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Silicon source from calcium silicate of steel making slag on leaf thickness, trichomes number, yield and silicon content in rice RD 49 variety grown under nutrient solution by deep water technique system

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Abstract

Silicon (Si) is a beneficial element for plant growth, even though it is not considered an essential nutrient. Si plays a crucial role in strengthening plant structures, improving resistance to pests and diseases, and enhancing stress tolerance. The present study investigates the effects of calcium silicate from steel-making slag as a Si source on the plant growth, leaf thickness, number of trichomes, yield, and silicon content of rice (RD 49 variety) grown in a nutrient solution by the deep water technique. The experiment was conducted with a completely randomized design (CRD) with ten replications and nine treatments using nutrient solutions of 0.0, 0.1, 0.5, 1, 5, 10, 50, 100, and 500 mg $CaSiO_3$/L. The results indicate that $CaSiO_3$ concentrations of 10, 50 and 100 mg/L could promote rice growth and yield of rice. $CaSiO_3$ concentrations of 50 and 100 mg/L effectively increased the cutin layer thickness. Additionally, the 100 and 500 mg/L $CaSiO_3$ concentrations in the nutrient solution by the deep water technique were found to enhance the Si content in leaves, stem, and husk in rice. These findings suggest that $CaSiO_3$ at concentrations of 50 and 100 mg/L can better promote a good yield and increased leaf thickness of rice (RD 49 variety) grown in a nutrient solution using the deep water technique.

Keywords: Hydroponic system, Rice growth, Tiller number, Trichome number

1. Introduction

Silicon (Si) is a beneficial nutrient for rice (*Oryza sativa*) and plays a crucial role in improving plant health, productivity, and resilience to biotic and abiotic stresses. Si significantly enhances rice growth by strengthening cell walls, increasing resistance to pests and diseases and improving tolerance to drought and heavy metal toxicity. Rice is a silicon-accumulating plant, absorbing Si from the soil in the form of monosilicic acid (H_4SiO_4) [1]. This accumulation forms silica bodies in plant tissues, leading to increased mechanical strength and improved photosynthetic efficiency [2, 3, 4, 5, 6, 7]. Steel-making slag is a byproduct generated during the production of steel in basic oxygen furnaces (BOF) and electric arc furnaces (EAF). It consists of various oxides, including calcium oxide (CaO), silicon dioxide (SiO_2), and iron oxides, among others. Si is a key component in steel and various industrial applications and is present in slag mainly as silica (SiO_2) and silicate compounds. Steel-making slag is often disposed of in landfills, contributing to the environmental burden. Repurposing it as a silicon fertilizer transforms this waste into a valuable agricultural input, aligning with circular economy principles by closing material loops, reducing the need for virgin mineral extraction, and lowering the environmental footprint of both steel production and agriculture. By thoroughly discussing how this approach supports sustainable waste management and resource efficiency in regions with high steel output, this study highlights the relevance of this approach to the sustainable development goals (SDGs). The recovery and introduction of Si from steel-making slag offer economic and environmental benefits by enhancing resource efficiency and reducing waste disposal concerns [8]. A previous study found that slag-based silicon fertilizers significantly enhanced rice growth and yield, while also reducing the incidence of brown spot disease [9]. For instance, research conducted in Thailand found that applying 250 kg/ha of calcium silicate increased plant height, number of tillers per plant, and yield of the Pathum Thani 80 rice variety in Sena and Roi-et soil series [10]. In addition, another study evaluated different silicon sources, including calcium silicate, rice hull, and rice hull ash, in both acidic and alkaline soils [11]. The results indicated that calcium silicate and rice hull applications significantly improved growth parameters such as the number of tillers, leaf area index (LAI), and single-photon avalanche diode (SPAD) values (a measure of chlorophyll content). Yield parameters, including the number of panicles per hill and filled grains per panicle, also showed significant improvement. The treatment of calcium silicate at 187.5 kg/ha resulted in maximum leaf thickness, with the vascular bundle and without the vascular bundle increasing by 24 and 43%, respectively, compared with the control treatment in tomato [12]. The application of Si at a rate of 100 mg/L calcium silicate concentration to rice had significant effects on tiller number, panicle weight, panicle length and panicle number [13].

