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ORIGINAL PAPER

# Silicate Fertilization in Sugarcane: Silicon Availability, Uptake, and Recovery Index Over Two Consecutive Cycles

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## Abstract

Multiple harvests of sugarcane with high silicon (Si) uptake decrease Si soil levels, and Si fertilization may be necessary. The association of Si levels in soil, uptake, and recovery from silicate could enhance the understanding of the efficiency of Si fertilization. The objectives were to evaluate the effects of silicate rates applied in furrows at planting on soluble Si contents at two depths, Si uptake, the correlation between Si in the soil and Si in the leaves, and the recovery index (RI) of Si from silicate during two consecutive cycles of sugarcane cultivars. The experiment was conducted in randomized blocks with four Si rates (0, 55, 110, and 165 kg $ha^{-1}$ Si) as silicate and two sugarcane cultivars (IAC87-3396 and SP89-1115) in two consecutive cycles. Silicate fertilization increased the Si extracted by 0.5 mol $L^{-1}$ acetic acid and 0.01 mol $L^{-1}$ $CaCl_2$ at 0–25 cm after 6, 17, and 29 months, while this only occurred with acetic acid at 25–50 cm and $CaCl_2$ after first ratoon. Both Si extractants showed a satisfactory correlation ($R = 0.40–0.52$) with Si concentration in the top visible dewlap leaves, enabling the evaluation of the Si availability in soil samples from 0 to 25 cm and 25 to 50 cm after 6 months. There was 40% Si recovery from silicate over the two consecutive cycles. Si application in furrows at planting is a potential tool to increase Si availability in soil at 0–25 cm, Si uptake by stalks, and Si recovery from silicate after two consecutive cycles.


**Keywords** *Saccharum* spp. · Absorption · Field conditions · Beneficial element · Plant nutrition

## 1 Introduction

Silicon (Si) is the principal element in soils (Haynes 2014, 2017), but high Si contents available to plants are not commonly found in agricultural areas because Si solubility is influenced by chemical, physical, and mineralogical characteristics inherent to each soil (Camargo and Keeping 2021) . Although Si is not classified as an essential element for growth by Arnon and Stout's criteria, most plants, including sugarcane, which is considered a Si-accumulating plant, take up Si from soil solution (Epstein 2009). This crop is important to the production of sugar, biofuel, and bioenergy (Ferreira et al. 2017) and is planted in various soil types, including those with low soluble Si contents, such as sandy and sandy loam soils (Camargo et al. 2013b). Areas that have experienced multiple harvests of sugarcane over multiple years and that are associated with low Si levels in soils could require Si supplementation.

Improvements in yield (Camargo and Keeping 2021; de Camargo et al. 2020a, b) and decreases in the deleterious effects of biotic (Camargo et al. 2013a; de Camargo et al. 2020a, b; Keeping et al. 2013; Majumdar and Prakash 2020) and abiotic stresses (Bezerra et al. 2019; de Camargo et al. 2017, 2019; Verma et al. 2020) have been reported with Si fertilization in sugarcane. Although several experiments on Si benefits in sugarcane have been conducted, few studies have assessed soluble Si in soils with Si fertilization in pots (Camargo et al. 2013b; de Camargo et al. 2017, 2019, 2020a, b; Keeping and Meyer 2006; Keeping et al. 2017; Sousa et al. 2010) and under field conditions (Borges et al. 2016; Crusciol et al. 2017, 2018; Keeping et al. 2013, 2017).

Moreover, the quantification of Si uptake is an important tool to enhance the understanding of the responses of sugarcane crops to Si fertilization under field conditions.

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Additionally, the dry biomass of stalks and leaves has not been measured as frequently Si contents after harvest, making it difficult to estimate the Si extracted during each cycle. Quantities between 86 and 795 kg $ha^{-1}$ of Si (Berthelsen et al. 1999; Borges et al. 2016; Crusciol et al. 2018) were reported in experiments without Si application. On the other hand, silicate experiments using rates of 1.6, 12, and 14.2 t $ha^{-1}$ Si showed 215, 207, and 408 kg $ha^{-1}$ Si in aboveground biomass (leaf + stalk) after 18 (Khalid et al. 1978), 14 (Ayres 1966), and 14 (Ross et al. 1974) months, respectively. Few studies have assessed both soluble Si and Si uptake as a function of Si fertilization in pots (Camargo et al. 2013b; de Camargo et al. 2020a, b; Sousa et al. 2010) and under field conditions (Ayres 1966; Borges et al. 2016; Khalid et al. 1978).

Furthermore, Si fertilization is commonly applied as silicate in broadcast fertilization and incorporated in cultivated areas before sugarcane planting using rates similar to liming rates (Berthelsen et al. 2003; Brassioli et al. 2009; Camargo and Keeping 2021; McCray and Ji 2012, 2018), but Si fertilization could also be used at lower rates, such as application in furrows at planting, as shown by Keeping et al. (2013). The greater contact between silicate and sugarcane root systems could improve the recovery of Si with the application of Si in furrows at planting than with broadcast fertilization. However, few studies have shown Si recovery in aboveground sugarcane in pots (Sousa et al. 2010), under field conditions (Khalid et al. 1978) or in furrows at planting. A comparison of data on soluble Si contents in soil, uptake by sugarcane, and recovery from silicate applied under field conditions over multiple cycles would enhance the understanding of Si dynamics in the soil-sugarcane system and the efficiency of Si fertilization in supplying Si to sugarcane crops over cycles.

