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SILICON SOURCE FROM CALCIUM SILICATE OF STEEL MAKING SLAG APPLICATION RATE ON GROWTH AND YIELD QUALITY IN SUGARCANE

FONTE DE SILÍCIO A PARTIR DE SILICATO DE CÁLCIO DE SUCATA DE AÇO TAXA DE APLICAÇÃO NO CRESCIMENTO E NA QUALIDADE DO RENDIMENTO DA CANA-DE-AÇÚCAR

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Chanida Jarunpong*
Department of Soil Science, Faculty of Agriculture
at Kamphaeng Saen,
Kasetsart University, Kamphaeng Saen Campus,
Nakhon Pathom, Thailand
agracp@ku.ac.th

Aunthicha Phommuangkhuk*
Department of Soil Science, Faculty of Agriculture
at Kamphaeng Saen,
Kasetsart University, Kamphaeng Saen Campus,
Nakhon Pathom, Thailand
Orcid: https://orcid.org/0000-0002-1286-1380
agracp@ku.ac.th

Nongpat Chaichana*
Department of Soil Science, Faculty of Agriculture
at Kamphaeng Saen,
Kasetsart University, Kamphaeng Saen Campus,
Nakhon Pathom, Thailand
Orcid: https://orcid.org/0000-0001-5308-2693
fagrnpch@ku.ac.th

Suphachai Amkha*
Department of Soil Science, Faculty of Agriculture
at Kamphaeng Saen,
Kasetsart University, Kamphaeng Saen Campus,
Nakhon Pathom, Thailand
Orcid: https://orcid.org/0000-0002-0797-0590
agrscak@ku.ac.th

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Abstract

Calcium silicate is widely recognized as an important silicon source for crop production however, its agronomic benefits remain controversial, particularly under tropical conditions in Thailand. This study evaluated the effects of calcium silicate on growth, yield, and yield quality of sugarcane (Saccharum officinarum L.) cultivar Khon Kaen 3 grown in Kamphaeng Saen soil. Two experiments were conducted. The first experiment assessed the

Resumo

O silicato de cálcio é amplamente reconhecido como uma importante fonte de silício para a produção agrícola; no entanto, seus benefícios agronômicos permanecem controversos, particularmente nas condições tropicais da Tailândia. Este estudo avaliou os efeitos do silicato de cálcio no crescimento, rendimento e qualidade do rendimento da cana-de-açúcar (Saccharum officinarum L.) cultivar Khon Kaen 3 cultivada no solo de Kamphaeng Saen. Foram effects of calcium silicate soaking on bud germination and early growth of sugarcane setts using a completely randomized design with four soaking concentrations (0, 100, 200, and 400 g L^{-1}) and ten replications. The results demonstrated that soaking in calcium silicate at 400 g L^{-1} significantly accelerated bud germination and enhanced early plant growth. The second experiment was a field trial arranged in a randomized complete block design with four fertilization rates (0, 125, 250, and 500 kg ha^{-1}) and four replications to examine the effects of calcium silicate fertilization on plant growth, yield, and yield quality. Although calcium silicate fertilization showed no statistically significant effects on vegetative growth, the highest yield and stalk number were obtained at 500 kg ha^{-1}. In contrast, the optimal yield quality, expressed as commercial cane sugar percentage, was achieved at 250 kg ha^{-1}. These findings suggest that calcium silicate management can improve sugarcane productivity and quality, with application rate influencing yield and sugar accumulation differently.

Keywords: Silicon Fertilizer. Calcium Silicate. Sugarcane Yield. Yield Quality.

realizadas duas experiências. A primeira experiência avaliou os efeitos da imersão em silicato de cálcio na germinação dos brotos e no crescimento inicial das mudas de cana-de-açúcar, utilizando um delineamento completamente aleatório com quatro concentrações de imersão (0, 100, 200 e 400 g L^{-1}*) e dez repetições. Os resultados demonstraram que a imersão em silicato de cálcio a 400 g* L^{-1} *acelerou significativamente a germinação dos brotos e melhorou o crescimento inicial das plantas. O segundo experimento foi um ensaio de campo organizado em um delineamento em blocos casualizados completos com quatro taxas de fertilização (0, 125, 250 e 500 kg* ha^{-1}*) e quatro repetições para examinar os efeitos da fertilização com silicato de cálcio no crescimento, rendimento e qualidade do rendimento das plantas. Embora a fertilização com silicato de cálcio não tenha mostrado efeitos estatisticamente significativos no crescimento vegetativo, o maior rendimento e número de colmos foram obtidos com 500 kg* ha^{-1}*. Em contrapartida, a qualidade ideal do rendimento, expressa como porcentagem comercial de açúcar de cana, foi alcançada com 250 kg* ha^{-1}*. Esses resultados sugerem que o manejo do silicato de cálcio pode melhorar a produtividade e a qualidade da cana-de-açúcar, com a taxa de aplicação influenciando o rendimento e o acúmulo de açúcar de maneira diferente.*

Palavras-chave: *Fertilizante de Silício. Silicato de Cálcio. Rendimento da Cana-de-açúcar. Qualidade do Rendimento.*

1 INTRODUCTION

Silicon (Si) is the second most abundant element in the Earth's crust; however, its availability to plants is often limited because it exists in soil solutions mainly as monosilicic acid [$Si(OH)_4$] at very low concentrations. Although silicon is not classified as an essential nutrient, it is widely recognized as a beneficial element for many crops, particularly graminaceous species such as sugarcane, rice and wheat (Epstein, 1999; Ma and Yamaji, 2015). Silicon uptake has been shown to enhance plant structural integrity, photosynthetic efficiency, and tolerance to both biotic and abiotic stresses, ultimately leading to improved crop productivity and yield quality (Marschner, 2012; Tubana et al. 2016).