Si an important nutrient since it promotes growth and development, and it is especially beneficial for monocots plant such as rice [14]. However, little research has been carried out in Thailand and there is a lack of localized data on silicon uptake efficiency or yield responses in Thai rice-growing conditions. In particular, there is a lack of research on the effects of Si sourced from calcium silicate ($CaSiO_3$) from steel making slag on the growth, yield and Si content in rice under the deep water technique. The deep water technique is a hydroponic method where plant roots are suspended in a nutrient-rich, oxygenated water solution. It is one of the simplest and most effective hydroponic systems, especially for beginners or commercial growers aiming for high efficiency. Therefore, the objective of this study was to investigate calcium silicate from steel making slag as a Si source on growth, number of trichomes, leaf thickness, yield, and Si content in rice grown in nutrient solutions by the deep water technique.

2. Materials and methods

2.1 Experimental details

Rice seedling research development (RD) (RD 49 variety) at 28 days after sowing were transplanted in a pot container (20 liters) in nutrient solution with a deep water technique system. The RD 49 rice variety in Thailand is a high-yielding, photoperiod-insensitive rice variety developed for both transplanting and direct seeding, making it especially suitable for irrigated lowland areas. It produces strong seedlings with good disease resistance and is widely cultivated due to its adaptability and stable grain quality. Pot experiments were conducted in a net house (temperature: 23.0-33.0°C, relative humidity: 68-80%, natural photoperiod with supplemental lighting of 850-1200 μmol/m²/s) at the Soil Science Department, Faculty of Agriculture at Kamphaeng Saen, Kasetsart University on June-November 2024. This experiment utilized a Completely Randomized Design (CRD) with ten replications and nine treatments using nutrient solution at concentrations of 0, 0.1, 0.5, 1, 5, 10, 50, 100, and 500 mg $CaSiO_3$/L, as shown on Table 1, and using Asher's nutrient solution [15]. The components of $CaSiO_3$ is Ca 40%, Mg 2% and Si 25%.

Table 1 The chemical composition of the nutrient solution in each treatment.

Chemical reagents	Composition of the nutrient solution followed by the level of calcium silicate added (mg/L)								
	T1	T2	T3	T4	T5	T6	T7	T8	T9
$CaSiO_3$	0	0.1	0.5	1	5	10	50	100	500
$Ca(NO_3)_2.4H_2O$	944.00	943.73	942.63	941.26	930.29	916.57	806.85	669.71	0.00
KNO_3	404.40	404.64	405.58	406.75	416.15	427.90	521.90	639.41	1213.20
KH_2PO_4	54.91	54.91	54.91	54.91	54.91	54.91	54.91	54.91	54.91
$MgSO_4.7H_2O$	246	246	246	246	246	246	246	246	246
Fe-EDTA	56.3	56.3	56.3	56.3	56.3	56.3	56.3	56.3	56.3
H_3BO_3	3.36	3.36	3.36	3.36	3.36	3.36	3.36	3.36	3.36
$MnSO_4.H_2O$	4.22	4.22	4.22	4.22	4.22	4.22	4.22	4.22	4.22
$ZnSO_4.7H_2O$	2.31	2.31	2.31	2.31	2.31	2.31	2.31	2.31	2.31
$CuCl_4.2H_2O$	0.51	0.51	0.51	0.51	0.51	0.51	0.51	0.51	0.51
$(NH_4) Mo_7O_{24}.4H_2O$	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04

Note: The ratio of $CaSiO_3$ increased from T1-T9 and then calculated the ratio of calcium and nitrate for balance $Ca(NO_3)_2.4H_2O$ and KNO_3. $CaSiO_3$ was used as a source of Si (0, 0.1, 0.5, 1, 5, 10, 50, 100, and 500 mg $CaSiO_3$/L), equal to 0, 0.0163, 0.0815, 0.163, 0.815, 1.63, 8.15, 16.31 and 81.54 mgSi /L, respectively.

