased by 9.35–26.6% as the number of fruits increased [5]. In India, several studies conducted on tomato and onion using diatomaceous earth at a rate of 500–700 kg/ha provided the highest yield for both of these crops [53,54].

3. Role of Si on Nutrients Availability and Accumulation

There are sixteen minerals playing essential roles in the plant's cell metabolism, energy transfer, osmosis, and reproduction. Among these sixteen elements, nitrogen (N) is a major constituent of the plant structure which works with a combination of H, C, and P. Si mostly affects the availability of N in soil and N accumulation in plants [55]. It forms the organic compounds such as protein and nucleotide in the plant. Similar to N, phosphorus (P) also forms some organophosphorus compound such as sugar phosphate, pyrophosphate bond (ATP), phytin, etc. On the other hand, potassium (K) maintains the ionic balance among the cells along with the activation of enzymes. It also provides mechanical strength against the lodging of plants in water deficit condition. Among the micronutrients, Fe and Mn work as a cofactor of enzymes and help in N metabolism. Availability of Fe in the soil increases the amount of Fe in plant parts, which is good if the plants are used as food. Zn and Cu are two redox active micronutrients which operate to maintain the structural integrity and permeability of the plasma membrane [56]. Si influences the availability and accumulation of these nutrients in various plants species. It also affects the presence of nutrients in the root and shoot. The discussion of nutrient availability and accumulation follows in the next three sections on macronutrients, micronutrients, and silicon accumulation.

3.1. Macronutrients

In the published literature, the results of Si application reveal a mixed trend regarding macronutrient accumulation. Needless to say, the environmental parameters, Si dosage, and soil type of the research sites were widely variable. Therefore, one cannot argue the results are contradictory.

Some reports claim the improvement of nutrient accumulation by using silicon. According to Cuong et al. [8] (Figure 2), the application of silica has a positive impact on almost all the aspects such as availability, assimilation, and uptake of N, P, and K in rice plants, especially in grains [57,58]. The increase in N, P, and K accumulation recorded up to 33%, 69%, and 36.8%, respectively, compared to the control [8]. Similar results were also found utilizing diatomaceous earth on the rice field [58]. It was concluded in another study that Si fertilization has a positive correlation with P uptake making P more available in soil [59]. Generally, P concentration increases in root areas but in potato a higher concentration of P was found in the leaves due to the application of Ca and Mg silicate fertilizers [60]. The plant's available forms of phosphorus also increased in soil because Si binds with iron and manganese, thus preventing phosphorus opportunity to bond with those elements [49]. Whereas potassium concentration in the shoots and roots decreased in lettuce due to the addition of Si and increased for some other crops such as maize and rice from 10–40% [42]. Hence, the accumulation of potassium with the addition of Si appears to be dependent on plant species. In addition to increased N accumulation, S and Mg accumulation also increased in total plant biomass with a high concentration in roots when Si treatments continued for a longer duration (3 weeks). Though, a very high dose of Si decreases the availability of Mg [42,61].