Sugarcane (*Saccharum officinarum* L.) is considered a moderate to high silicon-accumulating crop, typically containing 1–3% SiO_2 on a dry matter basis. Silicon accumulation in sugarcane contributes to stronger stalks, reduced lodging, improved resistance to pests and diseases, and enhanced tolerance to metal toxicity, drought, and nutrient imbalance (Samuels and Alexander, 1969; Meyer and Keeping, 2001). Consequently, silicon nutrition has been increasingly recognized as an important component of sustainable sugarcane production systems.

Among various silicon fertilizers, calcium silicate has received considerable attention due to its dual role as a source of plant-available silicon and calcium, as well as its liming effect on acidic soils. Calcium silicate materials derived from steelmaking slag are particularly attractive because they represent an industrial by-product that can be recycled as a soil amendment, thereby supporting circular economy and sustainable waste management strategies (Datnoff et al. 2001; Haynes, 2014). Steelmaking slag typically contains high levels of soluble silicates along with calcium, magnesium, and trace nutrients, which can improve soil chemical properties while supplying silicon to crops (Korndörfer and Datnoff, 1995; Savant et al. 1997).

Numerous studies have demonstrated that the application of calcium silicate slag can significantly improve sugarcane growth, yield, and juice quality. Early research by Ayres (1966) and Clement et al. (1977) showed that calcium silicate fertilization increased cane yield and sugar content, particularly in silicon-deficient soils. These benefits were associated with enhanced silicon uptake, improved root development, and reduced toxicity of aluminum and manganese. Subsequent studies confirmed that calcium silicate slag is more effective than traditional liming materials, such as calcium carbonate, in alleviating soil acidity while simultaneously increasing silicon availability (Samuels et al. 1971; Snyder et al. 2007).

In addition to yield improvement, silicon supplied through calcium silicate slag has been reported to enhance yield quality parameters in sugarcane, including sucrose concentration, juice purity, and fiber strength. Improved stalk rigidity and reduced pest infestation have been linked to silicon deposition in epidermal tissues, which acts as a physical barrier against insect feeding and pathogen penetration (Meyer and Keeping, 2005; Keeping et al. 2017). These effects are particularly important under tropical conditions, where sugarcane is frequently exposed to multiple environmental stresses.

Despite extensive global research, information regarding the optimal application rate of calcium silicate derived from steelmaking slag under tropical soil conditions remains limited, especially in Southeast Asia. In Thailand, sugarcane is a major economic crop cultivated predominantly on highly weathered soils with low silicon availability and frequent acidity-related constraints. The reuse of steelmaking slag as a silicon fertilizer presents a promising approach to improve sugarcane productivity while promoting sustainable soil management and industrial waste utilization.

Therefore, the objective of this study was to evaluate the effects of different application rates of calcium silicate derived from steelmaking slag on growth, yield, and yield quality of sugarcane grown under field conditions. The results are expected to provide practical recommendations for silicon management in sugarcane production and contribute to sustainable agricultural practices in tropical regions.

2 MATERIALS AND METHOD

This study comprised two independent experiments designed to evaluate the effects of calcium silicate on sugarcane establishment, growth, yield, and yield quality. The first experiment examined the influence of calcium silicate soaking on bud germination and early growth under pot conditions, while the second experiment evaluated the effects of calcium silicate fertilization on growth, yield components, yield quality, and calcium and silicon accumulation under field conditions.

2.1 Experiment 1: calcium silicate soaking in sugarcane

The first experiment was conducted using a completely randomized design (CRD) with four treatments and ten replications. Calcium silicate, used as the silicon source, was ground into a fine powder and passed through a 2-mm sieve. The powder was weighed at rates of 0, 100, 200, and 400 g and each amount was dissolved in 1 L of water to prepare the soaking solutions.

Single-bud sugarcane sets (10 cm in length) of cultivar *Khon Kaen 3* were immersed in the respective calcium silicate solutions for 30 s, air-dried for 10 min, and planted at a depth of 5 cm in 12-inch pots containing 10 kg of dry Kamphaeng Saen soil. Weed control was performed manually throughout the experimental period. Nitrogen–phosphorus–potassium fertilizers were applied uniformly to all pots at 1 and 3 months after planting, following standard recommendations by Malavota at al. 1997

Growth parameters, including germination period, plant height, number of plants per pot, leaf width, leaf length, and trichome density, were recorded at 2 and 4 months after planting. Dry plant weight and calcium and silicon concentrations were determined at 4 months after planting.

2.2 Experiment 2: calcium silicate fertilizer on growth, yield and yield component in sugarcane

The second experiment was carried out under field conditions using a randomized complete block design (RCBD) with four treatments and four replications. Calcium silicate was applied at rates of 0, 125, 250, and 500 kg ha^{-1}. Each experimental plot measured 5 × 6 m and was separated by 1.5-m ridged beds.

