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REVIEW PAPER

# Silicon in Sugarcane: Availability in Soil, Fertilization, and Uptake

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## Abstract

**Purpose** Silicon (Si) is the predominant element in soils, but is usually sparingly soluble and limited in its availability for plant uptake. Although Si is not a nutrient, Si fertilization may be necessary in weathered soils where Si is depleted to obtain increased yield, especially for Si-accumulating plants such as sugarcane. The multiple harvest of sugarcane crops in such soils may lead to Si depletion over time if Si supplementation is not practiced. However, there is a lack of information about soils type and Si concentrations in soils with positive responses to Si fertilization.

**Methods** Advances in methods of analysis of Si in soil and plants and their implementation in future studies can improve our understanding of the dynamics of Si in soil-sugarcane systems. Additionally, the responses to Si fertilization require further investigation in sugarcane, which is planted in tropical and sub-tropical regions of the world where soils are strongly weathered and Si-depleted.

**Results** Here, we review our current state of knowledge on Si solubility, availability for plant uptake, responses to Si fertilization, and its uptake in sugarcane.

**Conclusions** This paper summarized outcomes from early and recent research on Si in sugarcane, with a view to improving yields through appropriate Si nutrition.

**Keywords** *Saccharum* spp · Si absorption · Silicate · Plant nutrition · Soil

## 1 Introduction

Silicon (Si) is the second major element constituting the Earth's crust with an average of 28% total Si [1, 2]. Around 80% of igneous rocks, which originated from metamorphic and sedimentary rocks, are basically constituted by silicate minerals [3]. In the solid phase, Si is bound to four oxygen atoms in crystalline forms and amorphous compounds (allophane and phytolithic silica) [4, 5]. Thus, soils generally have large quantities of Si in their composition, but the soluble and plant available Si may be low, leading to the necessity of Si fertilization, even though Si is not an essential element [6].

The subject of Si in soil and plants in general has been reviewed numerous times [5–12] since the classic paper of Jones and Handreck (1967). However, very few reviews have focused exclusively on the importance of Si in sugarcane agriculture [4, 13, 14] while the recent review [15] examines its role in ameliorating abiotic and biotic stresses. However, the association of data of Si availability to soil type, methods of extraction of soluble Si contents, responses to Si fertilization, and Si uptake has not yet been reviewed for sugarcane. Sugarcane is relevant economically, being the world's main sugar producing plant. The crop is also important from an environmental perspective as a source of renewable energy through production of ethanol and therefore reduced dependence on fossil fuels [16, 17]. As sugarcane is considered a Si-accumulating plant [6], Si concentrations in soil will inevitably be reduced after multiple harvests, as the same areas have been used for cropping for several decades [4, 18, 19]. Despite advances in methods for Si analysis in soil and plants in the last decades, it is essential that we develop a better understanding of the association between soluble and plant-available Si and responses of sugarcane to Si fertilization, if we are to

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enhance yields through adequate management of this beneficial element in soils under sugarcane.

In consideration of these specific issues and the need to achieve a more generalized understanding of the topic in sugarcane agriculture, this review comprises an overview of Si availability in soil, responses to fertilization, and uptake in this crop. We expect that it will enhance our understanding of the direct effects of Si fertilization in maximizing stalk yield and contributing to the sustainability of sugarcane crops.

## 2 Silicon in Soil

### 2.1 Factors Influencing Si Availability to Plants and Responses to Fertilization

Although Si is the main constituent of soils, Si solubility and availability to plants differ greatly between soils. Silicon solubility and availability varies as a function of mineral composition, particle size, Fe and Al oxides and hydroxides, organic compounds and pH in soil [1, 10, 20, 21]. These factors influence the soluble and available Si dynamics in the soil-plant system and, consequently, responses to silicate fertilization.

The soil Si liquid phase is constituted by monosilicic acid ($H_4SiO_4$), polysilicic acid [6], and their complexes with organic compounds [5]. Silicic acid is the most important uptake form for growth of plants, and its concentration varies from 0.01 to 2 mM Si in soil [10]. Monosilicic acid ($H_4SiO_4$) is the main form of Si absorbed by plant roots [6] and it is the only form determined by the molybdenum blue method [22]. This form is also predominant in most soils with a pH lower than 7.0, due to the high pKa (9.6) of silicic acid [23]. At pH higher than 9 and 11, $H_3SiO_4^-$ and $H_2SiO_4^{-2}$ forms occur, respectively. In addition, the concentration of monosilicic acid in soils with $pH < 7.0$ is low when high quantities of Fe and Al oxides and hydroxides, and anionic adsorption are present [5, 23]. Under high Si concentrations in soil solution, $H_4SiO_4$ polymerizes to form polysilicic acid and complexes with organic compounds, which are not absorbed by plants. Dissolution mechanisms are complex and several intermediate stages are involved in deriving more soluble forms [5]. Monosilicic acids and their anions have weak acid properties and can react with many organic and inorganic compounds [24].