Therefore, the objectives of this study were to evaluate the effects of silicate rates applied in furrows at planting on soluble Si contents by two extractants in soil samples at two soil depths (0–25 cm and 25–50 cm), Si uptake by stalk and leaves, the correlation between Si in the soil and Si in the leaves, and the Si recovered during two consecutive cycles of sugarcane cultivars. It was hypothesized that (a) Si rates applied in furrows at planting would increase the Si extracted in acetic acid (0.5 mol $L^{-1}$) and $CaCl_2$ (0.01 mol $L^{-1}$) at depths of 0–25 cm and 25–50 cm as a result of greater contact between fertilizer and the root system to release Si from silicate in the two consecutive sugarcane cycles; (b) the Si levels in the soil of both soil extractants would have a strong correlation with the increase in the Si concentration in the TVD leaves as a function of applied Si; and (c) the Si rates applied in furrows at planting would increase the Si recovered due to the increase in Si solubility in the soil during two consecutive cycles.

## 2 Material and Methods

### 2.1 Experimental Design and Growth Conditions

The experiment was conducted in a commercial sugarcane area in Piracicaba (22° 42′ 30″ S; 47° 38′ 01″ W), São Paulo state (SP), Brazil, in planted cane (March 2009 to August 2010) and the first ratoon (August 2010 to August 2011). Soil samples were collected at 0–25 cm and 25–50 cm before planting, and for the chemical analysis (Raij et al.1997), the total contents of $SiO_2$, $Fe_2O_3$, and $Al_2O_3$ (Vettori 1969) and soluble Si contents in 0.05 mol $L^{-1}$ acetic acid and 0.01 mol $L^{-1}$ $CaCl_2$ (Korndörfer et al. 1999) were determined (Table 1). The minimum and maximum temperature and rainfall were 14.6 °C, 28.4 °C, and 1788 mm during the plant cane and 14.6 °C, 29.0 °C, and 1652 mm during the first ratoon, respectively.

Four Si rates (0, 55, 110, and 165 kg $ha^{-1}$ Si) and two sugarcane cultivars (IAC87-3396 and SP89-1115) were tested in a completely randomized factorial design (4 × 2) with four replications. Silicate (steel slag, powder, 262.1 g $kg^{-1}$ Ca, 56.8 g $kg^{-1}$ Mg, 108.4 g $kg^{-1}$ Si, Harsco®, Uberaba-MG) was used as the Si source. Lime (343 g $kg^{-1}$ Ca and 96 g $kg^{-1}$ Mg) and/or $MgCl_2$ (11.9% Mg) were also applied

**Table 1** Chemical, physical, and mineralogical characteristics of Rhodic Hapludox soil samples collected at depths of 0–25 and 25–50 cm before treatment applications

| Soil characteristics | 0–25 cm | 25–50 cm |
|---|---|---|
| Organic matter [(1)] (g $dm^{-3}$) | 16.0 | 10.0 |
| pH ($CaCl_2$ 0.01 mol $L^{-1}$) | 5.2 | 5.0 |
| P [(2)] (mg $dm^{-3}$) | 14.0 | 9.0 |
| K[(3)] ($mmol_c$ $dm^{-3}$) | 1.0 | 0.8 |
| Ca [(3)] ($mmol_c$ $dm^{-3}$) | 22.0 | 17.0 |
| Mg[(3)] ($mmol_c$ $dm^{-3}$) | 7.0 | 6.0 |
| Cation exchange capacity ($mmol_c$ $dm^{-3}$) | 55.0 | 46.0 |
| Base saturation (BS %) | 55.0 | 52.0 |
| Aluminum saturation (m%) | 0 | 4.0 |
| Si, 0.5 mol $L^{-1}$ acetic acid (mg $kg^{-1}$) | 6.9 | 6.5 |
| Si, 0.01 mol $L^{-1}$ $CaCl_2$ (mg $kg^{-1}$) | 2.9 | 3.2 |
| $SiO_2$ [(4)] (%) | 4.1 | |
| $Al_2O_3$ [(4)] (%) | 6.5 | |
| $Fe_2O_3$ [(4)] (%) | 3.1 | |
| Clay (%) | 16.0 | |
| Loam (%) | 2.0 | |
| Sand (%) | 82.0 | |

[(1)]Walkley and Black method; [(2)]extracted by anion-exchange resin; [(3)]ammonium acetate method used in routine chemical soil analysis for evaluation of soil fertility (Raij et al. 1997); [(4)]total contents by $H_2SO_4$ method (Vettori 1969) in the furrows at planting when necessary to provide the same quantities of Ca and Mg in all treatments. Cultivars were chosen due to their high yields, sugar contents, and sprouting rates under sugarcane residue mulch. Five 10-m rows were used for each plot.

Silicate treatments and basal fertilization were applied in the furrows at planting (March 21, 2009) and covered by a rotavator. Basal fertilization using nitrogen, phosphorus, and potassium was based on initial soil analyses (Table 1), according to Raij et al. (1997). The quantities used were 40 kg $ha^{-1}$ of N, 100 kg $ha^{-1}$ of $P_2O_5$, and 100 kg $ha^{-1}$ of $K_2O$ (10–25-25) at fertilization during planting. After 30 days of planting, 40 kg $ha^{-1}$ N as ammonium sulfate (20% N) and 60 kg $ha^{-1}$ $K_2O$ as KCl (60% $K_2O$) were applied at the surface of the sugarcane area. During the first ratoon, 100 kg $ha^{-1}$ of N; ammonium sulfate) and K (60 kg $ha^{-1}$ of $K_2O$; KCl) were also applied at the surface, according to Raij et al. (1997).