The nutrient solution was changed every 14 days during the seedling stage, every 10 days during the flowering stage, and every seven days from the development up until the harvest stages (120 days after sowing; DAS), while the pH level was adjusted to be within the range of pH 5.5-6.5.

2.2 Data collection

Rice growth data was collected including plant height and tiller number at 30, 60, 90 and 120 DAS. In addition, fresh leaves were transversely sectioned at the region of the midrib or interveinal areas. Using a sharp razor blade, thin sections were carefully sliced by hand to minimize tissue damage. Each thin section was immediately transferred onto a clean glass microscope slide containing a drop of distilled water. Once mounted, the prepared slide was observed under a compound light microscope (40X magnification). This method provides a simple approach to studying plant leaf anatomy distribution without the need for chemical fixatives or staining agents. Leaf thickness was measured as the perpendicular distance from the abaxial (lower) surface to the adaxial (upper) surface of the leaf.

Images were then taken and measured using an M-shot camera at 90 DAS. The leaves were analyzed at 30-40 cm (middle of leaves) of the third leaf from the flag leaf. The 30–40 cm section of the third leaf from the flag leaf was selected because it represents a mature, physiologically active, and standardized tissue that allows for accurate, repeatable, and comparable measurement in plant studies. Only three spots on one cutin layer cell were evaluated. The number of trichomes was counted four times per leaf using a stereomicroscope at 1.2X of the leaves being shot using an M-shot camera at 90 DAS. The analyzed section was the same as in the previous step. Only the trichomes clustering within 1 mm of the microscopic view were taken into consideration.

Dry weight was measured after the rice plant specimens were dried at 70 °C for 72 hours. All grains (filled and unfilled grains) from each panicle were removed and total grain weight per pot was determined and the weight of 1,000 grains was counted from 1,000 filled grain at 120 DAS.

2.3 Plant analysis

The leaf, stem (petiole) and husk sample were analyzed for Si content at 120 DAS. Rice samples were digested with concentrated HNO_3, then Si concentration in plant was determined using the colorimetric blue silicomolybdous acid method. The reagent used sulfuric acid as the acidifying agent, and oxalic acid to avoid interference with phosphate by destruction of the molybdatophosphate complex, which occurs via ligand exchange between oxalate and molybdate, to produce phosphate and molybdo-oxalate. Ascorbic acid was used as a reducing agent and ammoniummolybdate as the source of $H_6Mo_7O_{24}.4H_2O$. The resulting aqueous solution was analyzed by UV- vis spectrophotometry at 660 nm [16].

2.4 Statistical analysis

Analysis of variance (ANOVA) was conducted using R software (version 4.3.3 for Windows), and mean separation was performed using duncan’s multiple range test (DMRT).

3. Results and discussion

3.1 Growth of the rice

The application of calcium silicate ($CaSiO_3$) significantly influenced rice plant height and tiller number at different growth stages (Table 2). At 30 DAS, plant height increased significantly with higher $CaSiO_3$ concentrations, particularly at 50, 100, and 500 mg/L. At 60 and 90 DAS, the application of $CaSiO_3$ did not result in significant differences in plant height among treatments. It is possible that during these stages, the plants were primarily focused on vegetative expansion and tiller development rather than elongation, or that the accumulated effects of $CaSiO_3$ had not yet fully manifested in terms of height. By 120 DAS, plant height was again significantly affected, with the highest values observed in treatments of 5-500 mg/L. This suggests that the cumulative effect of $CaSiO_3$ became more pronounced during the later stages of growth, potentially enhancing cell wall strength, silicon uptake, and overall biomass accumulation. The highest plant heights were recorded in treatments receiving 50, 100, and 500 mg/L, indicating a dose-responsive relationship that peaks within this concentration range, making $CaSiO_3$ a potentially beneficial addition for improving rice structural growth at maturity.