The solubility of primary and secondary minerals is one of the principal factors related to Si concentrations in soil solution [5, 10, 25]. Soils containing greater contents of primary minerals (feldspar, plagioclase, orthoclase) and clay minerals (montmorillonite, vermiculite, smectite, kaolinite) have higher total and soluble Si contents compared to weathered soils. The desilication process is more intense in tropical humid regions where high levels of iron and aluminum oxides are found in soils [4, 10]. This is well illustrated in the weathering sequence as a function of Soil Order [26], where Mollisols contain the highest quantity of Si-minerals, followed by Vertisols, Inceptisols, Alfisols, Ultisols, and Oxisols, with predominant contents of Fe-Al oxides. Other examples of the importance of soil mineralogy regarding solubility and availability of Si were provided by [20]. These authors showed that a soil derived from basalt rock (Tolga series) showed higher Si (23.7 mg $L^{-1}$ Si in 0.01 mol $L^{-1}$ $CaCl_2$ ) compared with the Si level (9.7 mg $kg^{-1}$) in a soil from granitic rock (Nicotine series), in sugarcane-growing areas of Australia. Not only the quantity of silicate minerals in soils is important to provide Si to plants, but also the Si-mineral type. Soils with elevated contents of silicate minerals such as quartz, which are commonly found in sand and silt fractions, may have low Si concentrations [4, 21]. The Si solubility of quartz is lower (3 to 7 mg $L^{-1}$ Si, pH 7.0) than that of some amorphous Si compounds (50–60 mg $L^{-1}$ Si), including phytoliths [5, 23].

Soil texture is another important factor influencing soluble Si in soil. Positive correlations between clay content and soluble Si in several solutions were reported for soils under sugarcane in South Africa [14, 27], Australia [20, 28], Hawaii [29, 30] and Brazil [21, 31, 32]. Low Si concentrations are commonly found in soils with clay values less than 35%, but some soil types, such as Kandiustalf, can provide higher soluble Si due to relatively high Si-mineral contents (Table 1). [21] showed higher Si contents extracted by 0.01 mol $L^{-1}$ $CaCl_2$ in Cerrado soils containing 60% clay levels (Table 2). However, the highest soluble Si was not obtained from soils with the highest clay content, but rather from the Rhodic Kandiudox, which is a younger soil, as indicated by its greater silt level (Table 2) and presence of kaolinite [33]. It explains the absence of a response in sugarcane stalk yield when rates of up to 4 t $ha^{-1}$ cement were applied to a Kandiustalf soil (< 35% clay) by [33].

Other important factors affecting Si concentration in soil solution are the Fe and Al oxides and organic matter contents in soils. The first studies on silicate fertilization in sugarcane were conducted in oxidic soils and produced impressive yield increases [30, 37, 38]. This beneficial effect of increased Si in

**Table 1** Contents of clay and Si extracted by two solutions in soils from São Paulo state, Brazil

| Soil type | Clay<br>% | Acetic acid (0.5 mol $L^{-1}$) | $CaCl_2$ (0.01 mol $L^{-1}$) | Reference |
|---|---|---|---|---|
| | | mg $kg^{-1}$ Si | | |
| Quartzipsamment | 6.0 | 3.3 | 2.4 | [34] |
| Rhodic Hapludox | 16.0 | 6.9 | 2.9 | [35] |
| Rhodic Hapludox | 22.0 | 8.1 | 4.9 | [34] |
| Rhodic Acrudox | 68.0 | 10.7 | 5.7 | [35] |
| Kandiustalf | 28.0 | 27.5 | 11.5 | [36] |

**Table 2** Physical characteristics, total contents of silica ($SiO_2$), aluminum and iron oxides, and Si concentration in $CaCl_2$ (0.01 mol $L^{-1}$) in Cerrado soils from Brazil

| Soils | Clay | Silt | $SiO_2$ | $Al_2O_3$ | $Fe_2O_3$ | Ki | Si |
|---|---|---|---|---|---|---|---|
| | | | % | | | | mg $kg^{-1}$ |
| Rhodic Hapludox | 82 | 7 | 18.1 | 31.4 | 9.5 | 0.98 | 4.2 |
| Rhodic Kandiudox | 77 | 16 | --- | --- | --- | --- | 30.0 |
| Rhodic Acrustox | 65 | 20 | 10.4 | 25.9 | 20.9 | 0.68 | 9.2 |
| Kandiustalf | 36 | 8 | --- | --- | --- | --- | 7.7 |
| Rhodic Haplustox | 17 | 1 | 7.2 | 6.9 | 5.4 | 1.34 | 2.6 |

Adapted from [21]

soil solution was a consequence of the decreased adsorption of Si by Fe and Al oxides [8, 9, 29]. Additionally, organic soils in the Histosols order are well-known for their low Si-minerals contents with consequent positive responses to silicate fertilization [39–44]. However, [45] reported that some organic soils from Florida (USA) had high Si-minerals content (> 35%) in the clay fraction, such as the Torry muck soil series, and silicate fertilization is not necessary to provide Si to sugarcane, in contrast to Lake Okeechobee.

Additionally, soil pH is not an intrinsic soil characteristic, and can be changed in accordance with the chemical management of soil, unlike other factors influencing Si concentration. Si concentration showed a positive correlation with soil pH in soils with contrasting physical and chemical characteristics under commercial sugarcane production in South Africa [27] and Brazil [31]. Although Si concentration can be increased with application of acidity correctors, some soils, especially loam-sandy and sandy soils, do not contain sufficient Si to supply a Si-accumulator crop such as sugarcane, grown over several years in the same place [20].