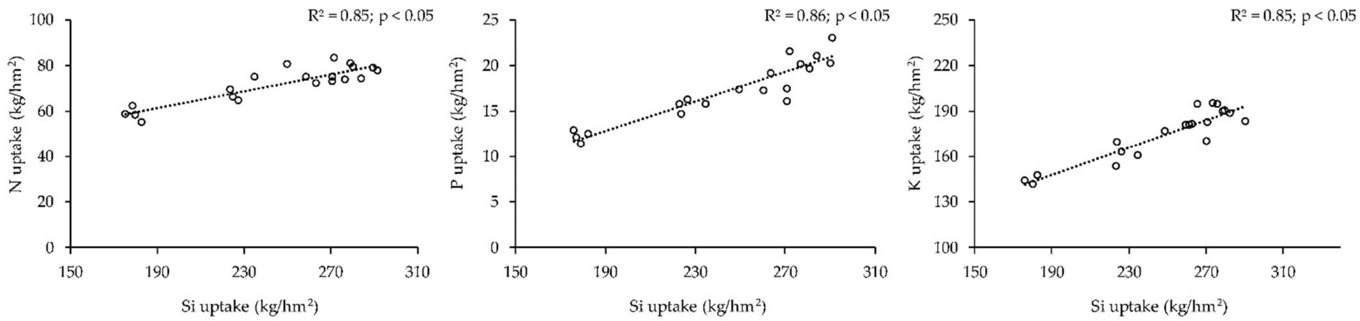

Figure 2. Linear regression between Si uptake and nitrogen (N), phosphorus (P), and potassium (K) uptakes in above-ground biomass of rice variety BC15 [8].

There appears to be evidence that very high doses of Si decreased the net accumulation of N and P in the plant's shoots and roots, though it is thought that the concentration of N decreased due to the increased growth rate and decreased Mg availability caused by Si treatment [42,62]. Silicon deposition in endodermal cells of plant roots, which may contribute to decreased P uptake, is one probable reason for the decrease in P accumulation. The generation of apoplastic barriers to P permeability across roots produced by Si deposition in roots, which reduces P uptake, is primarily responsible for this effect [63,64]. Another concept is that the creation of a cuticle-silica double layer in leaves as a result of Si deposition lowers the plant's transpiration rate. Transpiration is negatively connected with the Si content of rice aerial parts, and when the SiO_2 concentration of shoots surpasses 10% of the dry matter weight, the rice transpiration rate might be lowered by 20–30% [65]. In contrast, another study found Si application does not have any measurable effect on increasing extractable phosphorus from soil, in fact it may increase P fixation in soil because Si increases soil pH which influences soil P to be strongly adsorbed by soil particles and silicic acid is not strong enough to break that bond [66]. Therefore, the supplemental Si application slightly affects the availability of P.

3.2. Micronutrients

Very limited reports are available on Si applications associated with micronutrient accumulation; however, Si application appears to have an impact on crop accumulation of most of the micronutrients. The net accumulation of Fe and Mn has been improved by Si application as well as boron accumulation in plant leaves. Fe concentration increased in both the roots and shoots, respectively, 20–40% and 10% [43]. While Si did not influence the accumulation of Cl and Mo, it decreased the accumulation of Cu and Zn by 20%. [10]. In numerous studies, Si has been shown to limit Zn bioavailability in soil by redistributing the metal to more stable fractions such as organic materials and crystalline Fe oxides [67].

Silicon impacts the exudation of several organic acids (e.g., oxalic, acetic, tartaric, maleic, and fumaric acids) from rice roots, which may be involved in Zn toxicity mitigation via immobilization/co-precipitation in the soil solution [68]. In general, the immobilization of harmful Cu ions by increased cell wall binding capacity and the creation of Cu-binding molecules, both in roots and shoots, is attributed to Si-mediated reduction in Cu toxicity. Si lowered the expression of two Cu transporter genes in Arabidopsis roots, AtCOPT1 and AtHMA5. According to the authors, Si deposits generated in cell walls boosted Cu-binding sites, reducing the impact of elevated Cu levels in plant cells [69]. According to Flora et al. [70], the Si-mediated reduction in Cu toxicity in tobacco (Nicotiana tabacum) via decreasing root uptake of Cu also lowers the expression of NtCOPT1 and raises the expression of genes involved in ethylene production. Kim et al. [71] proposed that increased Si buildup in the roots of Cu-stressed rice plants inhibited Cu influx through down-regulating metal transporter genes OsHMA2 and OsHMA3.

In many cases, the combined application of Si with other minerals such as Zn increases the availability and accumulation of micronutrients. Zn concentration increased up to 10 µg/L in all organs of rice plants when additional Zn was applied in combination with Si fertilizers. On the other hand, in Zn deficient conditions, Si application increases the Ca concentration in rice and maize shoots and grains [10,22]. In boron (B)-deficient conditions, Si increases Zn, Mo, Mn, and Cu in sunflower shoots. However, it decreases Fe concentration in roots but increases Fe in fully developed leaves, increasing its mobility [72].