No significant differences were found for tiller number at 30, 60, and 120 DAS. However, the application of $CaSiO_3$ had significant effects on the tiller number at 90 DAS, with the maximum tiller number was revealed at 50,100 and 500 mg/L of $CaSiO_3$ concentration resulted 41.7, 41.1 and 41.5 tiller number/pot, respectively. For other growth stages, $CaSiO_3$ addition had no significant effects on tiller number at the 30 60 and 120 DAS. This could be because 30 DAS was beginning of the vegetative growth period, while at the 60 DAS it could be due to during the period of growth beginning with panicle development, competition for assimilates exists between the developing panicle and young tillers. At 120 DAS, representing the harvest stage, the number of tillers per pot did not differ significantly among treatments.

These results indicate that Si sourced $CaSiO_3$ concentration from steel making slag applications can enhance the rice height and tiller number compared to non-Si application. Si has a significant impact on rice height due to its role in plant structure, since it is deposited in the epidermal cells of rice plants, strengthening the cell walls. This leads to improved structural integrity, which can affect plant height by supporting upright growth [17].

Table 2 Effect of calcium silicate concentration on plant height and tiller number of rice at 30, 60, 90, and 120 DAS.

$CaSiO_3$ (mg/L)	Plant height (cm)				Tiller number (number/pot)			
	30 DAS	60 DAS	90 DAS	120 DAS	30 DAS	60 DAS	90 DAS	120 DAS
0	33.7^{c}	66.7	100.2	119.1^{c}	2.0	7.0	36.2^{c}	52.2
0.1	35.3^{b}	66.0	105.0	122.8^{b}	2.0	7.7	36.7^{c}	52.3
0.5	35.8^{b}	66.1	105.1	124.2^{b}	2.0	7.7	37.6^{bc}	52.5
1	37.7^{ab}	67.3	104.0	125.1^{b}	2.0	8.3	38.1^{bc}	53.2
5	38.0^{ab}	66.6	106.5	127.8^{a}	2.0	8.3	39.7^{b}	53.7
10	38.2^{ab}	69.7	109.0	128.4^{a}	2.0	8.3	39.6^{b}	56.1
50	39.7^{a}	68.7	107.0	128.0^{a}	2.0	8.3	41.7^{a}	54.1
100	40.6^{a}	68.0	106.5	127.0^{a}	2.0	9.0	41.1^{a}	54.3
500	40.3^{a}	68.0	107.6	126.0^{a}	2.0	9.5	41.5^{a}	55.3
F-test	**	ns	ns	**	ns	ns	*	ns
CV (%)	7.68	6.04	5.60	3.07	9.99	7.32	9.00	5.62

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

3.2 Leaf thickness and trichome number

Table 3 demonstrates the effect of $CaSiO_3$ concentration on leaf thickness and trichome number in rice at 90 DAS. Leaf thickness was significantly influenced by $CaSiO_3$ calcium application, with the highest values observed in the 50 mg/L (4.51 mm) and 100 mg/L (4.37 mm) treatments. These were significantly greater than the control and low-dose treatments (0–1 mg/L), which recorded thicknesses below 3 mm. This suggests that moderate to high levels of $CaSiO_3$ enhance structural leaf development, likely due to the role in cell wall fortification and epidermal tissue expansion. The high Si accumulation in rice leaves enhances the rigidity and abrasiveness of leaf tissues. This increased rigidity can reduce the quality of the leaves as food for insects by causing direct damage to insect mouthparts, leading to reduced insect growth rates and feeding efficiency [18]. Si plays a significant role in enhancing the structural integrity of rice leaves. A previous study indicates that Si accumulates primarily in the epidermal cells, stomata, and trichomes of rice leaves, leading to the thickening and strengthening of cell walls [19]. The variation of $CaSiO_3$ concentrations did not significantly affect the number of trichomes at 90 DAS, as shown in Table 3 and Figure 1. Another study reported the deposition of silicon in rice stomatal guard cells and suggested that Si has a mechanical and physiological role in the stomatal apparatus and that silicon deposition may reduce evaporative water loss [17]. This indicates that trichome formation may be less sensitive to $CaSiO_3$ levels or that it is regulated by other environmental or genetic factors. Overall, while $CaSiO_3$ strongly promotes increased leaf thickness, it does not appear to have a measurable impact on trichome density under the conditions of this study.

Table 3 Effect of calcium silicate concentration on leaf thickness and trichome number of rice at 90 DAS.