Increases in stalk yield using various sources of Si (crushed basalt, cement, slags) in soil were reported since the 1960s in sugarcane. Studies conducted in several countries have shown that soil characteristics such as mineralogical composition, texture, and contents of Fe and Al oxides and organic matter were critical to the success of silicon fertilization in this crop (Table 3). In addition, the soil pH must be considered before silicate applications. An assessment of the concentration in soils is essential for adequate recommendations for Si fertilization of sugarcane crops.

## 2.2 Silicon Status of Soils Under Sugarcane

Several extractant solutions have been used to obtain soluble Si concentrations in soil [8–12], which are commonly determined using the molybdenum blue method after the extraction procedure [22]. Widely used extractant solutions include water, 0.5 mol $L^{-1}$ $NH_4$-acetate, 0.005 mol $L^{-1}$ $H_2SO_4$, 0.025 mol $L^{-1}$ $H_2SO_4$, 0.01 mol $L^{-1}$ $CaCl_2$ and 0.5 mol $L^{-1}$ acetic acid. In general, the acidic solutions extract large concentrations compared to neutral solutions [9, 28], leading to overestimation of Si in calcareous soils [53] and in soils to which acidity correctors have been applied [21, 54]. Although the problems inherent in the use of each solution are still being debated, studies have been successfully conducted in an attempt to establish critical levels for soils under sugarcane in several countries.

**Table 3** Sugarcane yield responses (as a percentage of the untreated or lime-treated control) to source of Si incorporated before planting in field experiments under soils of contrasting soil texture

| Soil Texture | Source | Rate t/ha | Yield (%) | Country | Author |
|---|---|---|---|---|---|
| | Slag | 9.0 | 32 | Australia | [20] |
| | Slag | 12.0 | 35 | Australia | [20] |
| Clay, Fe and Al oxides | Slag | 8.0 | 34 | Hawaii | [46] |
| | Slag | 6–12 | 18–27 | Hawaii | [37] |
| | Slag | 4.5 | 29 | Hawaii | [29] |
| | Slag | 14.2 | 30 | Mauritius | [38] |
| | Slag | 14.2 | 20 | Mauritius | [47] |
| Clay | Slag | 2.8 | 6.5 | Brazil | [48] |
| | Slag | 9.0 | 13 | South Africa | [49] |
| Sand | Slag | 17.8 | 13 | USA | [42] |
| | Slag | 1.5 | 7–17 | Brazil | [34] |
| | Cement | 4.0 | 9.4 | Brazil | [50] |
| | Slag | 5.6 | 11–16 | Brazil | [51] |
| Organic soil | Slag | 17.8 | 13–22 | USA | [42] |
| | Slag | 6.7 | 12–24 | USA | [52] |
| | Slag | 20.0 | 39 | USA | [40] |
| | Slag | 15.0 | 68 | USA | [41] |
| | Slag | 6.7 | 25 | USA | [44] |

Water extraction was one of the first methods used to evaluate Si availability to sugarcane. In a study conducted in Hawaii (humic ferruginous latosol, humic latosol, low humic latosol, dark magnesium clay), [29] suggested the value of 90 mg $kg^{-1}$ Si in water (1:10 soil: solution, 4 h agitation) as a critical Si level for adequate sugarcane growth in soils developed from basalt rocks and in alluvial soils. They also found that Si extracted by water showed a strong correlation with leaf Si ($R^2 = 0.97$) extracted with trichloroacetic acid, unlike other solutions such as $H_2SO_4$, Ca ($H_2PO_4$), and HOAC. Based on field studies conducted during 1976–1982 in Hawaii, researchers proposed the application of silicate when Si concentration in soils was lower than 78 mg $kg^{-1}$ for sugarcane crop [51, 55]. The recommendation was 2.24 t $ha^{-1}$ of $CaSiO_3$ when silicate fertilization had been done within 2 years of planting sugarcane, and 4.48 t $ha^{-1}$ $CaSiO_3$ if no Si addition was done previously. They also suggested 2.55 t $ha^{-1}$ of silicate when the leaf Si concentration was less than 0.7% or the Mn/$SiO_2$ ratio was above 75 [51, 55]. However, water is not an adequate extractant because of its weak ionic strength, increasing the clay dispersion, causing underestimated values, especially in clay soils [9, 24, 32].

