Malaysian Applied Biology
https://doi.org/10.55230/mabjournal.v55i2.3629

Research Article

Role of Silicon Fertiliser in Enhancing Growth and Suppressing White Root Disease (*Rigidoporus microporus*) in Rubber Seedlings (*Hevea brasiliensis*)

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ABSTRACT

Silicon (Si) is recognised for its potential to enhance plant growth and improve resistance against various plant pathogens. This study comprised two experiments under nursery conditions using the same Randomised Complete Block Design. In the first experiment, the optimal Si concentration (0, 0.5, 1.0 & 2.0 g per seedling) for improving the growth performance of rubber seedlings (*Hevea brasiliensis*) was determined over an 11-month evaluation period. In the second experiment, the effectiveness of Si in suppressing white root disease caused by *Rigidoporus microporus* was evaluated over the 11-month experimental period following a three-month Si pre-treatment and artificial inoculation with the pathogen. Growth parameters, including seedling height, stem girth, chlorophyll content, and biomass accumulation, were measured monthly. Disease incidence, disease severity index (DSI), and area under the disease progression curve (AUDPC) were evaluated for eight months. The findings from the first experiment indicated that although Si application numerically improved several growth parameters, particularly at 1.0 g and 2.0 g, the differences were not consistently significant. In the second experiment, a higher Si concentration significantly suppressed disease development. The highest Si concentration (2.0 g) reduced disease incidence by 50.00%, reduced disease severity based on foliar symptoms by 75.00%, and reduced internal root rot severity by 75.93% compared with untreated inoculated seedlings. A consistent dose-dependent reduction in AUDPC values indicated delayed disease progression at the higher Si concentration. Moreover, Si-treated seedlings showed enhanced chlorophyll retention and increased root biomass, suggesting improved physiological resilience. In conclusion, while Si did not uniformly enhance growth, its application demonstrated significant potential in suppressing white root disease and promoting selected physiological traits. These findings support the integration of Si as a strategic input for early-stage disease management in rubber cultivation by promoting improved root system development and biomass accumulation, which likely contributed to delayed *Rigidoporus microporus* infection.

Key words: *Hevea brasiliensis*, plant defence, rubber seedling growth, silicon, white root disease

INTRODUCTION

Silicon (Si) has garnered increasing recognition in plant science for its multifaceted role in improving plant growth and productivity. Though not classified as an essential element, Si enhances physiological functions in many crops. Recent studies have demonstrated that Si application significantly enhances plant vigour by improving root architecture, photosynthetic capability, and chlorophyll content, in addition to stimulating nutrient uptake efficiency. For example, Ashfaq *et al*. (2024) reported that Si enhanced the root functional traits, such as length, moisture and nutrient uptake, while improving the photosynthesis, stomatal conductance, and overall canopy physiology in wheat under drought stress. Similarly, Sabir *et al.* (2024) showed that soil-applied Si in maize under combined drought and cadmium stress markedly improved physiological resilience, where plant height and chlorophyll content increased (by up to ~18%–26%) and leaf turgor potential was enhanced by approximately 63%, indicating improved drought tolerance. These findings reinforce Si's capacity to promote plant growth and biomass accumulation even in the absence of visible stress.

Beyond growth promotion, Si also functions as a key player in plant defence. Extensive research on crop plants, such as rice and cucumber, has demonstrated that Si supplementation leads to increased resistance against fungal pathogens (Ma & Yamaji, 2015). Similarly, in rubber rootstock inoculated with *Rigidoporus* (*R.*) *microporus*, the application of soluble Si significantly improves physiological parameters, including relative chlorophyll content, photosynthetic rate, stomatal conductance, and transpiration rate. It was also found to reduce disease incidence by 55.05%, which represents a markedly higher suppression compared with 25.57% achieved using propiconazole (Shaikh Abd Hadi *et al*., 2022). Complementary findings by Shabbir *et al*. (2020) further demonstrated that combining Si with microbial co-inoculants not only enhanced disease suppression but also promoted seedling growth. Similarly, Najihah *et al.* (2015) emphasised the protective role of Si accumulation in plant tissues against fungal penetration.

Article History
Accepted: 11 March 2026
First version online: 30 June 2026
Cite This Article:
Abdul Munir, F.D., Sulaiman, Z., Ahmad, K. & Ariffin, M.R. 2026. Role of silicon fertiliser in enhancing growth and suppressing white root disease (*Rigidoporus microporus*) in rubber seedlings (*Hevea brasiliensis*). Malaysian Applied Biology, 55(2): 41-53. https://doi.org/10.55230/mabjournal.v55i2.3629

Si-induced resistance mechanisms include the fortification of cell walls via lignin and callose deposition, activation of antioxidant enzymes (such as peroxidase, catalase & superoxide dismutase), and stimulation of systemic acquired resistance pathways. Silicon application in tomato was found to reduce bacterial wilt symptoms by suppressing the virulence gene expression and inhibiting biofilm formation in *Ralstonia solanacearum* (*Wang et al.*, 2022).

In the context of Malaysia's rubber industry, the relevance of Si becomes particularly apparent. Rubber remains a vital economic crop, contributing RM20.43 billion in export earnings in 2023 alone (Association of Natural Rubber Producing Countries, 2023). However, the sector is under persistent threat from the white root disease, caused by *R. microporus*, which is notorious for causing tree mortality, yield decline, and long-term stand losses. Conventional control methods, including soil fumigation, trenching, and fungicides, are often ineffective or unsustainable. Given Si's known benefits in enhancing both plant growth and disease resistance, there is strong justification to explore its role as a component in white root disease management for rubber seedlings.