The experimental soil was characterized by low soluble silicon (5.81 mg kg^{-1}), medium organic matter content (1.97%), very high available phosphorus (492.64 mg kg^{-1}), and high exchangeable potassium (149.28 mg kg^{-1}). Plant height and number of stalks per clump were measured at 2, 4, 6, and 8 months after planting. Yield and yield components including stalk length, stalk diameter, stalk weight, and stalk number were assessed 12 months after planting. Yield quality was evaluated by calculating commercial cane sugar (CCS) percentage using Brix (B), Pol (P), and Fiber (F) values according to the established equation.

$$CCS = \frac{3}{2} P \left(1 - \frac{F+5}{100}\right) - \frac{B}{2} \left(1 - \frac{F+3}{100}\right) \quad (1)$$

Calcium and silicon concentrations in sugarcane stalks and plant residues were determined at harvest using the method described by Korndorfer et al. (2004).

Also, the concentrations of calcium and silicon in the stalks and residues of the sugarcane were calculated based on Korndorfer et al. (2004) at 12 months-old.

2.3 Data analysis

The Duncan Multiple Range Test (DMRT) was employed to identify the mean differences at the statistical significance level of $p \leq 0.01$ by R-program.

3 RESULTS AND DISCUSSION

3.1 Effects of calcium silicate soaking on bud germination

Calcium silicate soaking significantly influenced bud germination time ($p \leq 0.01$), whereas no significant effects were observed on plant height or stalk number at later growth stages (Table 1). Bud germination was progressively accelerated with increasing calcium silicate concentration. The control treatment required 15.75 days for bud emergence, while soaking at 400 g L^{-1} reduced germination time to 9.56 days, representing a reduction of approximately 39%. Treatments at 200 and 400 g L^{-1} differed significantly from the control, indicating a clear dose-dependent response. The observed reduction in germination time can be attributed to the synergistic roles of calcium (Ca) and silicon (Si) during early plant development. Calcium plays a crucial role in membrane stabilization, cell division and signal transduction during seed or bud activation, which can enhance metabolic readiness for germination (White and Broadley, 2012). Silicon, although not considered an essential nutrient, has been widely reported to stimulate early growth processes by improving water uptake, strengthening cell walls, and enhancing enzymatic activity during the initial stages of plant establishment (Ma and Yamaji, 2015; Rizwan et al. 2015). Several studies have demonstrated that silicon application can promote faster germination and early vigor, particularly under suboptimal or stress-prone conditions (Guntzer et al. 2012; Coskun et al. 2019). Although the present experiment was not designed as a stress study, the enhanced bud emergence suggests that silicon may improve physiological efficiency during the early growth phase by regulating hormonal balance and reactive oxygen species (ROS) metabolism (Debona et al. 2017). These mechanisms likely explain the significant improvement in bud germination observed at higher calcium silicate concentrations.

3.2 Effects of calcium silicate soaking on plant height

Despite the clear response in bud germination, calcium silicate soaking did not significantly affect plant height at either the second or fourth month after planting (Table 1). Plant height ranged from 11.22 to 11.85 cm in the second month and from 30.56 to 32.69 cm in the fourth month with no statistically significant differences among treatments. The absence of a significant effect on plant height suggests that the benefits of calcium silicate soaking were primarily limited to the early developmental stage. Similar findings have been reported by Pavlovic et al. (2013) and Savant et al. (2017) who observed that silicon application often enhances early growth vigor without necessarily increasing plant height under non-stress conditions. Silicon is known to function mainly as a protective and structural element, improving mechanical strength and physiological resilience rather than promoting excessive vegetative elongation (Ma et al. 2014; Coskun et al. 2019). Moreover, once plants are established, growth is more strongly regulated by nutrient availability, genetic factors, and environmental conditions than by pre-plant soaking treatments. This may explain why the initial advantages in germination did not translate into sustained differences in plant height at later stages.

3.3 Effects of calcium silicate soaking on stalk number

Calcium silicate soaking also showed no significant effect on stalk number at either the second or fourth month (Table 1). Although a slight numerical increase in stalk number was observed at 200 g L^{-1} during the second month, the differences were not statistically significant. Stalk or tiller formation is a complex trait influenced by hormonal regulation, carbohydrate allocation, and environmental factors such as light and nutrient supply (Keller et al. 2011). The lack of response suggests that calcium silicate soaking alone is insufficient to modify branching or stalk initiation patterns. Previous studies have similarly reported that silicon application does not consistently affect tiller or stalk number unless combined with other agronomic practices or stress conditions (Detmann et al. 2012; Rizwan et al. 2015). Overall, the results indicate that calcium silicate soaking is an effective technique for accelerating bud germination but has limited influence on subsequent vegetative growth parameters such as plant height and stalk number. This suggests that calcium silicate soaking may be particularly useful for improving stand establishment and achieving uniform crop emergence, which is often a critical factor in crop management and productivity. From a practical perspective, the use of calcium silicate soaking at concentrations between 200 and 400 g L^{-1} could be recommended to enhance early establishment without negatively affecting later growth. These findings align with current understanding that silicon primarily enhances physiological efficiency and structural stability rather than directly stimulating biomass accumulation under normal growing conditions (Ma and Yamaji, 2015; Debona et al. 2017).