Although studies on the adequacy of Si levels in soils for sugarcane were reported only after 2001 [9, 20, 43–45], an increase in stalk yield was previously shown with cement application in several countries, such as Australia [9], South Africa [13, 49, 56] and Brazil [48, 50, 57]. One study involved the areas most commonly planted to sugarcane on the east coast of Queensland, Australia [20]. In these areas, the concentration of Si was evaluated in 0.01 mol$^{-1}$ $CaCl_2$ (1: 10) and 0.005 mol L$^{-1}$ $H_2SO_4$ (1:200). These authors also conducted six experiments in three contrasting soils with different rates of calcium silicate. At Innisfail, a 34% increase in stalk yield was obtained with a 9 t ha$^{-1}$ silicate application (189 t cane ha$^{-1}$; 8.6 mg kg$^{-1}$ soluble Si in 0.01 mol L$^{-1}$ $CaCl_2$) compared to the control treatment (128 t cane ha$^{-1}$) over two years. In Mossman soil (4.2 mg kg$^{-1}$ Si in $CaCl_2$ 0.01 mol L$^{-1}$), total yield increased to 161 t cane ha$^{-1}$ following application of 12 t ha$^{-1}$ of silicate compared with 105 t cane ha$^{-1}$ over two years, while in Bundaberg soil (9 mg kg$^{-1}$ Si in $CaCl_2$ 0.01 mol L$^{-1}$), silicate application at 12 t ha$^{-1}$ increased yield by 23% to 278 t cane ha$^{-1}$ over the control (213 t cane ha$^{-1}$). Based on these results, [20] suggested 10 mg kg$^{-1}$ soluble Si in 0.01 mol L$^{-1}$ $CaCl_2$ for adequate growth of sugarcane in Australia soils.

Silicate fertilization in sugarcane was studied in South Africa over the last decades, but only a few studies evaluated the soluble Si contents in soils [58–60]. Under field conditions, Keeping et al. (2013) reported increases in yield of plant cane and two ratoons using 8 t ha$^{-1}$ of silicate. The Si concentrations in soil extracted with 0.02N $H_2SO_4$ [37, 61] increased from 6.3 mg kg$^{-1}$ Si in the control treatment to 369 mg kg$^{-1}$ Si with silicate application in plant cane, while Si concentration in soil increased from 6.1 to 5.5 mg kg$^{-1}$ Si without Si to 319 and 99.8 mg kg$^{-1}$ Si with silicate application in the first and second ratoon, respectively. Additionally, [27] reported Si concentrations ranging from 5 to 123 mg kg$^{-1}$ Si in 0.01 mol L$^{-1}$ $CaCl_2$ and values from 2 to 293 mg kg$^{-1}$ Si in 0.02 mol L$^{-1}$ $H_2SO_4$ in 112 soils from principal soil types planted to sugarcane, including the following soil orders: Inceptisols, Alfisols, Mollisols, Vertisols, Oxisols, Entisols, and Ultisols [27]. In 28 sugarcane areas in their study, Si concentration in the leaves showed the highest correlation ($R^2 = 0.77$) with soluble Si in 0.01 mol L$^{-1}$ $CaCl_2$, in contrast to Si in 0.02 mol L$^{-1}$ $H_2SO_4$ ($R^2 = 0.47$).

In the United States, 0.5 mol L$^{-1}$ acetic acid is the most commonly used solution in studies of Si concentration in organic soils, almost 80% of which are planted to sugarcane in the Everglades area [44]. Positive responses to silicate fertilization in sugarcane have already been shown in these organic soils, and in sandy soils [39–42]. Initially, the recommendation for silicate fertilizer was based on sugarcane leaf analysis where values were less than 10 g kg$^{-1}$ Si in the TVD (top visible dewlap) leaf [62]. Later, silicate fertilization was also based on values of soluble Si in 0.5 mol$^{-1}$ acetic acid as required for rice crops [63] planted before sugarcane in crop rotation systems. For low (< 6 mg L$^{-1}$ Si), medium (6–24 mg L$^{-1}$ Si) and high (> 24 mg L$^{-1}$ Si) soluble Si levels in acetic acid, 1.5, 1.1, and zero t ha$^{-1}$ of silicate (20% Si) were indicated, respectively, for rice, followed by sugarcane crop. Despite low Si concentrations in organic soils (Histosols), some soil types have high silicate mineral contents, such as those located at Okeechobee in Florida, and, consequently, Si fertilization is not required [43]. This fact led to studies on Si fertilization in organic soils. [44] proposed a threshold level of 15 mg kg$^{-1}$ Si extracted by acetic acid (0.5 mol L$^{-1}$) for application of silicate in organic soils in the Everglades. Based on this study, they suggested the application of 6.7, 5.6, 4.5, 3.4, and 2.2 t ha$^{-1}$ of calcium silicate to soils with Si levels in the range: 0–5; 6–10; 11–15; 16–20, and 21–25 mg kg$^{-1}$ Si, respectively. According to the authors, these quantities are sufficient to supply Si over a 3-year cropping cycle. The strong correlation between Si contents extracted by acetic acid and Si in the plants was a consequence of the high buffering power of organic soils when acidity correctors such as lime or silicate are used, unlike most of the soils with clay contents lower than 35% (sandy, loamy sandy, sandy loam, sandy clay loam) from tropical humid areas.