### 2.2 Si Contents in Soil

Soil samples were collected from depths of 0–25 cm and 25–50 cm 6, 17 (plant cane), and 29 (first ratoon) months after silicate application. The soluble Si contents were determined in acetic acid (0.5 mol $L^{-1}$) and $CaCl_2$ (0.01 mol $L^{-1}$) according to Korndörfer et al. (1999).

### 2.3 Si Contents in Plant

For the evaluation of the Si concentrations, twenty of the youngest fully expanded leaves (top visible dewlap, TVD) without midribs (Anderson and Bowen 1992) were collected in each plot 9 months after sprouting (December 2009) in the plant cane and in March 2011 in the first ratoon. The Si contents in stalks and straw (old and new leaves + tops) were also evaluated at harvest of plant cane (17 months) and first ratoon (29 months). Samples were collected from 1 m of each row of sugarcane per plot.

The silicon contents in the dry matter tissue of the TVD leaves, straw, and stalks were determined according to Elliot and Snyder (1991) modified. Dry and ground leaves and stalks (0.100 g) and 2 mL of $H_2O_2$ solution (50%, v/v) were added to 100-mL polyethylene tubes that were previously washed with 0.1-M NaOH and distilled water. This solution was shaken for a few seconds, and it was added 3 mL of NaOH (1:1). Tubes were autoclaved for 1 h at 1.5 atm and 123 °C. Then, 45 mL of distilled water was added to tubes, and the extract was transferred to a plastic bottle. After 12 h of rest, 1-mL aliquot of the extract supernatant, 19 mL of distilled water, 1 ml of HCl (1:1), and 2 ml of ammonium molybdate were transferred to a plastic cup, and the samples were shaken. After 5 min, 2 mL of oxalic acid was added with stirring. The reading was performed in a spectrophotometer (410 nm).

### 2.4 Recovery Index of Si (RI)

The silicon uptake by the straw and stalks was determined by multiplying the Si content by the dry matter weight. The Si uptake by the sugarcane from silicate (SiFF) was calculated using the following equation: SiFF = Si uptake—Si uptake by the control (Khalid et al. 1978; Sousa et al. 2010). The recovery index of Si (RI) in plant cane and first ratoon with Si application was also calculated using RI (%) = (Si uptake by sugarcane from silicate/Si applied) *100.

### 2.5 Statistical Analysis

Analyses of variance of the data were performed using the F test. The effects of cultivars were analyzed by Tukey's test, and the Si rates were analyzed by linear and polynomial regression using the SAS (Statistical Analysis System) program.

#### 2.5.1 Results

### 2.6 Silicon Contents in Soil and TVD Leaves

Silicate fertilization applied in the furrows at planting influenced ($p < 0.05$) the Si contents extracted by both extractants, and no effects on the cultivars were found in any of the three periods of evaluation (Table 2). No effect of Si fertilization was found on Si contents in the soil samples at the 25–50 cm depth, except at 6 and 29 months using acetic acid (Fig. 1A, C). There was also a significant effect (Table 2) of Si application on soil Si at 25–50 cm at 29 months with $CaCl_2$. The Si contents extracted by acetic acid (0.5 mol $L^{-1}$) and $CaCl_2$ (0.01 mol $L^{-1}$) in the soil samples at the 0–25 cm depths increased as a function of the Si rates applied after 6 months, 17 months, and 29 months (Fig. 1A–D). In addition, the Si contents in the superficial layers were superior to those observed at the 25–50 cm depth (Table 2).

The correlation between the Si concentration in TVD leaves and the Si contents extracted by acetic acid in the soil samples at 0–25 cm showed values greater than 0.50 (Fig. 2A) as did those extracted by $CaCl_2$ in samples at 25–50 cm (Fig. 2D) at 6 months. This result also occurred for the Si levels in acetic acid in the soil at the 0–25 cm depth after 29 months of silicate application (Fig. 2C). Additionally, an average correlation of 0.47 was obtained between the Si in the TVD leaves and the soluble Si concentrations in $CaCl_2$ in the soil samples at 0–25 cm (Fig. 2D, E, and F).

**Table 2** Soluble silicon in acetic acid 0.5 mol $L^{-1}$ and $CaCl_2$ 0.01 mol $L^{-1}$ from soil samples collected at 0–25 and 25–50 cm depths after 6, 17, and 29 months of silicate application in Rhodic Hapludox soil grown with two sugarcane cultivars ($n=4$ replications)