Although Si is the second-most abundant element in the Earth's crust, much of it exists in the soil in forms that are not readily available for plant uptake, such as crystalline silicates (Greger *et al.*, 2018). Silicic acid, a soluble and neutral form of Si, is primarily taken up by plants and commonly found in soil solution at a concentration ranging between 0.1 and 0.6 mM, approximately two orders of magnitude greater than that of phosphorus (Yan *et al.*, 2018). The availability and amount of this element are influenced by the properties of soil, including pH, clay content, organic matter, iron or aluminium oxides/hydroxides (Fraysse *et al.*, 2009; Lisztes-Szabó *et al.*, 2020) and microbial activities (Raturi *et al.*, 2021). Si uptake by plants is largely passive, occurring through the transpiration stream (Fauteux *et al.*, 2005). Monocotyledonous species, especially grasses, are known to accumulate a higher Si level (0.3%–1.2% of dry weight), with rice exhibiting an exceptionally high concentration, reaching up to 10% (Orzoł *et al.*, 2023).

Si fertilisers are derived from both organic and inorganic sources, such as those derived from rock powders (volcanic tuff, natural zeolites, etc.), industrial by-products (blast furnace slag, steel slag, fly ash, bottom ash, etc.), and other materials, such as calcium silicate, sodium silicate, potassium silicate, and soluble silica fertiliser (Kovács *et al.*, 2022). The solubility of Si varies significantly across different forms of fertiliser (Schaller *et al.*, 2021), with liquid formulations typically exhibiting near-complete solubility (Kovács *et al.*, 2022). Upon dissolution, silicon from these fertiliser sources is converted into monosilicic acid (H_4SiO_4), which represents the principal bioavailable form for plant uptake. This variation in solubility is critical, as it determines the release of silicon into a soil solution as monosilicic acid (H_4SiO_4), the only form readily absorbed by plants (Schaller *et al.*, 2021).

Calcium silicate, which is frequently applied in paddy systems, functions as a liming agent by raising soil pH through the release of orthosilicate and calcium ions. However, its silicon release is relatively slow compared with those of more soluble sources, such as potassium or sodium silicate (Chong *et al.*, 2022). Potassium silicate is highly soluble and provides dual potassium and silicon nutrition, but it may interfere with soil potassium balance (Emerald Harvest, 2024). Sodium silicate, however, delivers Si in a readily available form and allows for precise dosage control in controlled environments. Although it introduces Na^+, the concentration can be managed effectively in glasshouse settings. Its high solubility and rapid uptake make it ideal for mechanistic studies on growth and disease suppression, justifying its selection in the present study (Jones & Handreck, 1967; Emerald Harvest, 2024).

However, despite extensive studies on silicon application in annual and semi-perennial crops, information on its role in rubber seedlings, particularly at the nursery stage and in relation to the white root disease, remains limited.

Therefore, this study's first objective was to determine the optimal concentration of Si for enhancing the growth performance of rubber seedlings, specifically in terms of plant height, stem girth, chlorophyll content, and biomass, and the second objective was to evaluate the effectiveness of different Si concentrations in suppressing *R. microporus* in rubber seedlings.

MATERIALS AND METHODS

Plant materials and fertiliser preparation

Three-month-old rubber seedlings from the clone RRIM 2002, characterised by one whorl of leaves, were obtained from the Rubber Industry Smallholders Development Authority's (RISDA) nursery in Jasin, Melaka, Malaysia. The seedlings were then transplanted into new polybags measuring 45.72×45.72 cm, each containing 20 kg of mixed soils in a 9:1 ratio of topsoil to sand. Sodium silicate liquid at an analytical reagent grade (34.2% SiO_2) was used as the Si source. Four treatment levels (0, 0.5, 1.0 & 2.0 g) were prepared, each in 100 mL of distilled water per plant.

Experimental design and treatments

The experimental setup was established at a nursery plot at Ladang 15, Universiti Putra Malaysia, Selangor, Malaysia. The experimental design was a randomised complete block arrangement with three replications. Each treatment within a replication consisted of four seedlings, which served as subsamples for data collection. The treatments consisted of Si at four different concentrations (0 g, 0.5 g, 1.0 g, 2.0 g per seedling). The silicon treatment levels applied in this study are summarised in Table 1. Si was applied as a one-time treatment, two weeks after transplanting. The seedlings were also applied with a compound fertiliser, which was RISDA 1 (10.7% nitrogen, 16.6% phosphorous, 9.5% potassium & 2.4% magnesium), as recommended by RISDA.

Table 1. Experimental treatments

Treatment code	Si concentration (g per seedling)*
S1	0 g
S2	0.5 g
S3	1.0 g
S4	2.0 g

*Sodium silicate solution (34.2% SiO_2) was prepared in 100 mL of distilled water and applied once per seedling

Assessment of growth parameters

In the first experiment, the effect of different Si concentrations on rubber seedling growth was assessed over 11 months. The plant growth parameters collected from the experiment were stem height, girth size, chlorophyll content, and whole-plant biomass partitioned into aboveground (shoot) and belowground (root) components. Stem height and girth size were measured by using a measuring tape and a digital calliper, respectively. A Minolta SPAD-502 chlorophyll meter was used to determine the chlorophyll content. The output is expressed as a unitless SPAD index, which correlates with chlorophyll content but does not directly represent absolute concentration, such as mg/m² or mg/g FW.

Disease suppression assessment

Disease suppression effects were evaluated in a second experiment using the same experimental design, treatment levels, and replication structure as in the first experiment. Silicon was applied once per seedling at four concentrations (0 g, 0.5 g, 1.0 g & 2.0 g per seedling) in the form of a sodium silicate solution (34.2% SiO_2). Each treatment consisted of three replications, with four seedlings per treatment per replication. The seedlings were artificially inoculated with *R. microporus* following a three-month pre-treatment with the Si fertiliser. Disease assessments comprised the evaluation of disease incidence and severity, calculation of the area under the disease progression curve, and the reduction of infection in rubber seedlings over eight months.