3.3. Silicon

Increased Si availability in soil solution is the main reason for increased Si uptake in plants. Additional Si application stimulates Si uptake by plants as it improves the root system. Si uptake and accumulation are highest for Si accumulator plants, which consist of more than 1% of total biomass silicon [73]. In Table 2, a few major crops are listed with Si percentage in total biomass. Rice plants are the highest Si accumulators, followed by wheat, barley, tomato, and sugarcane. In rice cultivation systems, the application of SiO_2 at a rate of 100–400 kg/ha increases Si uptake 26.8–58.5% in total plant biomass [8].

Table 2. Si% in above-ground parts of major crop plants [74].

Plant Species	Si% in Plant Biomass
Rice (*O. sativa*)	4.17
Wheat (*Triticum aestivum*)	2.45
Barley (*Hordeum vulgare*)	1.82
Tomato (*Lycopersicon esculentum*)	1.54
Sugarcane (*Saccharum officianum*)	1.51
Soybean (*Glycine max*)	1.39
Lettuce (*Lactuca serriola*)	0.97
Corn (*Zea mays*)	0.82
Potato (*Solanum tuberosum*)	0.4

In potato, the soil and foliar application of sodium metasilicate have different effects on the leaf, stem, and tuber Si concentration, and accumulation. The concentration of Si was maximum in stems for soil-applied Si compared to foliar-applied Si and untreated control. No significant differences were found in tuber Si concentration. Whereas Si accumulation in the stem was maximum for foliar application of Si. Overall, soil application of Si provides maximum Si concentration and accumulation in different parts of the potato plant [38]. Figure 3 shows the comparison of Si concentration and accumulation in leaves, roots, stems, and tubers of potato for soil- and foliar-applied sodium metasilicate.

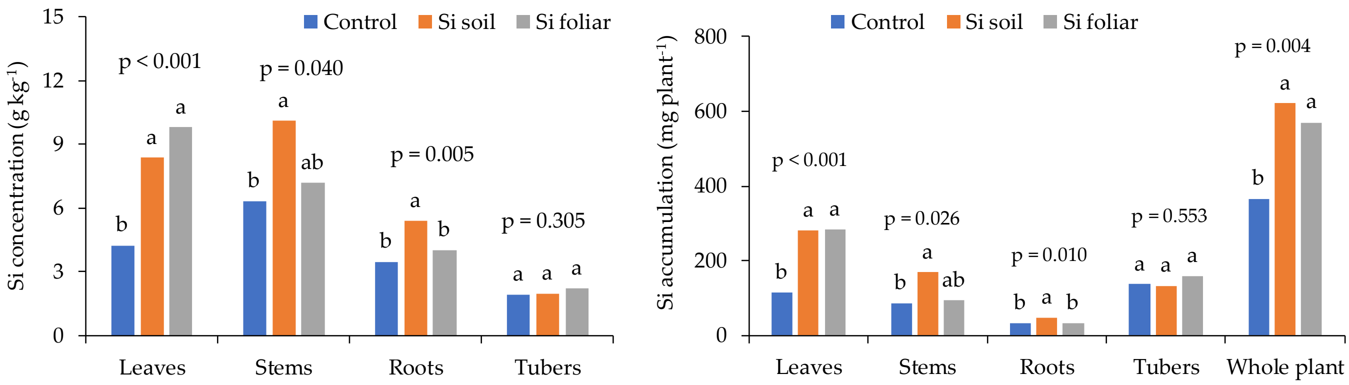

Figure 3. Comparison of soil- and foliar-applied sodium metasilicate on Si concentration and accumulation in potato leaves, roots, stems, and tubers [39]. Bars having common letters do not differ significantly at 5% level of significance.

In the same way, maximum uptake and accumulation of Si in cowpea (*Vigna unguiculata*) roots and leaves were observed for 800 g/kg soil-applied Si. Application of sodium metasilicate increased leaf Si concentration up to 4259.7 µg/g and root Si concentration up to 3126 µg/g [9].