In Brazil, the pioneering study of [32] on the evaluation of Si concentrations in soils using water and $CaCl_2$ (0.0025 mol$^{-1}$ and 0.01 mol L$^{-1}$) in 44 soils of Sao Paulo state was only followed decades later by experiments on silicate fertilization in sugarcane. Acetic acid extraction (0.5 mol L$^{-1}$) was only used to evaluate the Si concentration and responsiveness of soils to silicate fertilization for rice plants [64]. These authors obtained the best correlation between rice straw Si and soluble soil Si contents in acetic acid ($R^2 = 0.88$) and water ($R^2 = 0.84$), as opposed to $CaCl_2$ (0.0025 mol L$^{-1}$; $R^2 = 0.70$) and buffer solution (pH 4.0; $R^2 = 0.69$). Although water extraction showed a high correlation with Si in rice, the authors did not recommended it, in agreement with other studies [24, 32], due to the long time required for sedimentation of soil particles after the filtration process in clayed soils, which could make this method's inclusion in routine analysis difficult. However, later studies on soils with a wide range of mineralogical, physical and chemical characteristics, and incubated with lime and silicic acid [21] showed that acetic acid could overestimate soil Si concentration values. The low pH of the acetic acid solution produced large changes in pH of soils with a low buffering capacity, such as sandy and loamy sand soils.

Few studies have been carried out on Si fertilization in sugarcane through evaluation of soluble Si in soils in pots [19, 35, 58, 65–68] and under field conditions [31, 34, 58, 69, 70]. [68] reported increases in Si concentrations in sugarcane leaves and soluble Si in 0.01 mol $L^{-1}$ $CaCl_2$ when rates up to 400 kg $ha^{-1}$ Si were applied in a loamy sand soil. [35] have also shown a significant positive correlation between Si uptake and Si contents extracted by acetic acid (0.5 mol $L^{-1}$) and $CaCl_2$ (0.01 mol $L^{-1}$) in sand and loamy sand soils. In addition, application of silicate in the rows before sugarcane planting using rates up to 165 kg $ha^{-1}$ Si resulted in increased Si concentration in sugarcane leaves and Si extracted by acetic acid (0.5 $mol^{-1}$) in plant cane and first ratoon in a Rhodic Hapludox (16% clay) [34]. For soluble Si in $CaCl_2$, the correlation between soil Si and leaf Si concentration was only significant in the first ratoon. Acetic acid was the best solution for evaluation of Si availability to sugarcane plants in these studies [19, 34, 35], due to a similar soil pH in all treatments.

On the other hand, silicate application under sugarcane crop residues (dry leaves + tops) increased the Si concentration in $CaCl_2$ at 0–20 cm and 20–40 cm after 12 months, as shown by [70]. They evaluated the Si levels in $CaCl_2$ (0.01 mol $L^{-1}$), acetic acid (0.5 mol $L^{-1}$), KCl, and Na-acetate buffer in soils from eight commercial sugarcane areas of South Central Brazil, including clay, medium texture and sandy soils in plant and ratoon. The authors reported that acetic acid and KCl were more efficient in evaluating soluble silicon in three soils. They also suggested dividing the soils according to texture, in agreement with [21].

Finally, there is no calibration test at present for silicate fertilization in Brazilian soils. However, it has been accepted that values lower than 10 mg $kg^{-1}$ Si extracted with $CaCl_2$ (0.01 mol $L^{-1}$) in sugarcane research experiments justify Si supplementation, as proposed by [20] in Australia for soils with similar chemical characteristics. Also important, is that soils with clay values less than 35% are the most responsive to silicate applications. Nowadays, silicate recommendations can be made to totally or partially substitute the lime application for soil pH correction before planting, in accordance with [71]. These authors have also suggested quantities of silicate less than 800 kg $ha^{-1}$ when the soil pH is adequate for plant growth.

# 3 Silicon in Sugarcane

## 3.1 Silicon Uptake by Sugarcane

While for most plants the essentiality of Si has not yet been demonstrated, it is considered a beneficial element [6, 25]. Silicon is taken up by the roots, transported to the shoot by the xylem vessels, and, at least in rice, deposited as a double epidermal silica layer on the cell walls, strengthening the plant structure [72]. Most plant Si is opaline, with less than 1% soluble in the colloidal or ionic form, or combined with organic compounds [73]. Additionally, while most plant species are capable of taking up Si [6], sugarcane is considered a Si-accumulator plant. However, information is still scarce concerning the amounts of Si absorbed by sugarcane under field conditions, which vary as a function of soil texture, Si rates applied and plant age (Table 4).

Concerning sugarcane yield responses to silicate fertilization, [37] found that Si uptake increased from 61 kg $ha^{-1}$ in the control treatment to 207 kg $ha^{-1}$ of Si in the above-ground biomass after 14 months, following application of 12 t $ha^{-1}$ slag to a clay soil with high levels of oxides. In addition, [75] showed Si absorption of 379 kg $ha^{-1}$ Si in soils of Hawaii, while [38] reported 408 kg $ha^{-1}$ Si in above-ground biomass (tops + millable cane) in only one harvest in Puerto Rico. Later, [76] reported a sugarcane yield increase from 50 kg $ha^{-1}$ of stalk yield in the control treatment to 215 kg $ha^{-1}$ with 1.6 t $ha^{-1}$ of silicate in soil with pH 5.5, while lower values were obtained with pH 6.0 and pH 6.5.