Preparation of *R. microporus* culture and inoculum (rubber wood blocks)

A slant culture of *R. microporus* was obtained from Universiti Putra Malaysia's Collection Centre at the Department of Plant Protection. Then, it was sub-cultured on potato dextrose agar at 28°C for 7–10 days until the agar surface was fully colonised by mycelial growth. Rubber wood blocks measuring 3×3×6 cm were used as the inoculum and prepared following the method and procedure described in Idris *et al.* (2006) with some modifications. The blocks were soaked overnight in a Tween 20 solution and subsequently rinsed with tap water. Following this, they were autoclaved for 1 hr at 121°C and then oven-dried at 60°C for three days. After drying, each block was placed in a heat-resistant polypropylene bag, into which 100 mL of malt extract agar was added. The bagged blocks, along with the agar medium, were autoclaved at 121°C for another 45 min. After cooling, each block was inoculated with *R. microporus* by cutting the culture into small pieces and transferring 3 to 4 pieces to the surface of the block (Figure 1). The propylene bags were then sealed and tied up neatly with rubber bands, and then incubated in a dark-closed chamber at room temperature for 4−8 weeks until the blocks were fully covered by *R. microporus* (Figure 1). Only blocks that exhibited active, complete mycelial colonisation and were free from contamination by other fungi or microbes were selected for use in the subsequent artificial infection study.

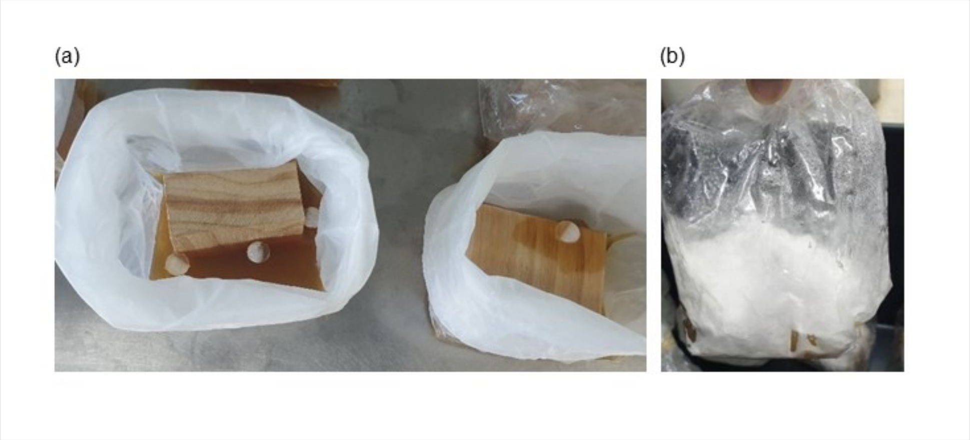

Fig. 1. Inoculation of rubber wood blocks with *R. microporus*: (a) rubber wood blocks inoculated with *R. microporus* and (b) rubber wood blocks fully colonised by *R. microporus* before artificial infection.

Inoculation of rubber seedlings with *R. microporus*

After the three-month pre-treatment period, the rubber seedlings were exposed to *R. microporus* by positioning the infected rubber wood blocks in proximity to the roots of the seedlings. Subsequently, all the seedlings were covered with soil. The glasshouse experiment proceeded for eight months following the inoculation with *R. microporus*.

Disease incidence

Disease incidence (DI) was defined as the proportion of seedlings showing disease symptoms relative to the total number of seedlings assessed, following Campbell and Madden (1990). In this study, DI was recorded at the plant level and scored based on the presence of any visible external symptoms of the white root disease (e.g., foliar discolouration or wilting and/or visible rhizomorph or basidioma). It was determined using the following formula:

$$\text{Disease incidence} = \frac{\text{number of seedlings infected}}{\text{Total number of seedlings assessed}} \times 100$$

Disease severity index on foliar and root

The DSI was used to assess the development of the white root disease caused by *R. microporus* on the infected rubber seedlings and to observe the virulence of the pathogen. The DSI was calculated by scoring the disease symptoms, including foliar discolouration and root rotting, on a scale from 0 to 4. Disease severity based on external disease symptoms (including foliar discolouration and visible rhizomorph development on plant surfaces) was assessed monthly for eight months following inoculation according to a visual rating scale adopted from Abdullah *et al.* (2003) and Ilias (2000) as follows: 0 = a healthy plant with green leaves and no visible fungal mycelium on any parts of the plant; 1 = up to three necrotic leaves, with or without visible white rhizomorph on any parts of the plant; 2 = more than three necrotic leaves, with or without visible white rhizomorph on any parts of the plant; 3 = more than three chlorotic leaves, with the formation of basidioma on any parts of the plant; and 4 = formation of a well-developed basidioma and the plant dried. Root disease severity was evaluated at the end of eight-month period, after which the roots were longitudinally sectioned to evaluate the extent of internal rotting based on a severity scale (adopted from Breton *et al.* (2006) and Shabbir *et al*. (2020) as follows: 0 = healthy, no internal rot, 1 = up to 20% rotting of root tissues, 2 = 21% to 50% rotting of root tissues, 3 = 51% to 90% rotting of root tissues, and 4 = more than 90% rotting of root tissues. The DSI on foliar and root symptoms was calculated using the formula derived from Chiang *et al.* (2017):

$$\text{Disease severity index} = \frac{\text{number of seedlings in rating} \times \text{rating}}{\text{Total number of seedlings assessed} \times \text{highest rating}} \times 100$$

Area under the disease progress curve

The disease progression curve was generated based on the disease incidence to evaluate the effectiveness of the treatment in suppressing the root rot disease in rubber. The area under the disease progression curve (AUDPC) was employed to quantify disease progress over time, following the monomolecular model described in Campbell and Madden (1990). The AUDPC is calculated as follows:

$$\text{AUDPC} = \sum_{i}^{n-1} \frac{(y_i + y_{i+1})}{2(t_{i+1} - t_i)}$$

where:

y_i and y_{i+1} = Disease severity ratings at i^{th} and $(i+1)^{th}$ observations, respectively
$t_{i+1}-t_i$ = Time interval between two consecutive observations
t_i = Assessment time (days)
n = Number of assessment times

Disease reduction

The efficacy of treatment was assessed based on the white root rot disease reduction (DR), calculated according to Khairulmazmi *et al.* (2020) as follows:

$$\text{Disease reduction} = \frac{\text{DI of positive control} - \text{DI of treatment}}{\text{DI of positive control}} \times 100$$

Treatment efficacy

The effectiveness of Si treatment in suppressing the white root disease was quantified using treatment efficacy (TE), calculated based on the reduction in disease progression over time. The AUDPC was computed following the method in Campbell and Madden (1990), which used disease severity scores recorded at monthly intervals. TE was then determined using the following formula:

$$\text{Treatment efficacy} = \frac{\text{AUDPC}_{\text{control}} - \text{AUDPC}_{\text{treatment}}}{\text{AUDPC}_{\text{control}}} \times 100$$

where $\text{AUDPC}_{\text{control}}$ refers to the cumulative disease severity in the untreated group and $\text{AUDPC}_{\text{treatment}}$ refers to the cumulative disease severity in the Si-treated group. This value reflects the relative reduction in disease progression attributable to the Si application.