4. Silicon Application as Nano-Fertilizers and Nano-Pesticides

Nanotechnology is a potential interdisciplinary research subject that has applications in a variety of sectors, including medical, pharmacology, electronics, and agriculture [74]. Because of their small size, higher surface-area-to-weight ratio, and distinct forms, nanoparticles may have different properties than their bulk material [75]. Similar to their bulk material, Si nanoparticles (Si-NPs) have been shown to have various physical and chemical properties [76]. As a result, it is crucial to understand how Si-NPs interact with their surroundings. Si-NPs have a lot of potential in agriculture because of their unique features, and they might be superior to bulk material in alleviating various abiotic stresses [77–80]. Si-NPs can be employed as nano-pesticides, nano-herbicides, and nano-fertilizers in addition to their direct impact on plant growth and development. Silicon nanoparticles can easily infiltrate plant cells and alter plant growth and development by affecting their metabolism through a variety of interactions, triggering the capacity to battle stress circumstances. In the present decade, where the focus is to increase crop productivity or to eradicate weeds, Si-NPs may act as an agent for target-specific delivery of herbicides and fertilizers [81]. Herbicides (chloroacetanilide, anilide, and benzimidazole) embedded in a diatom fistula have been seen to be carried by silicon nanocarriers and delivered to the field in their active state [82]. In the instance of fertilizer distribution, research has shown that using nano-silicon dioxide in conjunction with organic fertilizer can promote plant production [83]. Mesoporous silica nanoparticles (MSNs) with a specific pore size (2–10 nm) were found to be an effective delivery vector for urea, boron, and nitrogenous fertilizers [81,84]. As a result, Si-NPs have the potential to be employed as a stand-alone fertilizer for specific crops, as well as a delivery system for herbicides and fertilizers in plants. Nanotechnology has aided in the development of disease-free agricultural crops in the last decade [85]. Nanosilica, a unique sort of nanomaterial, is used as a nano-pesticide under the broad umbrella of nanotechnology. Several research studies suggest that Si-NPs could be used as nano-pesticides [86–90]. Si-NPs have been reported to be used in two ways: either as pesticides in the field, killing insects and larvae, or as nanocarriers that release commercial pesticides to improve their efficiency. SiO_2 NPs were found to have lethal properties for Callosobruchus maculatus [87]; it was discovered that the nanoparticles were more effective on adults than larvae, and it was speculated that the impact could be due to the dehydrating properties of silica, which could result in digestive tract impairment or integument surface enlargement. The deadly effect of Si-NPs on pests can also be attributed to the blockage of spiracles and tracheas, as well as sorption and abrasion damage to the protective wax layer on the cuticle. A modified hydrophobic nano-silica with a surface charge of 3 to 5 nm displayed the ability to eliminate a variety of crop insects, pests, and veterinary ectoparasites [86]. The process by which nano-silica kills pests is thought to be physisorption of nano-silica, which breaks the protective lipid water barrier, resulting in the death of the targeted organisms [86,91]. It is critical to release pesticides at the desired spot in order to improve their efficacy. However, mesoporous silica nanoparticles are required for the controlled release of bioformulations in order to deliver insecticides [92,93]. Several researchers have found that mesoporous nano-silica improved the durability and efficacy of commercial insecticides. The trials clearly showed that Si-NPs are effective pesticides that may be employed alone or to help other commercial pesticides get to where they need to go.