| Si | Plant cane (6 months) | | | | Plant cane (17 months) | | | | First ratoon (29 months) | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 0–25 cm | | 25–50 cm | | 0–25 cm | | 25–50 cm | | 0–25 cm | | 25–50 cm | |
| | SiAA[1] | SiCC[2] | SiAA[1] | SiCC[2] | SiAA[1] | SiCC[2] | SiAA[1] | SiCC[2] | SiAA[1] | SiCC[2] | SiAA[1] | SiCC[2] |
| kg $ha^{-1}$ | mg $kg^{-1}$ | | | | | | | | | | | |
| | IAC87-3396 | | | | | | | | | | | |
| 0 | 17.4 | 4.3 | 7.5 | 3.2 | 23.2 | 5.1 | 8.2 | 3.7 | 13.1 | 4.5 | 6.9 | 2.9 |
| 55 | 27.8 | 6.4 | 11.2 | 4.8 | 21.1 | 5.6 | 10.6 | 4.1 | 18.2 | 5.2 | 8.3 | 3.6 |
| 110 | 30.8 | 6.4 | 10.0 | 4.1 | 17.1 | 5.4 | 8.9 | 3.8 | 17.0 | 5.1 | 7.4 | 3.4 |
| 165 | 27.4 | 6.2 | 10.4 | 4.4 | 40.2 | 6.7 | 8.3 | 3.9 | 20.0 | 6.1 | 13.9 | 3.8 |
| | SP89-1115 | | | | | | | | | | | |
| 0 | 11.6 | 3.4 | 6.2 | 3.1 | 15.4 | 4.5 | 6.7 | 3.7 | 11.5 | 3.8 | 6.8 | 2.7 |
| 55 | 22.1 | 6.1 | 9.1 | 2.8 | 10.3 | 4.0 | 5.5 | 3.5 | 12.6 | 4.0 | 9.6 | 3.2 |
| 110 | 20.4 | 7.4 | 9.2 | 3.7 | 31.6 | 5.7 | 9.1 | 4.0 | 19.7 | 4.9 | 8.9 | 3.4 |
| 165 | 35.8 | 7.7 | 11.4 | 4.1 | 20.8 | 5.3 | 8.9 | 3.8 | 31.9 | 6.8 | 10.7 | 4.1 |
| | Prob > F | | | | | | | | | | | |
| Cult. (C) | 0.552 | 0.465 | 0.365 | 0.171 | 0.066 | 0.050 | 0.09 | 0.467 | 0.618 | 0.267 | 0.889 | 0482 |
| Rate (R) | 0.001 | 0.003 | 0.015 | 0.513 | 0.014 | 0.107 | 0.578 | 0.750 | 0.051 | 0.004 | 0.002 | 0.001 |
| C*R | 0.551 | 0.265 | 0.579 | 0.537 | 0.505 | 0.332 | 0.089 | 0.373 | 0.328 | 0.527 | 0.103 | 0.295 |
| | Average cultivars | | | | | | | | | | | |
| IAC873396 | 25.8a | 5.8a | 5.2a | 52.2a | 25.4a | 5.7a | 8.9a | 3.8a | 17.2a | 5.2a | 9.1a | 3.4a |
| SP891115 | 24.7a | 6.2a | 4.8a | 56.2a | 19.5a | 4.8a | 7.5a | 3.7a | 18.9a | 4.8a | 9.0a | 3.3a |
| MSD[3] | 3.8 | 1.0 | 0.4 | 10.8 | 6.3 | 1.8 | 1.7 | 0.3 | 7.0 | 0.8 | 1.5 | 0.3 |

[1]Sia = Si in acetic acid 0.5 mol $L^{-1}$; [2]Sic = Si in $CaCl_2$ 0,01 mol $L^{-1}$; [3]*3MSD* minimum significant difference. **Means followed by the same letter in the column do not differ based on a Tukey's test ($p<0.05$); *ns* nonsignificant; *significant at a 5% significance level

### 2.7 Silicon Uptake and Biomass Production of Sugarcane

The dry weight biomass of the leaves and stalks was only influenced by cultivar, and IAC87-3396 had the highest leaf biomass and stalk biomass in both harvests (Table 3). The leaf and stalk biomasses were in the ranges of 4.51–8.64 t $ha^{-1}$ and 63.59–76.73 t $ha^{-1}$ for the planted cane and 2.31–4.89 and 26.42–53.99 for the first ratoon, respectively.

A linear increase in the function of the Si rates ($x$) applied to the soil was obtained for Si uptake (y) by the stalks and by whole plant in both cycles. The linear regression was significant ($p<0.05$, F test) for the Si uptake by the stalks (plant cane: $y=3.005+0.0162\ x$, $R^2=0.83$*; first ratoon: $y=3.005+0.0162\ x$, $R^2=0.83$*) and total uptake (plant cane: $\hat{y}=3.005+0.0162\ x$, $R^2=0.83$*; first ratoon: $y=3.005+0.0162\ x$, $R^2=0.83$*). Cultivars did differ in their leaf and stalk Si uptake during the harvest of the first ratoon, and IAC87-3396 had the highest uptake values (Table 3). SP89-1115 had the highest values of Si uptake for the stalks only for the planted cane (17 months). The quantities of Si in the leaves varied between 31.20 and 42.70 kg $ha^{-1}$ Si in the planted cane and 29.76 and 91.26 kg $ha^{-1}$ Si in the first ratoon. For the stalks, the quantities were in the range of 6.38–15.68 kg $ha^{-1}$ Si (Table 3).

### 2.8 Recovery Index of Si from the Applied Silicate

The Si rates applied in the furrows at the planting of the sugarcane showed greater Si recovery in the plant cane than in the first ratoon, as shown by the recovery index of Si from the applied silicate (RI). The RI values were 9.3, 4.0, and 4.0 greater in the plant cane than in the first ratoon for IAC87-3396 with 55, 110, and 165 kg $ha^{-1}$ Si, respectively, and 20.7, 13.1, and 22.4 greater for SP89-1115 (Table 4). In addition, the RI was 36.6 and 43.6%, respectively, for IAC87-3396 and SP89-1115, after the two consecutive harvests.