Statistical analysis

The data were subjected to a two-way analysis of variance at $p<0.05$ using the PROC GLM procedure in the SAS software version 9.4 developed by SAS Institute Inc. The significant difference among the means of a parameter was determined using Tukey's Honestly Significant Difference (HSD) test at $p \leq 0.05$.

RESULTS

Plant growth evaluation

The result showed that plant height increased progressively across all treatments over time (Figures 2 & 3). Although the S3 treatment (1.0 g of Si) consistently demonstrated numerically greater height growth, particularly from Month 2 to Month 5, the differences among treatments were not statistically significant at any time point (*p*≤0.05). In contrast, significant treatment effects on girth increment were detected at Month 1, Month 5, and Month 10 (*p*≤0.05), as shown in Figure 4. For instance, at Month 1, S4 (2.0 g of Si) recorded the highest girth increment, which was significantly greater than those of S1 and S2, while the girth increment in S3 (1.0 g of Si) was statistically comparable to that of S4.

Chlorophyll content remained statistically similar across treatments during the early months (Figure 5). However, significant differences were observed at Month 7 and Month 11 (*p*≤0.05). At Month 7, S4 showed a higher chlorophyll content (63.03) compared with that of S1 (59.10). On the other hand, the chlorophyll contents in S2 (60.37) and S3 (61.13) were statistically comparable. At Month 11, a clear separation was observed between the treatments. S4 exhibited the highest chlorophyll content, with a mean of 68.27, significantly surpassing all other treatments. S3 recorded a significantly higher chlorophyll content (64.27) compared with that of S1 (60.57), reinforcing the positive response of leaf greenness to increased Si application.

The effects of different Si concentrations on the shoot and root biomass of the rubber seedlings after 11 months showed that the shoot biomass was not significantly affected by Si treatment (*p*>0.05), as shown in Figure 6. Although S4 recorded the highest shoot biomass at 38.11 g, followed by S2 (37.56 g), S3 (37.13 g), and S1 (36.57 g), the biomasses in all treatments were statistically comparable. In contrast, the root biomass was significantly influenced by Si concentration (*p*≤0.05). S4 produced the highest root biomass with a mean of 88.66 g, which was significantly greater than that of S1 (65.28 g). S2 (84.80 g) and S3 (80.44 g) also exhibited significantly higher root biomass values than that of S1 but were not statistically different from each other.

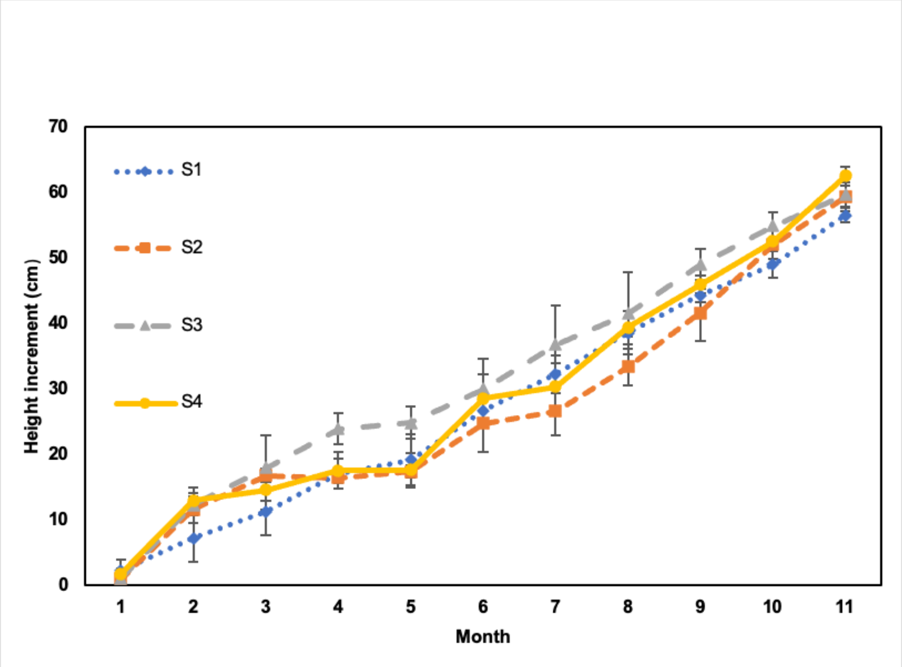

Fig. 2. Effect of Si concentration on height increment of rubber seedlings inoculated with *R. microporus* over 11 months of observation. Note: S1 = 0 g; S2 = 0.5 g; S3 = 1.0 g; S4 = 2.0 g. Error bars on lines represent standard error (*n*=3). Statistical differences among treatments at each month were determined using Tukey's HSD (*p*≤0.05).

Fig. 3. Plant height of rubber seedlings after 11 months of treatment, showing no significant differences between treatment groups. Note: S1 = 0 g; S2 = 0.5 g; S3 = 1.0 g; S4 = 2.0 g.