Table 1

Effects of calcium silicate soaking on the bud germination, plant height and stalk number

Calcium silicate soaking concentration (g L^{-1})	Bud germination (days)	Plant height (cm)		Stalk number/pot	
		2nd month	4th month	2nd month	4th month
0	15.75a	11.22	31.19	2.25	6.51
100	13.28ab	11.73	30.56	2.58	6.56
200	11.31b	11.71	32.69	2.81	6.21
400	9.56c	11.85	30.75	2.47	6.11
F-test	**	ns	ns	ns	ns
CV (%)	14.11	11.27	9.84	18.59	11.08

The same letters or without letters within the same column do not significantly different at 95%. **= Significant at 99% level of probability, ns= non-significantly different at 95% by DMRT.

3.4 Effects of calcium silicate soaking on leaf width and leaf length

Calcium silicate soaking did not significantly affect leaf width or leaf length at either the second or fourth month after planting (Table 2). Leaf width ranged from 1.60 to 1.79 cm in the second month and from 2.09 to 2.38 cm in the fourth month while leaf length varied from 45.17 to 52.19 cm and from 65.45 to 70.62 cm at the second and fourth months, respectively. Although a gradual numerical increase in both leaf width and leaf length was observed with increasing calcium silicate concentration these differences were not statistically significant. The absence of significant effects on leaf size parameters suggests that calcium silicate soaking does not directly stimulate leaf expansion under non-stress conditions. Leaf growth is primarily regulated by cell division and elongation processes driven by nitrogen availability, hormonal balance and environmental factors such as light and temperature (Taiz et al. 2015). Silicon has been reported to influence leaf morphology mainly by reinforcing cell wall structure rather than promoting dimensional growth which may explain the lack of significant variation in leaf width and length among treatments (Ma and Yamaji, 2015; Coskun et al. 2019). Previous studies have similarly reported that silicon application often results in subtle or non-significant changes in leaf size when plants are grown under optimal conditions (Guntzer et al., 2012; Savant et al., 2017).

3.5 Effects of calcium silicate soaking on trichome density

In contrast to leaf size parameters, calcium silicate soaking significantly affected trichome density at the fourth month ($p \leq 0.01$) while no significant differences were observed at the second month (Table 2). At the fourth month, the highest trichome density was recorded at 200 g L^{-1} (22.96 trichomes cm^{-1}), followed by 400 g L^{-1} (22.04 trichomes cm^{-1}), both of which were significantly higher than the control treatment (19.81 trichomes cm^{-1}). These results indicate that calcium silicate soaking enhanced trichome development during later stages of leaf maturation. Trichomes are specialized epidermal structures that play important roles in plant defense, water regulation, and microclimate modification at the leaf surface (Werker, 2010). The increase in trichome density associated with calcium silicate soaking may be linked to silicon deposition in epidermal tissues, which has been shown to stimulate structural differentiation and enhance protective features of leaves (Ma et al. 2014; Debona et al. 2017). Silicon accumulation in leaf epidermal cells can act as a physical barrier against biotic and abiotic stresses and has been associated with increased development of surface structures such as trichomes and silica bodies (Coskun et al. 2019). Although the present study did not evaluate stress responses, enhanced trichome density may contribute to improved tolerance to herbivory, excessive radiation, or water loss, thereby indirectly supporting plant performance (Rizwan et al. 2015; Luyckx et al. 2017). The lack of significant differences in trichome number at the second month suggests that the effects of calcium silicate soaking on epidermal differentiation require time to manifest and are more pronounced during later developmental stages. This delayed response aligns with previous reports indicating that silicon-related structural modifications often become evident after prolonged growth and tissue maturation (Guntzer et al. 2012; Ma and Yamaji, 2015). Overall, the results demonstrate that calcium silicate soaking has limited influence on leaf dimensional growth but plays a significant role in modifying leaf surface characteristics, particularly trichome density. This finding reinforces the concept that silicon primarily enhances plant structural and defensive traits rather than promoting rapid vegetative expansion under favorable growth conditions.

Table 2

Effects of calcium silicate soaking on the leaf width, leaf length, and number of trichomes.

Calcium silicate soaking concentration (g L^{-1})	Leaf width (cm)		Leaf length (cm)		Trichome (number/cm)	
	2nd month	4th month	2nd month	4th month	2nd month	4th month
0	1.60	2.09	45.17	65.45	19.07	19.81c
100	1.65	2.17	47.36	65.58	20.19	20.74bc
200	1.71	2.38	49.20	70.62	20.56	22.96a
400	1.79	2.31	52.19	69.77	21.85	22.04ab
F-test	ns	ns	ns	ns	ns	**
CV (%)	12.18	11.76	14.31	12.46	20.13	16.06

The same letters or without letters within the same column do not significantly different at 95%. **= Significant at 99% level of probability, ns= non-significantly different at 95% by DMRT.

3.6 Effects of calcium silicate coating on dry weight

Calcium silicate coating did not significantly affect plant dry weight (Table 3). Dry weight ranged from 55.66 g in the control treatment to 60.29 g at the highest calcium silicate concentration (400 g L^{-1}). Although a gradual numerical increase in dry weight was observed with increasing coating concentration, the differences among treatments were not statistically significant. The lack of a significant response in dry biomass indicates that calcium silicate coating did not markedly influence overall biomass accumulation under the prevailing growth conditions. Plant dry matter production is largely governed by photosynthetic capacity, nutrient availability and environmental factors, and silicon supplementation often does not translate into increased biomass when plants are grown under non-limiting conditions (Guntzer et al. 2012; Coskun et al. 2019). Similar findings have been reported by Savant et al. (2017) who observed that silicon application frequently improves plant physiological efficiency without significantly increasing dry matter yield.