#### 2.8.1 Discussion

Silicate fertilization applied in the furrows at planting increased the Si extracted by 0.5 mol $L^{-1}$ acetic acid and 0.01 mol $L^{-1}$ $CaCl_2$ in samples collected at 0–25 cm after 6, 17, and 29 months. A linear increase was also shown in the Si contents extract with acetic acid in samples after 6

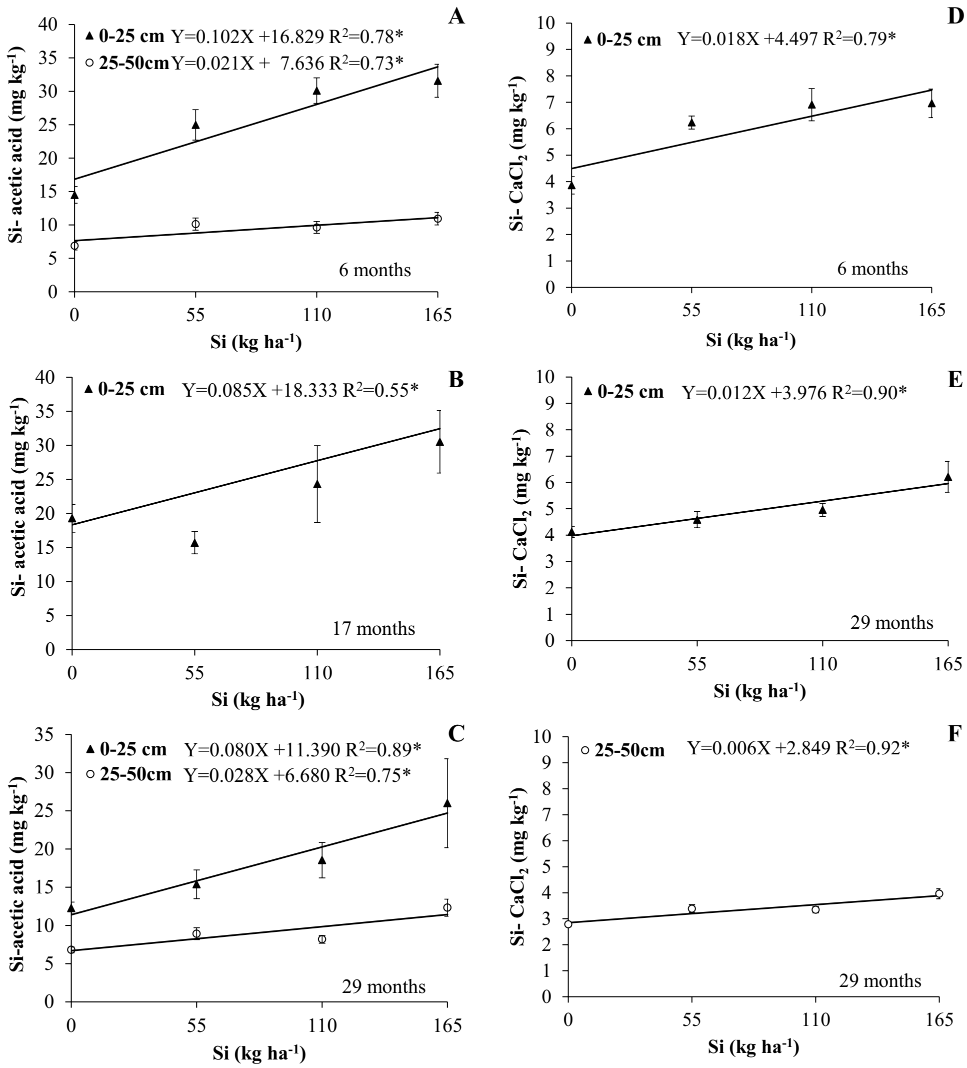


**Fig. 1** Soluble silicon contents in 0.5 mol $L^{-1}$ acetic acid (**A**, **B**, **C**) and 0.01 mol $L^{-1}$ $CaCl_2$ (**D**, **E**, **F**) in soil samples collected at 0–25 cm (▲——) and 25–50 cm (○——) 6, 17, and 29 months after sugarcane planting as a function of Si application ($p < 0.05$). $n = 4$ repetitions. The linear regressions applied used the mean values of two cultivars. *Significant by the F test ($p < 0.05$). Standard error bars are included in all figures. $n = 4$ repetitions

and 9 months and with $CaCl_2$ after 29 months for samples collected at 25–50 cm. Both Si extractants showed satisfactory correlations ($R = 0.40$–$0.52$) with the Si concentrations in the TVD leaves to evaluate the Si availability of the soil samples at 0–25 cm in all evaluations and at 25–50 cm after 6 months. Increased Si levels in soil as a function of Si fertilization were followed by Si uptake in the stalks, which reached 83 kg $ha^{-1}$ without Si and 154 kg $ha^{-1}$ with 165 kg $ha^{-1}$ applied Si in both harvests. An average of both cultivars showed 40.6% Si recovery from silicate after 29 months with 165 kg $ha^{-1}$ Si applied in soil. These results confirmed that Si fertilized in furrows at planting could be an alternative management option to supply Si to sugarcane crops.