$CaSiO_3$ (mg/L)	Leaf thickness (mm)	Trichome number
0	2.40^{d}	3.25
0.1	2.56^{d}	3.75
0.5	2.90^{d}	3.37
1	2.88^{c}	3.87
5	3.81^{b}	4.00
10	3.65^{b}	4.12
50	4.51^{a}	3.75
100	4.37^{a}	4.12
500	3.98^{b}	3.62
F-test	**	ns
CV (%)	14.67	15.50

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

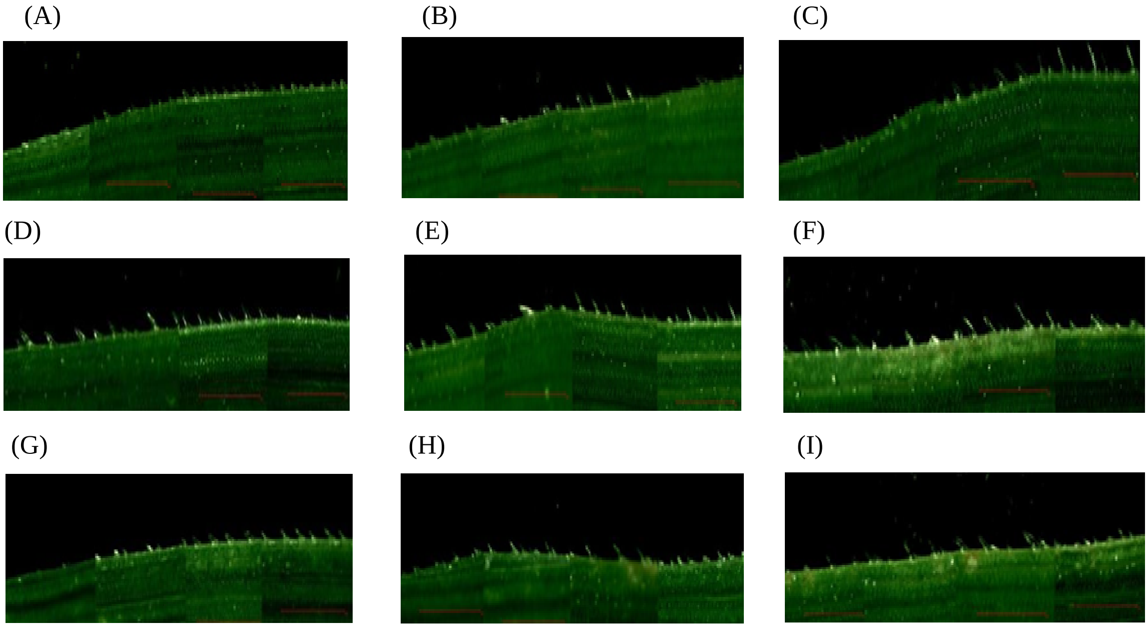

Figure 1 Effect of calcium silicate concentration on trichome number of rice at 90 DAS, in which A=0, B=0.1, C=0.5, D=1, E=5, F=10, G=50, H=100, and I=500 mg $CaSiO_3$/L.

3.3 Plant dry weight and yield of rice

Table 4 presents the effect of varying $CaSiO_3$ concentrations on plant dry weight, yield, and 1,000 grain weight of rice at 120 DAS. The results indicate that increasing $CaSiO_3$ concentrations generally improved the growth and yield parameters up to certain levels. The variation of $CaSiO_3$ concentrations had non-significant effects on the plant dry weight of rice at 120 DAS. The plant dry weight increased progressively, reaching a peak at 50 mg/L $CaSiO_3$ (335.60 g/plant), after which it slightly declined.