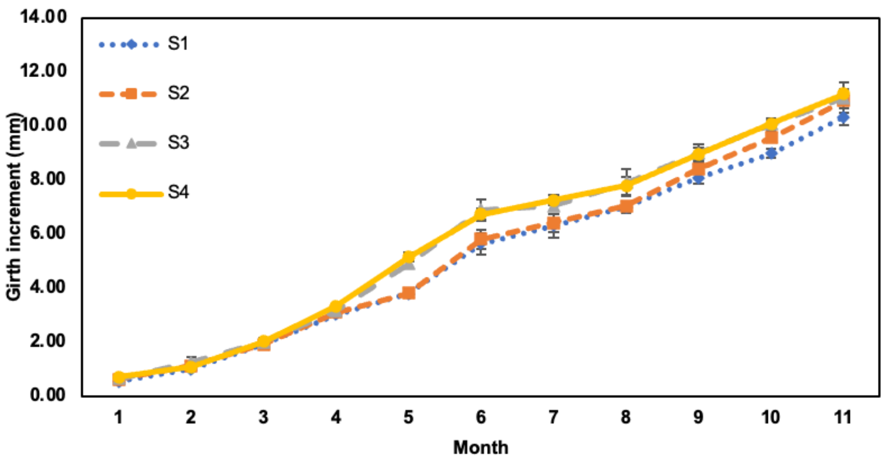

Fig. 4. Effect of Si concentration on girth increment of rubber seedlings inoculated with *R. microporus* over 11 months of observation. Note: S1 = 0 g; S2 = 0.5 g; S3 = 1.0 g; S4 = 2.0 g. Error bars on lines represent standard error (*n*=3). Statistical differences among treatments at each month were determined using Tukey's HSD (*p*≤0.05).

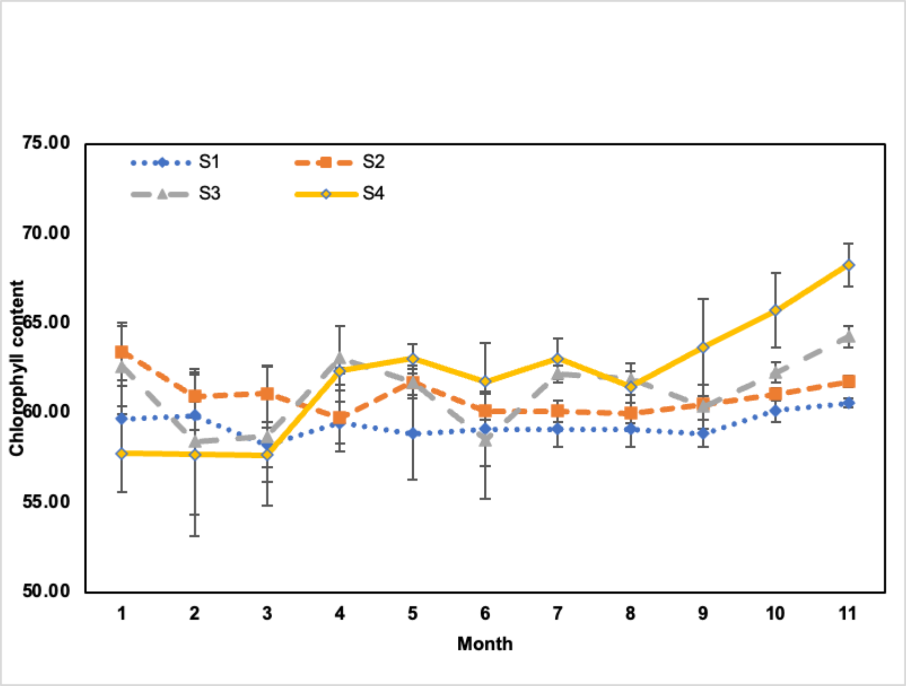

Fig. 5. Effect of Si concentration on chlorophyll content of rubber seedlings inoculated with *R. microporus* over 11 months of observation. Note: S1 = 0 g; S2 = 0.5 g; S3 = 1.0 g; S4 = 2.0 g. Error bars on lines represent standard error (*n*=3). Statistical differences among treatments at each month were determined using Tukey's HSD ($p \leq 0.05$).

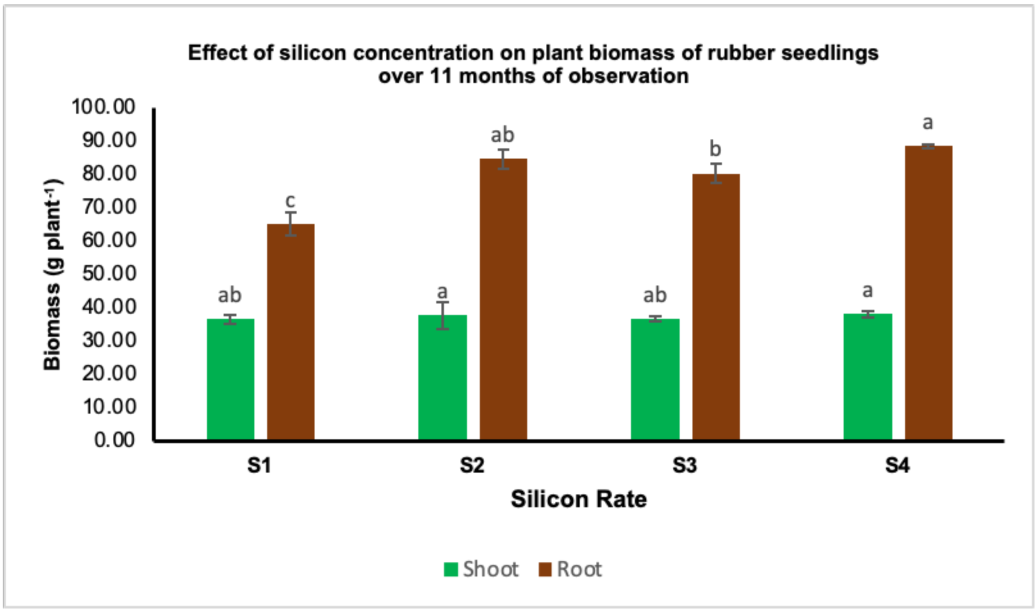

Fig. 6. Effect of Si concentration on plant biomass of rubber seedlings over 11 months of observation. Note: S1 = 0 g; S2 = 0.5 g; S3 = 1.0 g; S4 = 2.0 g. Bars represent means with the same letter that are not significantly different, according to Tukey's HSD test ($p \leq 0.05$). Error bars represent standard error (*n*=3).