In this study, the initial Si levels in the soil (Table 2) were less than the 10 mg $kg^{-1}$ Si in 0.01 $CaCl_2$ mol $L^{-1}$, which is low enough to produce a response to Si fertilization in sugarcane (Berthelsen et al. 2003) and has not been evaluated in several experiments, explaining the positive effect of Si fertilization on the Si levels in both extractants in the soil and the Si concentrations in the TVD leaves. The responsiveness to Si fertilization was also associated with high sand contents because the concentration of soluble and available Si is low in quartz ($SiO_2$), which was the major component of the soil studied (Camargo and Keeping 2021; Haynes 2017). Additionally, the highest Si concentrations in both extractants at 0–25 cm in all evaluations were due to silicate being applied in the furrows at planting, where the soil samples were collected. These concentrations could also be associated with higher values of organic matter in this superficial layer (Table 1) because it is a Si source in soil. However, the Si levels after Si fertilization, including 165 kg $ha^{-1}$ Si, were less than those proposed as adequate (10 mg $kg^{-1}$ Si soluble in 0.01 mol $L^{-1}$ $CaCl_2$) by Berthelsen et al. (2003). These results showed that the highest Si rates could be applied in the furrows at planting to supply Si to sugarcane crops. As silicate is also an acidity corrector, the highest levels were

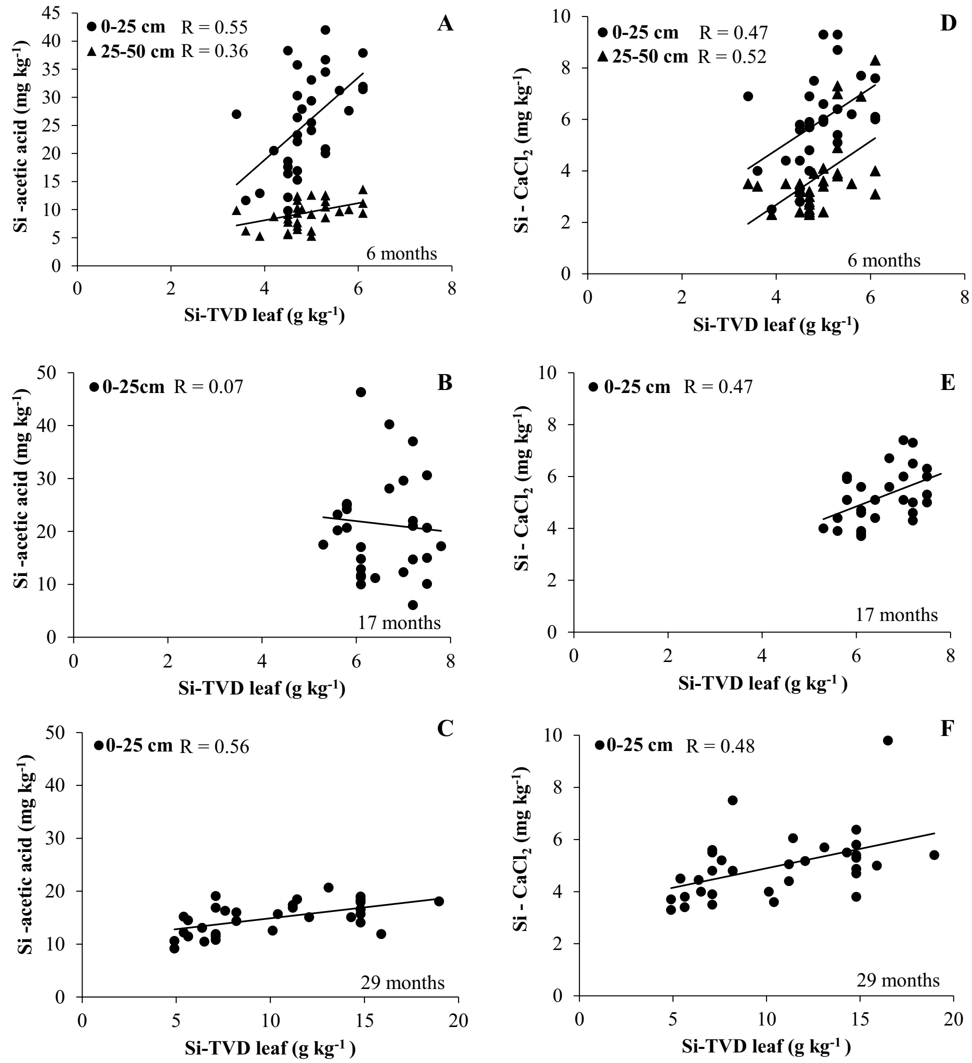


**Fig. 2** Correlation between Si concentration in the top visible dewlap (TVD) leaf and soluble silicon contents in 0.5 mol $L^{-1}$ acetic acid (**A**, **B**, **C**) or 0.01 mol $L^{-1}$ $CaCl_2$ (**D**, **E**, **F**) in soil samples collected at 0–25 cm (●——) and 25–50 cm (▲——) 6, 17, and 29 months after sugarcane planting as a function of Si application ($p < 0.05$). $n = 4$ repetitions. The linear regressions applied used the mean values of two cultivars. $n = 8$ repetitions

not used in this study to avoid excessive soil pH increases, which could reduce micronutrients availability in soil, but further studies are necessary.

Acetic acid (0.5 mol $L^{-1}$) measures easily soluble Si and some exchangeable Si, while dilute solutions such as $CaCl_2$ (0.01 mol $L^{-1}$) extract only easily soluble Si (Berthelsen et al. 2001). Therefore, the highest Si concentrations are usually obtained in acetic acid rather than in $CaCl_2$, as shown in this study. These higher values are due to the low pH (1.0–2.0) of acetic acid, which can lead to extraction of the unavailable Si fraction when acidity correctors such as lime and/or silicate are applied in soil, as has been reported previously (Camargo et al. 2007; Camargo and Keeping 2021; Pereira et al. 2004). As similar quantities of Ca and Mg were used in all plots in this study, no difference in soil pH among the treatments (data not shown) was found, and consequently, there was no overestimation of the Si levels extracted by acetic acid. Additionally, the strong correlation of the Si concentration in the TVD leaves and their Si levels in the soil confirmed that acetic acid was able to determine Si availability in soil in this study.