Other studies have investigated Si uptake by sugarcane where silicate fertilization was not practiced. [18] reported 56 kg $ha^{-1}$ Si in leaves and 30 kg $ha^{-1}$ Si in stalks, i.e. a total of 86 kg $ha^{-1}$ Si in above-ground biomass for the second ratoon crop, in a sugarcane-growing region of Australia. These authors also verified that more recently released cultivars accumulated double the quantity of Si compared with those released between 1930 and 1980, although Si uptake was still the same (84 kg $ha^{-1}$ Si). The more recent cultivars absorbed 62 kg $ha^{-1}$ Si in leaves and 22 kg $ha^{-1}$ Si in stalks,

**Table 4** Si uptake in above-ground biomass of sugarcane grown under field conditions as a function soil texture, rate of silicate fertilization and plant age

| Soil texture | Rates of Silicate t $ha^{-1}$ | Plant Age Months | Si uptake kg $ha^{-1}$ | Author |
|---|---|---|---|---|
| Variable | 0 | 2nd ratoon | 86 | [18] |
| Clay | 0 | variable | 200–300 | [31] |
| Clay | 0 | variable | 215–795 | [74] |
| Medium texture | 0 | 36 (plant cane+2 ratoons) | 406 | [36] |
| Clay | 0 | 12 | 379 | [75] |
| Clay | 1.6 | 18 (plant Cane+1 ratoon) | 215 | [76] |
| Clay | 12 | 14 | 207 | [37] |
| Clay | 14 | 14 | 408 | [38] |

while the older cultivars showed an average of 36 kg ha$^{-1}$ Si in leaves and 40 kg ha$^{-1}$ Si in stalks. In India, quantities of Si uptake were between 215 and 795 kg ha$^{-1}$ in an average of 30 sugarcane genotypes evaluated under field conditions [74]. In Brazil, [77] observed 120 and 240 kg ha$^{-1}$ of Si in crop residue in nine cultivars after plant cane was grown in soil with high levels of mineral Si (11.5 mg kg$^{-1}$ Si $CaCl_2$; 27.5 mg kg$^{-1}$ acetic acid), while 100 and 172 kg ha$^{-1}$ of Si were recorded in the first and second ratoon, respectively. Among these cultivars, IAC91-1099 showed the greatest total uptake across 3 cycles (406.5 kg ha$^{-1}$ Si), which is still lower than in previous studies from Hawaiin soils. Recently, [31] reported quantities between 200 and 300 kg ha$^{-1}$ Si for one harvest of different cultivars, plant ages, and with and without silicate applications.

## 3.2 Silicon Concentrations in Sugarcane Leaves and Responses to Silicate Application

Silicon concentrations in sugarcane vary between tissues, and higher values are found in the leaves than in stalks [34, 36, 58, 78]. Regarding root tissues, [19] found values between 13 and 16 g kg$^{-1}$ Si in 6 months-old plants. [79] obtained increased Si from 10 g kg$^{-1}$ Si concentration in the roots in the control to 15 g kg$^{-1}$ Si with sodium silicate in 18 weeks-old plants. Values higher than 25 g kg$^{-1}$ Si Si in the roots were found in 23 and 26 weeks-old plants with sodium silicate applied in sandy loam soil [80, 81]. Additionally, leaf age also influences Si concentration, with values varying from 1.4 g kg$^{-1}$ Si in young leaves to 67 g kg$^{-1}$ Si in old leaves [50].

Differences between cultivars in sugarcane leaf Si concentrations are also commonly found in experiments conducted in pots and under field conditions. In Brazil, [82] reported values ranging from 10.3 to 19 g kg$^{-1}$ Si for leaves at harvest in 11 cultivars. [50] showed an average of 0.7, 10.4, and 11.4 g kg$^{-1}$ Si in the third leaf for RB72-454, SP79-1011 and SP71-6163, respectively, grown in sandy soil. Values higher than 10 g kg$^{-1}$ Si in TVD leaves at 8 months in IACSP 93-3046, IACSP 93-6006 and IAC 91-1099 cultivars were also shown by [36] in soil with high soluble Si. However, [34] found values of less than 6 g kg$^{-1}$ Si in TVD leaves of sugarcane grown in low Si content soil under field conditions, despite the higher values in SP89-1115 compared to RB86-7515 in plant cane and ratoon. In the United States, [83] obtained values between 6.4 and 10 g kg$^{-1}$ Si in 52 genotypes grown in sandy and organic soils (low available Si). In addition, values from 6.0 to 15.5 g kg$^{-1}$ Si were found in TVD leaves of plant cane and 4.0 and 8.7 g kg$^{-1}$ Si in second ratoon in 12 cultivars in Australia [18]. These authors also reported values from 0.8 to 2.5 g kg$^{-1}$ Si in the stalk of second ratoon cane. These results show that Si contents varied as a function of plant phase and Si fertilization.