3.7 Effects on calcium and silicon concentration in plant tissue

Calcium and silicon concentrations in plant tissue were not significantly influenced by calcium silicate coating (Table 3). Calcium concentration ranged from 0.06 to 0.08%, while silicon concentration varied from 1.93 to 2.00% across treatments. Although plants coated with 200 g L^{-1} exhibited the highest numerical values for both calcium and silicon concentration, these differences were not statistically significant. The absence of significant changes in tissue calcium and silicon concentrations suggests that calcium silicate coating did not substantially enhance the uptake or accumulation of these elements. Silicon uptake in plants is known to be highly species-dependent and strongly regulated by specific transporter proteins, rather than being directly proportional to external silicon supply (Ma and Yamaji, 2015; Coskun et al. 2019). Similarly, calcium uptake is tightly regulated by transpiration-driven mass flow and internal homeostasis mechanisms, which may limit excessive accumulation even when external supply increases (White and Broadley, 2012). Moreover, silicon applied as a coating may exert localized or surface-level effects, such as improving physical protection or early-stage physiological responses, without significantly altering bulk tissue concentrations. Previous studies have shown that silicon can enhance structural integrity and stress tolerance even when changes in total tissue silicon concentration are minimal or statistically insignificant (Debona et al. 2017; Luyckx et al. 2017).

The results from Table 3 reinforce the conclusion that calcium silicate treatments primarily influence early developmental processes and structural traits rather than biomass accumulation or elemental enrichment. While calcium silicate soaking accelerated bud germination (Table 1) and increased trichome density at later growth stages (Table 2), coating did not significantly affect dry weight or tissue calcium and silicon concentrations.

This pattern highlights the functional role of silicon as a beneficial element that enhances plant resilience and structural differentiation rather than acting as a conventional growth-promoting nutrient. Such characteristics are particularly relevant in sustainable agricultural systems, where improving plant robustness and early establishment can contribute to long-term productivity and reduced dependency on external inputs, aligning with environmentally responsible management practices

(Guntzer et al. 2012; Debona et al. 2017).

Table 3

Effects of calcium silicate coating on the dry weight, calcium and silicon concentration.

Calcium silicate coating concentration (g L^{-1})	Dry weight (g)	Calcium concentration (%)	Silicon concentration (%)
0	55.66	0.06	1.93
100	56.81	0.07	1.98
200	57.97	0.08	2.00
400	60.29	0.07	1.98
F-test	ns	ns	ns
CV (%)	9.60	16.67	13.44

ns= non-significantly different at 95% by DMRT.

3.8 Experiment 2

3.8.1 Effect of calcium silicate fertilizer on plant height

Calcium silicate fertilizer did not significantly affect plant height at any growth stage evaluated, including the second, fourth, sixth, and eighth months after planting (Table 4). Plant height increased progressively over time in all treatments, reflecting normal crop development. At the eighth month, plant height ranged from 124.72 cm in the control to 139.17 cm at 500 kg ha^{-1}, although these numerical differences were not statistically significant. The absence of a significant response suggests that calcium silicate fertilizer did not directly promote vertical growth under the prevailing soil and environmental conditions. Plant height is largely controlled by genetic potential, nitrogen availability and environmental factors such as light and water, which often override the effects of silicon fertilization when conditions are optimal (Coskun et al. 2019; Ma et al. 2021). Silicon has been widely reported to enhance structural integrity and stress tolerance rather than stimulating elongation growth, which is consistent with the present findings (Debona et al. 2017; Luyckx et al. 2017). Several recent studies have also shown that soil-applied silicon fertilizers may increase plant height only under abiotic stress conditions, such as drought or nutrient imbalance, whereas under non-stress conditions, the effects are often minimal or statistically insignificant (Hussain et al. 2018; Meena et al. 2020). This may explain why calcium silicate fertilization did not significantly influence plant height throughout the growth period in this study.

3.8.2 Effect of calcium silicate fertilizer on stalk numbers

Similarly, calcium silicate fertilizer did not significantly affect the number of stalks at any observation time (Table 4). The number of stalks increased from the second to the sixth month across all treatments, followed by a slight decline at the eighth month, which likely reflects natural self-thinning or resource competition within the clump. At the eighth month, stalk number ranged from 3.17 in the control to 3.51 at 500 kg ha^{-1}, with no statistically significant differences among treatments. Stalk or tiller formation is a complex physiological process regulated by hormonal signaling, carbohydrate partitioning, and nutrient balance, particularly nitrogen and phosphorus availability (Liu et al. 2015; Meena et al. 2020). Silicon fertilizer alone is generally insufficient to modify these regulatory pathways unless combined with other agronomic factors or stress conditions. Recent research indicates that silicon contributes more to mechanical strength, lodging resistance and stress mitigation than to the stimulation of branching or stalk initiation (Coskun et al. 2019; Ma et al. 2021). From the results indicate that calcium silicate fertilizer at rates up to 500 kg ha^{-1} does not negatively affect plant growth but also does not significantly enhance plant height or stalk number under non-stress conditions. While the numerical trends suggest a slight increase in plant height and stalk number at higher application rates, the lack of statistical significance implies that such responses are unlikely to translate into consistent yield advantages. In the context of sustainable agriculture and environmental management, these findings are relevant because they suggest that calcium silicate fertilization should not be evaluated solely on the basis of growth stimulation. Instead, its value may lie in improving plant structural stability, stress tolerance, and long-term soil health, which are increasingly important in environmentally responsible farming systems (Debona et al. 2017; Meena et al. 2020).