The positive correlation between the Si contents in the TVD leaves and the Si in the soil extracted by $CaCl_2$ from the soil samples from 0 to 25 cm in all periods evaluated and after 6 months at 25–50 cm showed satisfactory potential to evaluate Si availability in soil. Although acetic acid and $CaCl_2$ have been used to evaluate Si availability in the USA (McCray and Ji 2018) and Australia (Berthelsen et al. 2003), respectively, for sugarcane crops, it is worth noting that each has problems, as shown by Camargo and Keeping (2021), and both extractants should be used in future studies on Si fertilization in sugarcane.

There was also a decrease in the Si concentrations in the soil with both extractants after 6 months to 29 months, as shown in this study. The Si uptake during two consecutive harvests and leaching could explain these results. These results were in agreement with those of several studies that evaluated Si levels in the soil over cycles of sugarcane under

**Table 3** Dry weight biomass and Si uptake by stalks and leaves in plant cane and first ratoon of two sugarcane cultivars grown on a Rhodic Hapludox with varying rates of Si application

| Si | Plant cane | | | | | First ratoon | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| kg ha$^{-1}$ | Biomass (t ha$^{-1}$) | | Uptake(kg ha$^{-1}$) | | | Biomass (t ha$^{-1}$) | | Uptake(kg ha$^{-1}$) | | |
| | Leaves | Stalks | Leaves | Stalks | Total | Leaves | Stalks | Leaves | Stalks | Total |
| | IAC87-3396 | | | | | | | | | |
| 0 | 6.99 | 63.59 | 32.37 | 29.76 | 62.13 | 4.89 | 53.99 | 13.81 | 6.58 | 20.39 |
| 55 | 7.38 | 72.02 | 31.20 | 50.41 | 81.61 | 4.46 | 37.95 | 14.89 | 7.59 | 22.48 |
| 110 | 7.22 | 68.95 | 33.85 | 52.26 | 86.11 | 4.77 | 47.64 | 13.29 | 13.04 | 26.32 |
| 165 | 8.64 | 76.73 | 42.77 | 76.73 | 119.50 | 4.68 | 41.49 | 15.68 | 18.93 | 34.61 |
| | SP89-1115 | | | | | | | | | |
| 0 | 4.51 | 69.78 | 24.47 | 44.66 | 69.13 | 2.31 | 26.42 | 6.38 | 7.81 | 13.40 |
| 55 | 7.07 | 74.59 | 37.95 | 63.00 | 100.95 | 2.63 | 33.03 | 6.92 | 8.02 | 14.94 |
| 110 | 5.68 | 69.76 | 34.43 | 69.76 | 104.19 | 2.68 | 29.08 | 7.28 | 8.80 | 16.08 |
| 165 | 5.59 | 71.23 | 34.34 | 91.26 | 125.60 | 2.40 | 27.74 | 7.78 | 8.14 | 15.92 |
| | Prob > F | | | | | | | | | |
| Cult. (C) | 0.011* | 0.797 | 0.561 | 0.001* | 0.077 | 0.001* | 0.001* | 0.001* | 0.001* | 0.001* |
| Rate (R) | 0.393 | 0.479 | 0.334 | 0.001* | 0.001* | 0.983 | 0.617 | 0.873 | 0.001* | 0.022* |
| C*R | 0.504 | 0.731 | 0.449 | 0.979 | 0.847 | 0.910 | 0.139 | 0.857 | 0.109* | 0.118 |
| | Average cultivars, Tukey test | | | | | | | | | |
| IAC87-3396 | 7.56 a | 70.32 a | 35.05a | 52.29 b | 87.34 a | 4.71 a | 45.27 a | 14.42 a | 11.53 a | 25.95 a |
| SP89-1115 | 5.71 b | 71.34 a | 32.79 a | 67.17 a | 99.97 a | 2.51 b | 29.07 b | 7.97 b | 7.09 b | 15.08 b |
| MSD[8] | 1.39 | 7.72 | 7.91 | 8.40 | 14.19 | 0.77 | 6.88 | 2.74 | 2.38 | 3.78 |

[**]Means followed by the same letter in the column do not differ by Tukey test ($p < 0.05$); *ns* nonsignificant, *significant at a significance level of 5%

field conditions (Anderson et al. 1991; Berthelsen et al. 1999; Keeping et al. 2013; Khalid et al. 1978) and in pots (Camargo et al. 2013b; Sousa et al. 2010).

Silicon fertilization also increased the Si uptake by stalks, independent of cultivar, but no influence was observed on the Si uptake by leaves. An average of 83 kg ha$^{-1}$ of Si was taken up by the aboveground biomass (leaf + stalk) during the two consecutive harvests without Si fertilization, and 154 kg ha$^{-1}$ Si was obtained with an 165 kg ha$^{-1}$ Si application as silicate in the sandy soil. In clay soils, 207 kg ha$^{-1}$ of Si after 14 months with 12 t ha$^{-1}$ slag was reported by Ayres (1966), and 215 kg ha$^{-1}$ of Si with 1.6 t ha$^{-1}$ of silicate during two consecutive cycles was obtained by Khalid et al. (1978). The higher values obtained in those studies than in this study were associated with soil type, which resulted in the greatest