In addition, the variation of $CaSiO_3$ concentrations had a significant effect on the yield of rice at 120 DAS, except for the $CaSiO_3$ concentrations of 10, 50, and 100 mg/L. In contrast, the application of 1, 5, 10, 50, 100, and 500 mg/L of $CaSiO_3$ significantly increased the weight of 1,000-grain weight compared with 0, 0.1, and 0.5 mg $CaSiO_3$/L, demonstrating the benefits of this concentration of $CaSiO_3$ on rice grain size. Statistical analysis reveals that the differences in plant dry weight were not significant, but the yield and 1,000-grain weight showed significant differences at 95% and 99% levels of probability, highlighting the positive impact of $CaSiO_3$ on rice productivity. These findings suggest that moderate levels of $CaSiO_3$ can enhance rice growth and yield, although excessive application may reduce efficiency. It is worth noting that higher concentrations of $CaSiO_3$ might bring on adverse rather than positive effects, such as dry weight and yield. For this reason, there was no response of rice yield to the high rate of Si application in the 500 mg $CaSiO_3$/L treatment. Si is beneficial rather than essential, so plants have a limited capacity to uptake and utilize excess amounts. Si toxicity is rare but can occur when applied in excess, especially in hydroponic or soilless systems. Excess calcium (Ca^{2+}) can interfere with the uptake of other essential nutrients like magnesium (Mg^{2+}), potassium (K^+), and phosphorus (P), leading to nutrient antagonism [17].

Instead, maximum rice grain yield was found with the 10, 50, and 100 mg $CaSiO_3$/L treatments. Calcium silicate 50-100 mg/L provides moderate levels of available silicon, which improves plant resistance to abiotic stress and strengthens cell wall. Calcium supplement supports cell division and membrane integrity. This range supports optimal physiological responses, including improved chlorophyll content and enhanced enzyme activity related to photosynthesis and stress responses [17]. Si strengthens leaf erectness, allowing better light interception and improving photosynthesis efficiency, which leads to higher biomass production and grain yield [20]. Si application improves grain weight, size, and overall yield by reducing spikelet sterility and increasing panicle number [21]. Silicon improves the uptake of essential nutrients like nitrogen (N) and phosphorus (P), enhancing grain filling and overall productivity [22]. Then, Si sourced $CaSiO_3$ concentration from steel making slag applications therefore enhanced the rice yield and 1,000 grain weight when compared with non-Si application.

Table 4 Effect of calcium silicate concentration on plant dry weight, yield, and 1000 grain weight of rice at 120 DAS.

$CaSiO_3$ (mg/L)	Plant dry weight (g/plant)	Yield (g/plant)	1,000 grain weight (g)
0	270.7	103.10^{c}	23.98^{c}
0.1	278.9	105.14^{bc}	24.77^{b}
0.5	287.0	106.43^{bc}	25.00^{ab}
1	296.9	110.32^{b}	25.14^{a}
5	290.8	113.88^{ab}	25.07^{a}
10	312.0	120.88^{a}	26.00^{a}
50	335.6	122.27^{a}	25.59^{a}
100	309.3	118.38^{a}	25.61^{a}
500	302.5	110.03^{b}	25.65^{a}
F-test	ns	*	**
CV (%)	13.25	8.87	3.43

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

3.4 Silicon content in the plant

Table 5 presents the effect of $CaSiO_3$ concentration on the silicon content in the leaves, stems, and husks of rice at 120 DAS. The $CaSiO_3$ concentration of 500 mg/L significantly increased leaf, stem, and husk silicon to the highest level, although this did not differ significantly from the outcomes of the $CaSiO_3$ concentrations of 50 and 100.0 mg/L. The $CaSiO_3$ concentration of 500 mg/L significantly increased to the highest level of Si content in the stems. The maximum content of Si was found in 100 and 500 mg $CaSiO_3$/L treatments, which were significantly different from other treatments in Table 5. Silicon accumulation in all plant parts significantly increased with higher concentrations of $CaSiO_3$. In the leaves, silicon content rose from 39.26 g/kg at 0 mg/L to a maximum of 69.56 g/kg at 500 mg/L, showing a consistent upward trend. A similar pattern was observed in the stems, where silicon content increased from 48.09 g/kg at 0 mg/L to 69.02 g/kg at 500 mg/L. In husks, silicon content also improved significantly, starting from 8.13 g/kg at 0 mg/L and reaching 13.89 g/kg at 500 mg/L. The statistical analysis indicates highly significant differences at 99% probability across all plant parts, suggesting that $CaSiO_3$ application effectively enhances silicon uptake. These results highlight the importance of calcium silicate in improving silicon content, which is beneficial for plant strength, stress resistance, and yield quality.