Table 4

Effects of calcium silicate fertilizer on the plant height and stalks number.

Calcium silicate (kg ha^{-1})	Plant height (cm)				Number of stalks per clump			
	2nd month	4th month	6th month	8th month	2nd month	4th month	6th month	8th month
0	5.92	18.07	67.93	124.72	1.73	2.23	5.09	3.17
125	6.70	18.35	69.93	124.19	1.81	2.31	5.16	3.48
250	6.68	18.34	69.49	132.99	1.87	2.26	5.33	3.44
500	6.65	18.58	74.18	139.17	1.76	2.37	5.23	3.51
F-test	ns	ns	ns	ns	ns	ns	ns	ns
CV (%)	14.80	14.85	13.80	13.23	21.11	16.23	16.31	17.34

ns= non-significantly different at 95% by DMRT.

3.8.3 Effects of calcium silicate fertilizer on stalk length and stalk diameter

Calcium silicate fertilizer did not significantly affect stalk length or stalk diameter (Table 5). Stalk length ranged from 160.9 to 169.17 cm, while stalk diameter varied narrowly between 2.87 and 2.98 cm across treatments. Although the highest application rate (500 kg ha^{-1}) showed numerically greater stalk length and diameter, these differences were not statistically significant. The lack of significant response in stalk length and diameter suggests that calcium silicate fertilizer does not directly stimulate morphological enlargement of stalks under the prevailing field conditions. Stalk elongation and thickening are primarily regulated by genetic factors, nitrogen availability, and environmental conditions, particularly light interception and water status (Meena et al. 2020; Ma et al. 2021). Silicon is widely recognized for enhancing structural rigidity and mechanical strength rather than increasing organ size, which is consistent with the present results (Coskun et al. 2019; Luyckx et al. 2017). Similar observations have been reported in recent field studies, where silicon fertilizer had minimal influence on stalk dimensions but contributed to improved lodging resistance and tissue firmness, traits not directly captured by simple length or diameter measurements (Hussain et al. 2018; Meena et al., 2020).

3.8.4 Effects of calcium silicate fertilizer on stalk weight

In contrast, calcium silicate fertilizer significantly affects stalk weight ($p \leq 0.01$).

Stalk weight increased progressively with increasing application rate, from 0.74 kg in the control treatment to 1.01 kg at 500 kg ha^{-1}. Treatments receiving 125 and 250 kg ha^{-1} also produced significantly heavier stalks than the control, although lower than the highest rate. The increase in stalk weight without corresponding increases in stalk length or diameter suggests an improvement in internal tissue density or dry matter accumulation per unit length. Silicon has been reported to enhance carbon allocation efficiency, strengthen vascular tissues, and promote silica deposition in cell walls, which can increase organ mass without markedly altering external dimensions (Debona et al. 2017; Coskun et al. 2019). This mechanism may explain the significant increase in stalk weight observed at higher calcium silicate application rates. Recent studies have also shown that silicon fertilizer can improve assimilate translocation and structural carbohydrate accumulation, leading to heavier stems or stalks, particularly under field conditions where mechanical support and tissue strength are agronomically important (Ma et al. 2021; Meena et al. 2020).

3.9 Effects of calcium silicate fertilizer on stalk number

Calcium silicate fertilizer significantly increased the number of stalks per hectare ($p \leq 0.01$). The control treatment produced 46,618 stalks ha^{-1}, while all fertilized treatments resulted in significantly higher stalk numbers, ranging from 54,187 to 59,280 stalks ha^{-1}. No significant differences were observed among the fertilized treatments, indicating that even the lowest application rate was sufficient to enhance stalk population density. The increase in stalk number per hectare is likely associated with improved early establishment, tiller survival, or reduced mortality during vegetative growth. Silicon has been shown to enhance plant resilience by improving tolerance to abiotic stresses, strengthening cell walls, and reducing susceptibility to mechanical damage and disease, which collectively contribute to higher plant survival and stand density (Debona et al. 2017; Hussain et al. 2018; Coskun et al. 2019). Overall, the results demonstrate that calcium silicate fertilizer plays a meaningful role in improving yield components related to stalk mass and population density, even when effects on stalk size are not significant. Increased stalk weight and higher stalk numbers are key contributors to yield formation, indicating that calcium silicate fertilizer can enhance productivity through structural and physiological pathways rather than simple growth stimulation. From a sustainability perspective, these outcomes support the use of calcium silicate as a complementary soil amendment that enhances crop performance by improving plant robustness and stand stability. Such benefits align with environmentally responsible production systems, where yield gains are achieved through improved resource-use efficiency and plant resilience rather than excessive input intensification. (Meena et al. 2020; Ma et al., 2021).

Table 5

Effects of calcium silicate fertilizer on the yield components.