**Table 4** Silicon uptake by leaves and stalks in sugarcane (uptake), quantities of Si provided by silicate (SiFF), and recovery index of Si (RI) in Rhodic Hapludox soil with Si application in plant cane and the first ratoon of two sugarcane cultivars

| Si | Plant cane | | | First ratoon | | | Total | | |
|---|---|---|---|---|---|---|---|---|---|
| applied | Uptake | SiFF | RI | Uptake | SiFF | RI | Uptake | SiFF | RI |
| kg ha$^{-1}$ | kg | kg | % | g | g | % | Kg | kg | % |
| | IAC87-3396 | | | | | | | | |
| 0 | 62.13 | 0.0 | | 20.39 | 0.0 | | 82.52 | 0.0 | |
| 55 | 81.61 | 19.48 | 35.41 | 22.48 | 2.09 | 3.80 | 104.09 | 21.6 | 39.21 |
| 110 | 86.11 | 23.98 | 21.80 | 26.32 | 5.94 | 5.40 | 112.43 | 29.9 | 27.19 |
| 165 | 119.50 | 57.37 | 34.77 | 34.61 | 14.22 | 8.62 | 154.11 | 71.6 | 43.39 |
| | SP89-1115 | | | | | | | | |
| 0 | 69.13 | 0.0 | | 13.40 | 0.0 | | 83.53 | | |
| 55 | 100.95 | 31.82 | 57.85 | 14.94 | 1.54 | 2.80 | 115.88 | 33.35 | 60.64 |
| 110 | 104.19 | 35.06 | 31.87 | 16.08 | 2.68 | 2.44 | 120.27 | 37.34 | 34.31 |
| 165 | 125.60 | 56.56 | 34.22 | 15.92 | 2.52 | 1.53 | 141.52 | 58.99 | 35.75 |

SiFF (Si from silicate) = Si uptake – Si uptake by control; RI = recovery index(%) = (Si from silicate/Si applied) * 100 responses to Si and nutrient fertilization compared to those in sandy soil. For example, Camargo et al. (2014) reported 406.5 kg $ha^{-1}$ of Si during three cycles of sugarcane grown in soil where the Si level was considered adequate (11.5 mg $kg^{-1}$ Si $CaCl_2$), according to criteria of Berthelsen et al. (2003). In this study, the absence of Si fertilization and Si uptake by leaves could be associated with a greater number of young leaves being present when the stalks were harvested, which may have resulted in less uptake of Si by the TVD leaves. In fact, the Si levels were usually much less (1.4 g $kg^{-1}$ Si) than those in the TVD leaves (6–10 g $kg^{-1}$ Si) and old leaves (67 g $kg^{-1}$ Si) in sugarcane receiving Si fertilization under field conditions (Camargo and Keeping 2021).

The average of recovery index of Si from the applied silicate (RI) by both sugarcane cultivars was 34.5% in the plant cane and 5% in the first ratoon when the highest rate (165 kg $ha^{-1}$ Si) was applied as silicate in soil. This decreased RI in the first ratoon could be explained by differences in the yield and Si concentrations in the stalks and leaves associated with Si uptake in the plant cane, which is consistent with the results of Camargo et al. (2013b). Additionally, the RI was 40.6%, with an average of two cultivars for the 165 kg $ha^{-1}$ of Si applied as silicate in the furrows at planting after two harvests (29 months). Under field conditions, Khalid et al. (1978) showed an RI of 10% after two consecutive cycles of sugarcane (18 months) grown in clay soil with a high oxide content and a pH of 5.5, when 1.6 t $ha^{-1}$ silicate was applied before planting. In this study, the RI was greater than that shown by Khalid et al. (1978) because of the adsorption of Si based on the high Fe and Al contents and clayey texture, which are not related to silicate management. However, when a similar texture (sandy loam) of soil and Si rate (200 kg $ha^{-1}$ Si) were used for sugarcane grown in pots, Sousa et al. (2010) found an RI of 35.8% after 9 months. Furthermore, Camargo et al. (2013b) showed a 22% RI after plant cane and the first and second ratoons of sugarcane with 555 kg $ha^{-1}$ Si applied as silicate in pots containing sandy soil. These results showed that Si application in the furrows at planting increased the RI of Si under field conditions. Based on these results, further studies should be performed comparing other Si sources and application in the furrows at planting or broadcast before planting to enhance the Si supply to sugarcane with the highest RI over multiple cycles.

These results confirmed that Si application in furrows at planting is a potential tool to increase Si availability in soil at 0–25 cm, Si uptake by stalks, and Si recovery from silicate after two consecutive cycles. However, further studies on increasing the Si supply to sugarcane in low-Si soils are needed.

## 3 Conclusions

**1.** Application of silicate rates in furrows at planting increased the Si extracted in acetic acid (0.5 mol $L^{-1}$) after 6 and 29 months at 0–25 cm and 25–50 cm and in plant cane at 0–25 cm soil depths.

**2**. Increased Si concentrations in $CaCl_2$ (0.01 mol $L^{-1}$) as a function of Si rates were only shown after 6 months at 0–25 cm soil depth and after 29 months in both depths.

**3.** Acetic acid (0.5 mol $L^{-1}$) and $CaCl_2$ (0.01 mol $L^{-1}$) indicated Si availability at depths of 0–25 cm in the soil samples 6 months, 17 months, and 19 months after silicate application.

**4**. The recovery index of Si reached 43% of the Si rates applied in the furrows at planting after two consecutive cycles of sugarcane.

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## Declarations

**Conflict of Interest** The authors declare no competing interests.

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