Disease assessment

Disease incidence

The progression of disease incidence in the rubber seedlings inoculated with *R. microporus* at different Si concentrations across eight months is presented in Figure 7. The rubber seedlings in the negative control (S0), which were not inoculated, consistently recorded 0% disease incidence throughout the observation period, confirming the absence of natural infection under the experimental condition. All Si-treated groups (S1 to S4) remained asymptomatic during the first month post-inoculation.

By the second month, disease symptoms began to emerge in S1, S2, and S3, with incidences of 33.33%, 25.00%, and 16.67%, respectively. Notably, S4 maintained complete resistance (0%), suggesting a potential delay in pathogen development. At Month 3, disease incidence increased in all Si-treated groups except S4, which maintained the lowest recorded incidence at 25%, while S1 displayed the highest at 58.33%.

Over time, disease severity continued to rise across all treatments, except the negative control. By the final observation, at Month 8, 100% disease incidence was recorded in the seedlings treated with S1 and S2, whereas the seedlings receiving S4 exhibited a markedly lower incidence of 50%, indicating a sustained reduction in disease progression. This pattern suggests that a higher Si concentration, particularly at S4 (2.0 g of Si), may have delayed or suppressed pathogen establishment, although no statistical analysis was conducted to verify significance.

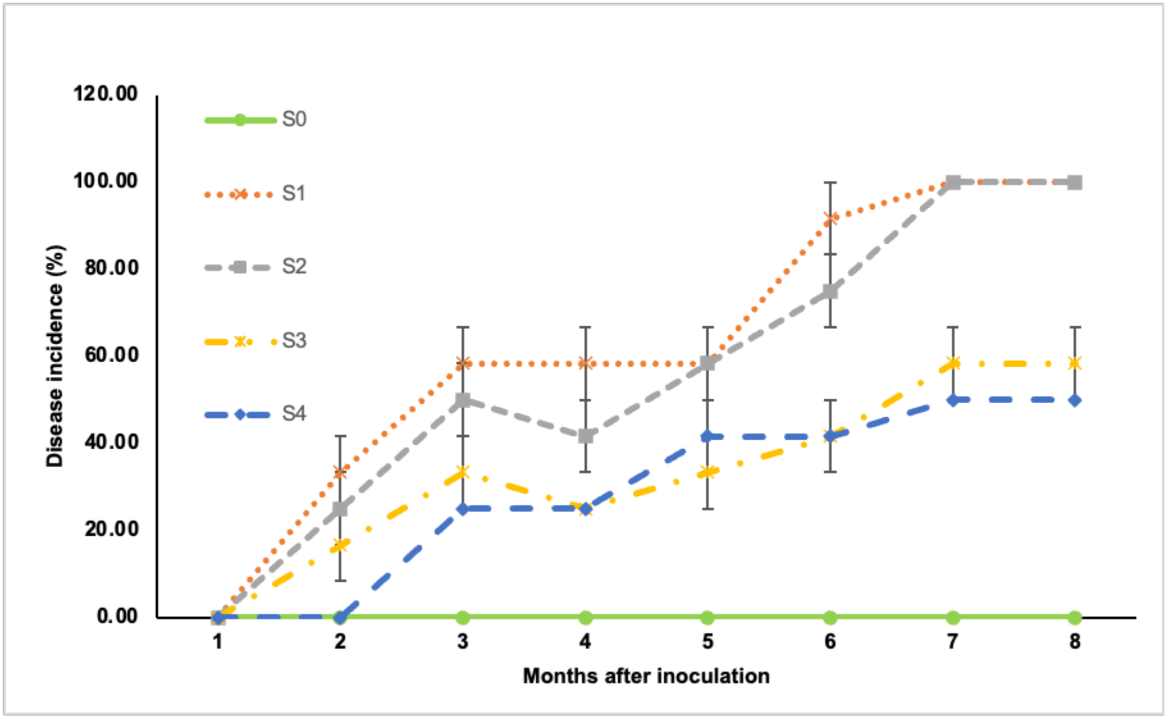

Fig. 7. Effect of Si concentration on disease incidence of rubber seedlings throughout eight months of infection. Note: S0 = without any application of Si and infection; S1= 0 g; S2 = 0.5 g; S3 = 1.0 g; S4 = 2.0 g. Values are means from three replicates, with vertical bars for standard errors.

Following the pattern illustrated in Figure 7, Table 2 summarises the effect of Si concentration on the AUDPC, DR, and TE after eight months of infection. A clear inverse relationship was observed between Si concentration and the AUDPC, indicating that increased Si concentration effectively delayed disease progression. The highest AUDPC value (450.00 unit²) was recorded in S1, while the application of S4 resulted in the lowest AUDPC value of 208.34 unit², reflecting the slowest rate of disease development. The AUDPC value decreased as the Si dosage increased, indicating that the overall plant disease decreased over time with higher Si concentration. The application of S1 achieved a DR of 41.67%, while S4 improved disease suppression, reaching 50.00% DR. This highlights the protective potential of Si against *R. microporus* infection. Additionally, TE improved from 11.11% in the S2 treatment to 53.70% in the S4 treatment. The result demonstrates the dose-dependent mitigation of white root disease symptoms through Si supplementation, with the highest concentration (S4) offering the most substantial protection.

Table 2. Effect of Si concentration on AUDPC, DR, and TE in rubber seedlings inoculated with *R. microporus* after eight months of observation

Treatment	AUDPC (unit²)	DR (%)	TE (%)
S1	450.00	-	-
S2	400.00	0.00	11.11
S3	237.50	41.67	47.22
S4	208.34	50.00	53.70

Note: S1 = 0 g; S2 = 0.5 g; S3 = 1.0 g; S4 = 2.0 g. Values are means from three replicates.