There is also a strong correlation between Si concentration in the leaves and Si fertilization [4]. The quantity of silicate, soil type, and cultivar are important in these responses to Si fertilization. Under field conditions, [52] reported 2.78 g kg$^{-1}$ Si without Si treatment and 6.16 g kg$^{-1}$ Si with silicate (6.7 t ha$^{-1}$) for leaf Si concentration in the plant crop, and 2.5 and 5.5 g kg$^{-1}$ Si in the ratoon, respectively, in organic soil. As shown by [38], greater quantities applied in a clay soil with oxides resulted in leaf Si concentrations increasing from 5.1 g kg$^{-1}$ in the control treatment to 7.3 g kg$^{-1}$ Si with 7.1 t ha$^{-1}$ of silicate applied over an average of five cropping cycles. Using the same quantity, soil type and different cultivars, [47] verified that leaf Si concentration in plant cane of cultivar M93/48 was 5.7 g kg$^{-1}$ in the control and 9.1 g kg$^{-1}$ Si when treated with 7.1 t ha$^{-1}$ silicate, while the corresponding values in cultivar E1/37 were 4.9 and 6.8 g kg$^{-1}$ Si. Soil Si extracted using the Truog method was in the range of 36–110 mg kg$^{-1}$ Si. For the first ratoon, [47] also showed that leaf Si concentration increased in M93/48 from 6.3 g kg$^{-1}$ Si in the control to 9.9 g kg$^{-1}$ Si with silicate, and in E1/37 from 6.0 g kg$^{-1}$ Si (control) to 7.8 g kg$^{-1}$ Si (7.1 t ha$^{-1}$ silicate). These results showed that some cultivars are likely to have stronger responses to Si fertilization than others.

Positive responses to Si fertilization were also found by [58]. They showed Si concentrations in the TVD leaves increased from 3.2, 3.6 and 3.4 g kg$^{-1}$ Si without silicate in plant cane to 3.9, 4.2 and 4.7 g kg$^{-1}$ Si with 8 t ha$^{-1}$ of silicate. Higher applications were used by [41], who found that Si concentration in TVD leaves was 8.3 g kg$^{-1}$ without Si and 14.0 g kg$^{-1}$ Si with 12 t ha$^{-1}$ of silicate in a plant crop, and 3.1 for the control and 7.6 g kg$^{-1}$ Si with silicate in the ratoon crop. The Si in leaves and soil were determined, respectively, according to [30], and [29]. These authors demonstrated that Si in soil increased from 15 to 52 mg kg$^{-1}$ Si in plant cane, and from 10 to 28 mg kg$^{-1}$ Si the ratoon crop for the control and 12 t ha$^{-1}$ of silicate, respectively. However, low Si contents in the leaves were found by [84], even with similar quantities of silicate. These authors found Si concentrations in TVD collected at 7 months increased from 1.4 g kg$^{-1}$ Si for the control to 7.3 g kg$^{-1}$ Si for 12 t ha$^{-1}$ silicate in Mossman soil, while the values were 2.9 and 5.3 g kg$^{-1}$ Si in Innisfail and 4.7 and 7.4 g kg$^{-1}$ Si in Bundaberg, using the same silicate application rate. On the other hand, values between 1.0 and 21.3 g kg$^{-1}$ Si in the TVD leaves were found in 28 sugarcane production areas over a wide range of soils types with and without silicate fertilization [84].

Similar variations were also found in pot studies with variable Si sources, Si rates and pot sizes. [85] showed that TVD leaf Si of sugarcane plants grown in sandy soil in 100 L pots with 555 kg ha$^{-1}$ Si increased to values greater than 10 g kg$^{-1}$ Si at 8 months in the plant crop. [86] showed Si concentrations in TVD leaves increased from 3.75 g kg$^{-1}$ Si without Si application to 6.27 g kg$^{-1}$ Si at 6 months age and from 1.75 to 8.3 g kg$^{-1}$at 8 months, with a silicate rate in pots (100 L) equivalent to 600 kg ha$^{-1}$ Si. [19] found that 750 kg ha$^{-1}$ Si as silicate

Table 5 Threshold levels of Si in leaf tissues and silicate recommendations for sugarcane

| Country/state | Leaf tissue | Age months | Threshold Si (g kg$^{-1}$) | Silicate t ha$^{-1}$ | Reference |
|---|---|---|---|---|---|
| Australia | TVD leaf, without midrib | | 10.0 | --- | [20] |
| Florida | TVD leaf, without midrib | 4–6 | 10.0 | 2–10 | [39, 62] |
| | TVD leaf, without midrib | 7 | 5.0 | --- | [44] |
| Hawaii | 1–4 leaf | 9–15 | 5.0 | 1–5 | [55, 62, 88] |
| Mauritius | 3rd leaf | 6 | 11.7 | --- | [88] |
| | 3rd to 6th leaf | 3 | 10–20 | -- | [62] |
| South Africa | Green leaves | 4 | $<10$ | 1.5-9 | [56] |
| | TVD leaf, without midrib | 3–4 | 7 | --- | [90] |

produced Si concentrations greater than 10 g kg$^{-1}$ in TVD leaves at 6 months in sugarcane grown in 20 L pots with sandy soil. Using other Si sources, [60] reported that Si concentrations in the leaves at 6 months age increased from 1.3 g kg$^{-1}$ without Si to 2.3 g kg$^{-1}$ Si and 3.6 g kg$^{-1}$ Si with 4 and 8 t ha$^{-1}$ of silicate, respectively, for sugarcane planted in 6.4 L pots. However, data obtained from pot studies cannot simply be extrapolated to field conditions.