Calcium silicate (kg ha^{-1})	Stalk length (cm)	Stalk diameter (cm)	Stalk weight (kg)	Stalks number/ha
0	160.9	2.92	0.74c	46,618b
125	166.36	2.87	0.89b	54,187a
250	162.99	2.89	0.86b	55,650a
500	169.17	2.98	1.01a	59,280a
F-test	ns	ns	**	**
CV (%)	12.42	6.25	21.13	20.55

The same letters or without letters within the same column do not significantly different at 95%. **= Significant at 99% level of probability, ns= non-significantly different at 95% by DMRT.

3.9.1 Effects of calcium silicate fertilizer on yield

Calcium silicate fertilizer significantly affected crop yield (Table 6). Yield increased progressively with increasing application rate, ranging from 5.54 t rai^{-1} in the control treatment to 9.42 t rai^{-1} at 80 kg rai^{-1}. Compared with the control, yield increases of 37.36%, 38.27%, and 70.04% were observed at application rates of 20, 40, and 80 kg rai^{-1}, respectively. The highest fertilization rate produced a significantly greater yield than all other treatments. The pronounced yield response indicates that calcium silicate fertilization substantially improved yield formation under field conditions. This effect is consistent with previous results in this study, where calcium silicate application increased stalk weight and stalk number per hectare (Table 5), both of which are major determinants of final yield. Silicon has been widely reported to enhance yield through improved plant structural strength, enhanced photosynthetic efficiency, and increased tolerance to abiotic stresses, even when effects on vegetative growth parameters are limited (Debona et al. 2017; Coskun et al. 2019; Meena et al. 2020). Recent field studies have demonstrated that silicon fertilization can significantly increase crop yield by improving stand establishment, reducing lodging, and enhancing assimilate translocation to harvestable organs (Hussain et al. 2018; Ma et al. 2021). These mechanisms likely contributed to the substantial yield increase observed at higher calcium silicate application rates in the present study.

3.9.2 Effects of calcium silicate fertilizer on cane yield

Calcium silicate fertilizer exerted a significant effect on sugarcane yield (Table 6). Compared with the unfertilized control, all calcium silicate application rates markedly increased cane yield, indicating a strong positive response to silicon and calcium supplementation. Yield increased by 37.36–38.27% at 125 and 250 kg ha^{-1}, respectively, while the highest application rate (500 kg ha^{-1}) resulted in a 70.04% increase over the control. The progressive yield enhancement suggests that calcium silicate improved plant growth and biomass accumulation, particularly at higher rates. The yield response can be attributed to the beneficial role of silicon in enhancing photosynthetic efficiency, improving leaf erectness, and increasing resistance to biotic and abiotic stresses, including lodging and drought, which are common constraints in sugarcane production systems (Luyckx et al. 2017; Tubana et al. 2016). In addition, calcium supplied through calcium silicate may have contributed to improved cell wall stability and root development, facilitating greater water and nutrient uptake (White and Broadley, 2015). These combined effects likely promoted sustained vegetative growth, culminating in higher cane yield at elevated fertilization rates.

3.9.3 Effects calcium silicate fertilizer on yield quality

In contrast to yield, yield quality expressed as commercial cane sugar (CCS) responded non-linearly to calcium silicate application. CCS increased significantly at 125 and 250 kg ha^{-1}, with the maximum CCS value (12.89%) recorded at 250 kg ha^{-1}, representing a 62.96% increase relative to the control. However, at the highest rate (500 kg ha^{-1}), CCS declined to 10.53%, despite the substantial increase in cane yield. This pattern indicates that moderate calcium silicate application optimized sucrose accumulation, whereas excessive application favored structural biomass production rather than sugar partitioning. Similar trade-offs between yield and sugar concentration have been reported in sugarcane and other graminaceous crops when silicon inputs stimulate vegetative growth beyond the optimal balance for assimilate allocation to storage organs (Reis et al. 2018; Camargo et al. 2021). Excessive silicon deposition in cell walls may increase culm rigidity and fiber content, potentially diluting sucrose concentration in the stalks (de Oliveira et al. 2019). The differential responses of yield and CCS highlight the importance of optimizing calcium silicate fertilization rates according to production goals. While higher rates maximize biomass yield, moderate rates are more effective for improving sugar quality. From a sustainability perspective, calcium silicate fertilizers—particularly those derived from industrial by-products such as steel slag—represent a promising strategy for improving crop productivity while recycling mineral residues and reducing reliance on conventional inputs (Paye et al. 2018; Haynes, 2017). Moreover, improved nutrient use efficiency and enhanced stress tolerance associated with silicon nutrition may contribute to more resilient sugarcane production systems under changing climatic conditions, aligning with broader goals of sustainable agriculture and environmental stewardship (Coskun et al. 2019; Rizwan et al. 2015). Overall, the results demonstrate that calcium silicate fertilization significantly enhances sugarcane yield and yield quality, but the optimal rate depends on the desired balance between total cane production and sugar concentration.

Table 6

Effects of calcium silicate fertilizer on the yield and yield quality.

Calcium silicate (kg ha^{-1})	Yield (t/ha)	Yield increase (%)	CCS (%)	CCS increase (%)
0	34.62c	-	7.91c	-
125	47.56b	+37.36	11.53b	+45.76
250	47.88b	+38.27	12.89a	+62.96
500	58.87a	+70.04	10.53b	+33.12
F-test	**		**	
CV (%)	14.84		14.41	

The same letters or without letters within the same column do not significantly different at 95%. **= Significant at 99% level of probability by DMRT.