Disease severity index on foliar

Disease severity in the rubber seedlings infected with *R. microporus* was assessed based on visible foliar symptoms and expressed as a percentage, where a lower severity value indicated more effective suppression of the white root disease.

The progression of disease severity in rubber seedlings subjected to different Si concentrations over eight months following *R. microporus* inoculation is shown in Figure 8. As expected, the seedlings in the control group (S0), which were uninoculated, remained symptom-free throughout the study. In contrast, all inoculated treatments (S1 to S4) displayed varying levels of disease severity over time. From the second month onward, S3 (1.0 g of Si) and S4 (2.0 g of Si) consistently exhibited lower disease severity compared with those of S1 (0 g of Si) and S2 (0.5 g of Si), with S4 maintaining the lowest severity beginning in the third month. At Month 2, the values of the disease severity of foliar symptoms (DSF) recorded for S1, S2, S3, and S4 were 10.42%, 6.25%, 4.17%, and 0%, respectively. By the eighth month, the highest DSF was observed in S1 at 77.10%, followed by S2 at 58.33%, while S3 and S4 showed substantially lower severities of 29.18% and 18.75%, respectively. The finding suggests the dose-dependent suppressive effect of Si on disease development in rubber seedlings.

The AUDPC, DR, and TE in the rubber seedlings inoculated with *R. microporus* and treated with varying concentrations of Si are summarised in Table 3. Across the eight-month assessment period, a clear trend emerged, where increasing Si concentration was associated with decreased disease progression, as reflected in the lower AUDPC values. The highest Si concentration (S4) resulted in the lowest AUDPC value of 67.71 unit², indicating effective disease suppression, in contrast to that of the untreated control (0 g of Si), which was the highest at 248.98 unit². This corresponded to a 75.68% reduction in disease severity and a protection index of 72.81%.

The seedlings receiving S4 exhibited an AUDPC value of 91.57 unit², reflecting a 62.15% reduction in disease severity and a treatment efficacy of 63.22%. In contrast, the S2 treatment recorded an AUDPC value of 168.75 unit², representing only a 24.35% reduction and a treatment efficacy of 32.23%. The finding further reinforces the dose-dependent suppressive effect of Si on white root disease severity and progression in rubber seedlings.

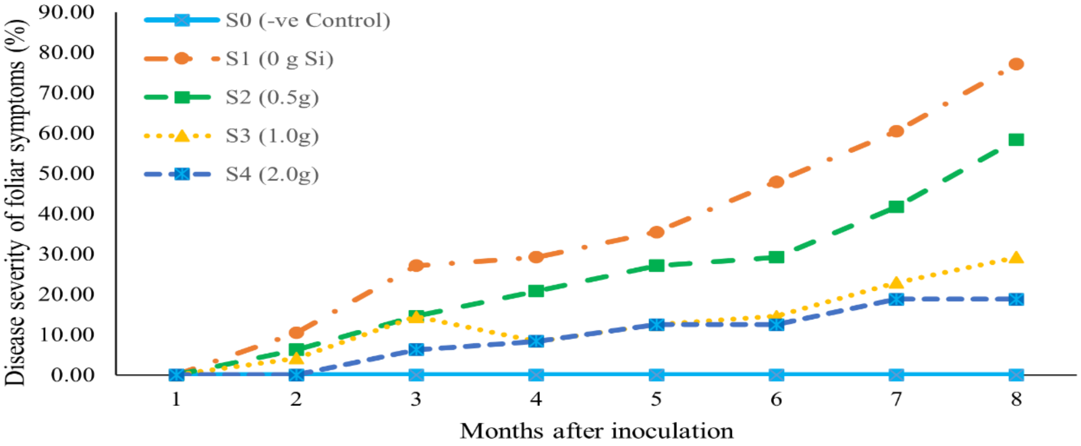

Fig. 8. Effect of different Si concentrations on the percentage of disease severity of foliar symptoms in rubber seedlings over eight months of observation. Values are means from three replicates. Note: S0 = neither Si application nor infection; S1 = 0 g; S2 = 0.5 g; S3 = 1.0 g; S4 = 2.0 g.

Table 3. Effect of different Si concentrations on AUDPC, DR, and TE after eight months of infection on the disease severity of foliar symptoms

Treatment	AUDPC (unit²)	DR (%)	TE (%)
S1	248.98	-	-
S2	168.75	24.35	32.23
S3	91.57	62.15	63.22
S4	67.71	75.68	72.81

Note: Values are means from three replicates. S1 = 0 g; S2 = 0.5 g; S3 = 1.0 g; S4 = 2.0 g.

Disease severity index of internal root rot symptoms

The influence of varying Si concentrations on the DSI and DR of internal root rot symptoms in the rubber seedlings following eight months of infection with *R. microporus* is presented in Table 4. The effectiveness of each Si concentration in mitigating disease impact was quantified through DR.

The DSI and DR values varied significantly among treatments. The seedlings treated with the highest Si concentration (S4) exhibited the lowest disease severity (3.87%), which was statistically lower than that of the seedlings treated with S1 (7.96%) and S2 (7.11%). Although S4 recorded the lowest DSI, its value was statistically comparable to that of S3 (4.83%). Among all inoculated treatments, S1 exhibited the highest DSI, indicating the most severe internal root rot symptoms. The negative control (S0), which was neither inoculated nor treated with Si, recorded no disease symptoms, confirming the absence of infection.

In terms of disease reduction, S4 achieved the highest DR at 75.93%, significantly outperforming S2, which achieved only 18.52%. S3 also demonstrated strong disease suppression, with a DR of 62.04%. Although S2 moderately reduced disease severity compared with S1, it resulted in the lowest disease reduction among all Si treatments. The finding confirms that a higher Si concentration is more effective in suppressing internal root rot development in rubber seedlings.