5. Effect of Si on Drought Tolerance in Plants

The prevalence of drought is increasing due to global warming worldwide, which is one of the greatest threats to crop production because one-third of the world land area is drought prone [16]. Drought has several harmful impacts on plant growth, metabolic activity, photosynthesis, and nutrient uptake [73]. Lack of water due to drought stress inhibits photosynthesis, damages the cell membranes, and limits cell division. About 5% to 10% of leaf transpiration occurs through the leaf cuticle, not the stomata [94]. When Si deposits under the leaf cuticle, it forms a double layer which creates an extra barrier to prevent water loss (Figure 4). Si deposition has been observed in stomata as well, and it has been reported that Si can reduce transpiration up to 30% in rice, which has a thin cuticle. It also increases structural reinforcements and changes the photosynthetic rate to increase water use efficiency [95]. Furthermore, Si application was reported to increase drought tolerance by elongating roots. These elongated roots are strong enough to extract water from soil at a drought-stressed condition [96].

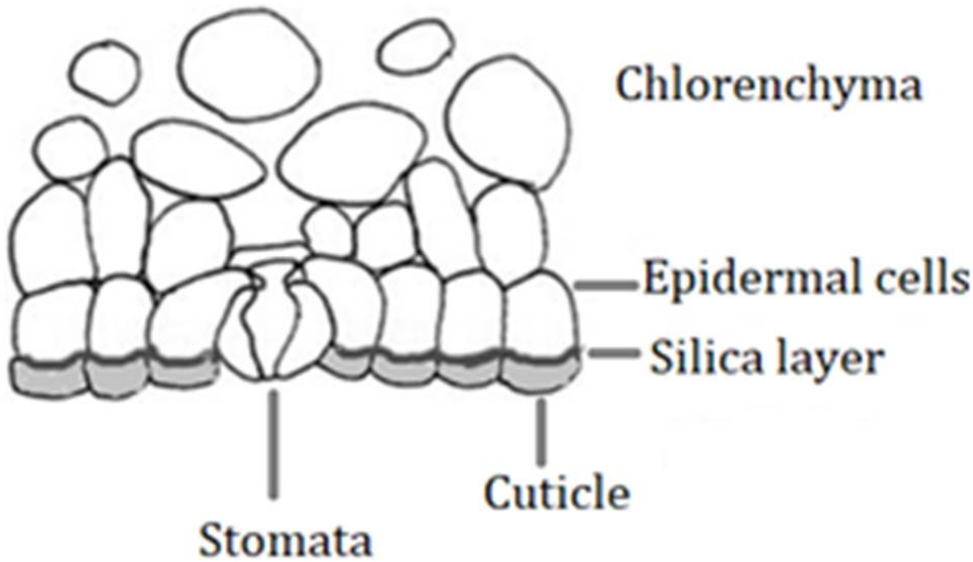

Figure 4. Diagram of Si deposits between cuticle and epidermal cells in plant leaf.

Drought stress is a severe constraint to rice production [97,98]. Si has been verified to increase rice plant resistance against the drought stress condition. To prove the increased drought resistance of rice due to Si, one experiment was conducted using K_2SiO_3 at a concentration of 0. 0.5, 1.0, 1.5, and 2.0 mm Si. They imposed drought treatment for 15 days after 28 days of rice transplanting. The study showed that Si application decreases the leaf water potential up to −1.92 Mpa, which was −1.33 Mpa for the wet field with Si. It also increased water utilization efficiency from 0.16 g/cm^2 to 0.39 g/cm^2. Biomass accumulation, nutrient accumulation of K, Ca, and Mg, and root activity of rice plants were increased significantly under the drought-stressed condition after Si application [99]. Similarly, in an Egyptian study, 70, 80, 90 100, and 120% soil saturation were maintained to identify the effect of Si on drought tolerance of rice. Reduction in water saturation from 120% to 70% without Si application decreased the plant height by 32% and grain yield by 27%. Whereas with the application of Si 8.4 mg/10 increased the plant height by 38% and grain yield by 106% compared to no Si application [100]. In the same way, Ca and Mg silicate applications at a rate of 200–600 kg/ha in different soil water contents, 60, 70, and 80% of field capacity, also increased the rice yield [101].