3.9.4 Effects of calcium silicate fertilizer on calcium and silicon accumulation in stalks

Calcium silicate fertilizer significantly influenced silicon concentration in sugarcane stalks, while calcium concentration showed a gradual but statistically non-significant increase (Table 7). Silicon concentration in stalks increased markedly from 0.47% in the control to values exceeding 1.0% at all fertilized treatments, indicating effective silicon uptake following calcium silicate application. The highest silicon concentrations were observed at 250 and 500 kg ha^{-1}, with no significant difference between these two rates. The pronounced increase in stalk silicon concentration reflects the high silicon-accumulating capacity of sugarcane, a characteristic common to graminaceous crops that actively absorb silicon in the form of monosilicic acid (Coskun et al. 2019; Ma and Yamaji, 2015). Once absorbed, silicon is deposited in epidermal and vascular tissues, contributing to improved structural integrity and resistance to lodging, pests, and diseases (Luyckx et al. 2017). The absence of a strong calcium response in stalk tissues may be explained by the relatively low mobility of calcium within the plant, with preferential accumulation in transpiring organs rather than storage tissues such as culms (White and Broadley, 2015).

3.9.5 Effect of calcium silicate fertilizer on calcium and silicon concentration in plant residues

Calcium silicate fertilizer also enhanced silicon concentration in plant residues, with values increasing from 1.26% in the control to a maximum of 1.86% at 250 kg ha^{-1}. Although silicon concentration declined slightly at 500 kg ha^{-1}, it remained significantly higher than in unfertilized plants. Calcium concentration in plant residues showed a moderate increasing trend with fertilizer rate, reaching the highest value at 500 kg ha^{-1}.The accumulation of silicon in plant residues has important agronomic and environmental implications. Residual silicon remained in leaves and tops can be recycled into the soil through residue incorporation, contributing to sustained silicon availability in subsequent cropping cycles (Reis et al. 2018; Haynes, 2017). This recycling mechanism is particularly relevant in intensive sugarcane systems, where residue retention is increasingly promoted as a strategy to improve soil quality and nutrient cycling. Furthermore, higher silicon content in residues may enhance residue persistence and soil aggregation, indirectly supporting long-term soil health (Paye et al. 2018).

The differential accumulation of silicon and calcium between stalks and plant residues underscores the complementary roles of these elements in sugarcane nutrition. While silicon is readily accumulated in aboveground tissues and contributes directly to crop performance, calcium plays a more structural and regulatory role, with benefits that may not be immediately reflected in tissue concentration alone. From a sustainability perspective, calcium silicate fertilizers, especially those derived from industrial by-products, offer a dual benefit by improving crop nutrition and promoting circular resource use (Camargo et al. 2021; de Oliveira et al. 2019). Overall, the results confirm that calcium silicate fertilizer effectively enhances silicon accumulation in sugarcane, particularly in stalks and residues, supporting improved crop performance and providing residual benefits for soil–plant systems. These findings reinforce the value of silicon-inclusive nutrient management strategies for sustainable sugarcane production under tropical conditions.

Table 7

Effects of calcium silicate fertilizer on calcium and silicon concentration in sugarcane.

Calcium silicate	Stalks		Plant residues	
(kg ha^{-1})	Calcium (%)	Silicon (%)	Calcium (%)	Silicon (%)
0	0.66	0.47b	1.00	1.26c
125	0.72	1.01a	1.14	1.45bc
250	0.76	1.07a	1.05	1.86a
500	0.77	1.05a	1.18	1.66ab
F-test	ns	**	ns	**
CV (%)	19.12	13.57	17.21	11.98

The same letters or without letters within the same column do not significantly different at 95%. **= Significant at 99% level of probability, ns= non-significantly different at 95% by DMRT.

4 CONCLUSION

According to the findings, calcium silicate soaking at the concentrations of 400 g L^{-1} had significant effects on the germination and growth of the sugarcane 2 and 4 months-old. In terms of calcium silicate fertilizer, although it had statistically non-significant effects on the growth of sugarcane, it led to the highest yield and number of stalks when the concentration was increased to 500 kg ha^{-1} and the greatest CCS percentage when the concentration was varied to 250 kg ha^{-1}.

This study demonstrates that calcium silicate application produces rate-dependent effects on sugarcane establishment, growth, nutrient accumulation, yield, and yield quality. Calcium silicate soaking significantly accelerated bud germination, confirming the role of silicon in enhancing early physiological vigor, whereas early vegetative growth parameters were only marginally affected. Leaf morphological responses, particularly increased trichome density, indicate enhanced structural protection associated with silicon deposition. Calcium silicate coating and fertilization consistently increased silicon concentration in stalks and plant residues, while calcium concentration remained relatively stable. Field applications improved yield components and total cane yield, with the highest calcium silicate rate producing the greatest biomass. However, sugar quality, expressed as commercial cane sugar (CCS), was maximized at intermediate application rates, indicating an optimal balance between vegetative growth and sucrose accumulation. The substantial silicon accumulation in plant residues suggests potential residual benefits through nutrient recycling and improved soil–plant system resilience. Overall, moderate calcium silicate fertilization optimizes both yield and quality, supporting its inclusion in sustainable sugarcane nutrient management strategies under tropical conditions.

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Authors' Contribution

All authors contributed equally to the development of this article.

Data availability

All datasets relevant to this study's findings are fully available within the article.

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