The present findings are supported by previous reports [22, 23], which found that the application of more highly concentrated Si fertilizer could boost the amount of Si in rice stems, leaves, and ears. The $CaSiO_3$ concentrations of 100 and 500 mg/L significantly elevated leaves, stem, and husk silicon to the highest level, but the outcome did not differ significantly from those with $CaSiO_3$ concentrations of 50 mg/L. However, the Si concentration in rice organs was accumulated in leaf $\geq$ stem > husk. However, the practical application of higher concentrations (e.g., 500 mg/L) should be evaluated considering cost efficiency and potential environmental impacts.

Table 5 Effect of calcium silicate concentration on silicon content in leaves, stem, and husk of rice at 120 DAS.

$CaSiO_3$ (mg/L)	Leaves (g/kg)	Stem (g/kg)	Husk (g/kg)
0	39.26^{e}	48.09^{e}	8.13^{c}
0.1	44.64^{d}	51.15^{d}	8.97^{c}
0.5	46.72^{cd}	57.02^{c}	10.06^{c}
1	51.18^{c}	57.63^{c}	9.07^{c}
5	60.41^{b}	59.27^{bc}	11.24^{b}
10	60.98^{b}	61.08^{b}	12.32^{ab}
50	63.56^{ab}	63.06^{ab}	12.96^{ab}
100	66.09^{ab}	64.03^{ab}	13.12^{a}
500	69.56^{a}	69.02^{a}	13.89^{a}
F-test	**	**	**
CV (%)	9.14	6.64	8.61

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

Calcium silicate from steel making slag application in rice (RD 49 variety) in a nutrient solution using the deep water technique was associated with increased leaf thickness to improved structural integrity, and enhanced yield. From the previous study that leaf thickness increased from 105 µm to 128 µm (+21.9%) under 100 mg/L $CaSiO_3$. This is consistent with the findings of a previous study which reported a 26% increase with 1.5 mM Si to enhance physiological functions which resulted in better yield outcomes [24].

Using steel making slag as a Si source in agriculture, including in hydroponic systems, introduces promising sustainability benefits, but also warrants a balanced discussion of its practical, economic, and environmental implications. Steel slag, a byproduct of the steel industry, is rich in calcium silicate and other minerals, making it a cost-effective alternative to conventional Si fertilizers like potassium silicate (K_2SiO_3) or sodium silicate (Na_2SiO_3). Its use promotes circular economy principles, reduces industrial waste disposal, and can lower fertilizer input costs, particularly in regions with local steel production. However, the solubility of silicon in slag is generally lower, making it less efficient in hydroponic systems, where rapid and precise nutrient delivery is essential [25]. Environmentally, slag use may raise concerns about the release of heavy metals (e.g., chromium, vanadium, and lead) or pH imbalances in nutrient solutions if not properly treated or formulated. In contrast, conventional Si fertilizers offer high solubility and purity, which are ideal for controlled systems, but are energy-intensive to produce and often more expensive [26]. Therefore, while steel slag presents an eco-friendly and economical option for soil-based agriculture, its use in hydroponics remains limited by solubility and purity constraints and requires further optimization and safety validation.

4. Conclusions

$CaSiO_3$ concentrations from steel making slag at concentrations of 10, 50, and 100 mg/L were found to promote rice growth, yield, and Si content in a nutrient solution using the deep water technique. In addition, the 50 and 100 mg/L $CaSiO_3$ concentrations gave the highest cutin layer thickness compared to the other treatments. Moreover, the 100 and 500 mg/L $CaSiO_3$ concentrations were found to enhance the Si content in leaves, stems, and husk in rice. The research findings suggested that $CaSiO_3$ at a rate of 50 and 100 mg/L is better for improving the yield and increasing leaf thickness of rice (RD 49 variety) grown in a nutrient solution using the deep water technique.

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6. Conflicts of interest

The authors declare that they have no conflict of interest.

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