Application of sodium silicate increased chlorophyll contents and maintained required leaf water potential by reducing leaf transpiration in the drought stress condition of wheat. Sodium silicate at a rate of 6 mM increased relative water content under the drought-stressed condition. Foliar application of sodium silicate at the active tillering and anthesis stage provided maximum positive influence both in a drought-stressed and non-stressed condition [102]. In the same way, under reduced moisture level, potassium metasilicate (K_2SiO_3) at a rate of 12 kg/ha also increased leaf water potential by increasing K contents in wheat [17]. Another experiment in China observed the regulatory activities of Si on water relations of wheat leaves in a drought condition. They maintained drought treatments in the field by withholding irrigation and used moveable rainwater shelter. They did not find any differences in soil moisture contents under drought condition, but Si-applied plants had better water potential and moisture content in the leaf area [38,103].

A study in Utah found that the additional application of Si also increased drought tolerance in corn. The effects of Si on corn were studied under three cultivation techniques: hydroponic and subjected to salt stress, gradual drought stress in low Si soilless medium, and acute drought stress in low Si soilless medium. They found inconsistent results in the case of drought tolerance but about an 18% increase in the corn dry mass. According to the study, Si increased water use efficiency in corn up to 36% [6]. It was also found that applications of Si increase corn growth and grains per cob in drought-stressed plants [7].

Recently, in a study in Pakistan, it was reported that application of plant growth-promoting rhizobacterium in combination with Si in a drought stress condition, increases the drought tolerance and mineral nutrient (K, Ca and Mg) accumulation in tomato. They followed two drought conditions: 45% field capacity and 35% field capacity with 50 mg/L Si as sodium silicate. Maximum fruit yields were reported to be 92.9 g/plant at 45% field capacity and 8.6 g/plant at 35% field capacity [104]. On the other hand, foliar application of Si reduces flower drop and young pod drop of soybean. An experiment was conducted on soybean following 25–70% water capacity of the soil. They used optysil and silvit stimulators at a concentration of 0.25%. It was observed that optysil and silvit stimulators decreased flower drop and increased the number of pods per plant compared to the control by 20% and 18%, respectively [5]. Antioxidant parameters and the photosynthetic rate of soybean were also influenced significantly by Si application [105]. It has also been reported that Si also increases drought tolerance in cucumber [106], sorghum [96], and sunflower [107] (Table 3).

Table 3. Si used as a fertilizer for major crops in different parts of the world with time of research, materials used as a source of Si, and the outcomes (SA: Soil Application, FA: Foliar Application).

Crop Species	Place & Time	Materials Used	Dosage	Application Method	Findings	References
Rice (*O. sativa*)	a. India (2018) b. Vietnam (2017) c. Florida (1997)	a. Diatomaceous earth, bc. SiO_2	a. 0, 150, 300, 600 kg/ha (DE) bc. 100, 200, 300,400 kg/ha (SiO_2)	a. SA (pot) bc. Broadcast in 3 split doses	ab. Significant increase in biomass and grain yield (up to 600 kg/ha) c. Compete with arsenic ions in root entry point bc. Disease management and yield of rice	a. Sandhya et al. [4], b. Cuong et al. [8], c. Savant et al. [45]
Wheat (*Triticum aestivum*)	a. India (2016) b. Florida, [b] Louisiana (2017), c. Iran (2015)	K_2SiO_3	a. 0 and 12 kg/ha (Iran) b. Survey on different dose (LA)	SA	ac. Si application causes increased grain yield, no. of spikelets, number of grains per spike b. Increased K concentration up to 28.65 mg/g shoot and 3.5 mg/g grain abc. Increased drought tolerance	a. Ahmad et al. [17] b. Dupree et al. [106] c. Savant et al. [45]
Potato (*Solanum tuberosum*)	c. Israel (2012) a. Brazil (2013) b. India (2017), [c] Poland (2018)	bc. Silicic acid (H_4SiO_4), a. Ferti-silica, aSilamol	a. 250 L/ha (Silamol) a. 50 mg/dm^3 Si (Ferti-silica)	c. SA ab. FA	a. Delayed skin maturation abc. Average tuber weight increase b. Yield increase approximately 15%	a. Gong and Chen [38] b. Khan et al. [21] c. Artyszak [5]