### 3.3 Diagnosis of Silicon Deficiency in Sugarcane Plants

The evaluation of Si concentration in sugarcane is done using several plant tissues, which varies between countries (Table 5). However, the central part (200 mm) of the TVD leaf without the midrib is now used worldwide. There are various extraction methods, including dry ashing [29], but the most frequently used is acid digestion [87] and determination is done by colorimetry. X-ray-fluorescence is also used as a standard method in the South African sugarcane industry and the calibration frequently checked using colorimetry [27]. The first studies to establish threshold Si levels in plant tissue were done in Mauritius [88], while in South Africa [56] and Hawaii [89] recommendations for silicate application were proposed based on analysis of leaf Si content.

The recommendation for silicate fertilization of soils under sugarcane production in Hawaii was also based on Si contents in soils. Research indicated application of 2.5 t ha$^{-1}$ of silicate to soils with less than 7 g kg$^{-1}$ Si, or when the Mn/SiO$_2$ ratio was above 75 [51, 55]. And [56] initially proposed 1 to 9 t ha$^{-1}$ of silicate based on leaf Si analysis in South Africa. Decades later, leaf Si values greater than 7.5 g kg$^{-1}$ are currently considered sufficient for growth in South African sugarcane [90].

Values lower than 10 g kg$^{-1}$ of leaf Si are generally considered as deficient for this Si-accumulator plant, and application of 2 to 10 t ha$^{-1}$ of silicate before sugarcane planting is recommended in Florida, United States [40, 62]. More recently, [44] suggested that levels greater than 7.0 g kg$^{-1}$ Si in TVD leaves were adequate for sugarcane plants grown in the Everglades region. Additionally, [43] proposed the utilization of soil Si contents extracted using 0.5 N acetic acid as a guide for the recommendation of silicate applications for sugarcane (Table 5), rather than leaf Si diagnosis, which can only be used to evaluate the plant Si status. In Australia, [20] reported that maximum yields of sugarcane were obtained at TVD leaf Si levels greater than 5.5 g kg$^{-1}$. These results were based on experiments involving different soil types, rates and sources of Si.

Studies on threshold Si levels in TVD leaves are still being conducted in Brazil, as well as the Si concentration in soils adequate to ensure no decline in sugarcane growth (loss of yield) due to Si deficiency. For example, [34] reported that under field conditions, the greatest stalk yield with Si concentrations lower than 7 g kg$^{-1}$ Si in the TVD leaf were obtained in plant cane, while in the first ratoon higher yields were obtained when TVD concentrations were greater than 10 g kg$^{-1}$ Si after silicate application (165 kg ha$^{-1}$ Si) applied in rows in Rhodic Hapludox soil (2.9 mg kg$^{-1}$ Si in 0.01 mol L$^{-1}$ CaCl$_2$). The higher values in the TVD leaves in the ratoon were associated with a concentration effect of Si as a consequence of the lower ratoon crop yield. However, threshold Si levels in Australia [20] and the United States [44] are now used as a reference in research studies, as at present there is no calibration test.

## 4 Conclusions

The reviewed outcomes show that enhanced yield from Si fertilization is still underestimated in sugarcane crops. This fact is associated with scarce information about: (a) soil type and Si levels of plant available contents in soil with positive responses to Si fertilization; (b) Si uptake in leaves and stalks, which is variable according to plant age, cultivar, soil type, and presence or absence of Si fertilization. It is concluded that low Si levels in soils for sugarcane are commonly found in the following situations: (a) soils with low pH, and high levels of iron and aluminum oxides; (b) loam-sandy and sandy soils; (c) organic soils. Additionally, Si levels in soils should be used to evaluate whether Si fertilization is necessary for sugarcane plants. Silicon fertilization should be applied when values less than 10 mg kg$^{-1}$ Si in 0.01 mol L$^{-1}$ $CaCl_2$ in mineral soils or less than 15 mg kg$^{-1}$ Si in 0.5 mol L$^{-1}$ acetic acid in organic soils. Moreover, the evaluation of leaf tissues is also reliable for showing adequate Si supply to sugarcane. Values less than 6 g kg$^{-1}$ of Si in TVD leaves collected during grand growth period are not sufficient for sugarcane plants to achieve maximum yield. Even thought Si levels in soil and plant indicated in this review are reliable and provided from field conditions, further studies would contribute to maximizing yield and additional benefits of Si fertilization, and to sustainability of sugarcane agriculture.

### 4.1 Future Perspectives

The impact of Si fertilization in increasing sugarcane biomass and sucrose yield, and ameliorating environmental stresses could be enhanced by joint efforts among researchers worldwide, conducting experiments in commercial sugarcane areas during several harvests and that focus on:

* The definition of soil Si levels responsive to Si fertilization, especially those based on the Si extractants commonly used for sugarcane soils (0.01 mol L$^{-1}$ $CaCl_2$; 0.5 mol L$^{-1}$ acetic acid);
* Calibration tests of Si sources and rates of application required to provide adequate Si nutrition to sugarcane;
* Management of Si sources (powder or solution/suspension) under field conditions over multiple crop cycles.

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## Compliance with Ethical Standards

**Conflict of Interest** The authors declare that there is no conflict of interest.

**Research Involving Human Participants and or Animals** The authors declare this study does not contain studies with human participants or animals.

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