Table 3. *Cont.*

Crop Species	Place & Time	Materials Used	Dosage	Application Method	Findings	References
Lettuce (*Lactuca sativa*), Pea (*Pisum sativum*), Carrot (*Daucus carota*)	Sweden (2018)	K_2SiO_3	80 and 1000 kg Si/ha Soil 100, 500, 1000 and 5000 µM Si in nutrient medium	SA	Increases mineral nutrient (Ca, P, S, Mn, Zn, Cu) accumulation	Bocharnikova et al. [41], Greger et al. [42]
Chard (*Beta vulgaris*), Kale (*B. oleracea var. sabellica*)	Brazil (2019)	$NaKSiO_3$, K_2SiO_3	0.00; 0.84; 1.68 and 2.52 g/L	FA	Increased accumulated Si in both sources and vegetables Increased fresh matter content	Pedreira et al. [107]
Corn (*Zea mays*)	Turkey (2017)	Exogenous Si	0, 300, 750 kg Si/ha	SA (broadcasting)	Formation of less soluble zinc silicates in the cytoplasm	Keeping et al. [20]

6. Conclusions

A careful review of the published article suggests that soil silicon has a positive impact on growth and development of most of the major crops, especially when they are under environmental stress. It increases crop yield significantly for the crops such as rice, wheat, maize, and sugarcane which are Si accumulators. Si has limited effects on vegetable crop growth and yield because of less absorption capability and availability of Si. In the case of nutrient accumulation, Si increases availability and accumulation of macronutrients N, K, Ca, and S except for P. Phosphorus availability in soil decreases due to high soil pH caused by Si application. On the other hand, Si application was noted to increase availability and accumulation of micronutrients, Fe and Mn, but decreased Cu and Zn. Though, it is worth mentioning that the Si effects on yield, nutrient availability, and accumulation varied between crops and different soil environmental conditions. However, in a drought-stressed condition, Si application resulted in a positive impact in almost every case. It increases drought tolerance as it increases plant water use efficiency and reduces water transpiration loss. All these positive attributes make Si application an important aspect of crop production. Numerous plant yield and growth studies were focused on Si-accumulating cereal crops such as rice and wheat. However, the vegetable cultivation did not attract enough research attention in this regard. Research efforts may need to be directed to highly cultivated vegetables to improve understanding and potential value in horticulture. As discussed earlier, contradictory outcomes were observed on nutrient uptake after silicon application. In some cases, the same nutrient uptake is reported to be increased and decreased by different research groups. Thus, further investigations are essential for understanding the exact mechanism and environmental conditions of nutrient uptake. In addition, the application method (soil and foliar) of Si fertilizer is known to have an impact on plant growth and nutrient uptake. Different application methods have relevant pros and cons on different varieties of crops. Comparative studies can be conducted to understand the models involved in different application methods to determine the optimum method. In summary, research on Si application for agricultural products is an emerging field. The systematic study of Si application in farmlands has commercial prospects to increase crop production as well as profit.

Author Contributions: Conceptualization, R.S.R. and K.M.; software, M.R.I. and M.M.R.; validation, M.R.I., M.M.R. and B.N.; data curation, R.S.R., M.R.I., M.M.R., B.N. and. K.M.; writing—original draft preparation, R.S.R.; writing—review and editing, M.R.I., M.M.R., B.N. and K.M.; visualization, M.R.I., M.M.R. and K.M.; supervision, K.M. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not Applicable.

Informed Consent Statement: Not Applicable.

Data Availability Statement: The data used to support the findings of this study are available from the corresponding authors upon request.

Acknowledgments: The graduate research assistantship to author one by the Department of Agricultural Sciences, Texas State University is gratefully acknowledged. The authors are thankful to Shihab Uddin of Bangladesh Agricultural University for his effort in editing the manuscript.

Conflicts of Interest: The authors declare no conflict of interest.

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