Table 4. Effect of different Si concentrations on DSI and DR of internal root rot symptoms in rubber seedlings eight months after inoculation with *R. microporus*

Treatment	DSI (%)	DR (%)
S0	0.71 ± 0.00^c	-
S1	7.96 ± 0.39^a	-
S2	7.11 ± 0.00^a	18.52 ± 7.41^c
S3	4.83 ± 0.22^b	62.04 ± 6.48^b
S4	3.87 ± 0.26^b	75.93 ± 4.89^a

Note: S1 = 0 g; S2 = 0.5 g; S3 = 1.0 g; S4 = 2.0 g. Values presented as mean ± standard error (*n*=3). Mean followed by a letter indicates significant differences at $p≤0.05$ according to Tukey's HSD test.

DISCUSSION

Plant growth performance

The evaluation of growth responses in the rubber seedlings indicated that Si supplementation did not consistently enhance all measured parameters. This observation aligns with earlier findings suggesting that plant responses to Si are highly species-specific and influenced by environmental and physiological contexts (Richmond & Sussman, 2003; Shaikh Abd Hadi *et al.*, 2022). Variability in Si responsiveness has been extensively documented, with certain species, particularly Si-accumulating monocots, demonstrating more pronounced physiological benefits than others (Pavlović *et al.*, 2021).

In the present study, although the S3 treatment showed a tendency to promote height increment during the early growth phase, the effect was not statistically significant. This result further supports the notion that shoot elongation may not be the primary trait influenced by Si in woody or non-accumulator species, such as *Hevea* (*H.*) *brasiliensis*. In contrast, stem girth responded more consistently to Si application, indicating that radial growth may be more sensitive to Si than vertical elongation. This observation is in agreement with findings in herbaceous peony *(Paeonia lactiflora)*, where Si application enhanced stem strength through increased secondary cell wall thickness and lignin accumulation in subepidermal tissues, thereby improving mechanical support (Zhao *et al.*, 2021). Collectively, these findings highlight the role of Si in reinforcing structural tissues rather than promoting elongation growth.

In addition to stem development, Si supplementation was associated with improved chlorophyll status at later growth stages, particularly at higher Si application. This enhancement may be attributed to Si's role in preserving the chloroplast structure and photosynthetic efficiency under stress or prolonged cultivation. Several studies have shown that Si mitigates oxidative damage by enhancing antioxidant enzyme activity and reducing lipid peroxidation, thereby stabilising chlorophyll pigments (Singh *et al.*, 2022). Moreover, improved nitrogen-use efficiency under adequate Si conditions may further contribute to sustained chlorophyll synthesis and retention.

Interestingly, while shoot biomass remained statistically comparable across treatments, root biomass demonstrated a clear and significant positive response to increasing Si concentration, with the highest value also observed in the S4 treatment. This preferential allocation of biomass to root tissues may reflect Si's role in enhancing root architecture, possibly through increased lignification, root elongation, and branching. This preferential root allocation aligns with findings from Tripathi *et al*. (2021), who reported increased root weight, branching, and surface area in various crop species following Si application. Supporting this, Ramírez-Olvera *et al*. (2021) demonstrated a 27.5% increase in root dry biomass in rice under osmotic stress at 1 mM of Si. For rubber seedlings, a robust root system is critical not only for water and nutrient uptake but also for stable establishment under field conditions.

Overall, the findings underscore the selective and organ-specific responses of rubber seedlings to Si concentration. While the shoot-related parameters, which were height and biomass, showed limited responsiveness, traits associated with structural reinforcement (girth), photosynthetic stability (chlorophyll content), and belowground development (root biomass) responded positively to higher Si concentration. These results reaffirm that Si acts not as a universal growth promoter but as a conditional beneficial element, particularly effective under specific physiological targets and growth stages in certain crop species.

White root disease suppression

Following the limited response observed in plant growth parameters, the second experiment of this study shifted focus to disease-related assessment to clarify the role of Si in plant defence. Given that Si is widely recognised for its function in fortifying plant defence mechanisms, particularly through reinforcing cell walls, stimulating phytoalexin production, and limiting pathogen ingress, the second assessment aimed to determine Si's potential in suppressing the white root disease caused by *R. microporus*. The control group (S0), which received no Si, remained disease-free throughout the eight months, thereby establishing a reliable baseline for treatment comparison.

The disease incidence data clearly demonstrate a protective role of silicon in mitigating *R. microporus* infection in rubber seedlings. The seedlings receiving higher Si concentrations consistently exhibited lower disease incidence and delayed symptom development compared with those receiving zero-silicon and low-silicon treatments. This is consistent with the established role of Si in strengthening plant defence primarily through the structural reinforcement of root tissues and the restriction of initial pathogen ingress. Previous studies have demonstrated that Si accumulates in the epidermal and cortical cell walls of roots, forming physical barriers that limit hyphal penetration, and thereby reduce successful infection establishment (Ahammed & Yang, 2021; Verma *et al*., 2024; Kumar *et al*., 2025). The delayed onset of symptoms in S4 and S3 treatments also pointed toward the role of Si in suppressing initial pathogen establishment. This is supported by Shaikh Abd Hadi *et al.* (2022), who reported a 55% reduction in disease incidence in rubber rootstock seedlings treated with soluble Si versus only a 25% reduction using propiconazole.

Consistent with these findings, disease progression, as reflected by the AUDPC, declined progressively with increasing silicon concentration. The lowest disease progression was consistently associated with the highest silicon treatment, indicating that elevated silicon availability effectively slowed pathogen development over time, as shown in Table 2. The dose-dependent reduction has been similarly reported in cereal crops, such as rice and wheat, where Si limits pathogen ingress by forming amorphous silica deposits in the apoplast (Ma & Yamaji, 2006; Wang *et al*., 2017). Similarly, in *Arabidopsis thaliana* engineered to accumulate Si, enhanced resistance was restored against powdery mildew in immune-compromised mutants, implying that apoplastic Si deposition provides broad-spectrum protection (Wang *et al*., 2020). Furthermore, an *in vitro* application of 1.7 mM of Si in wheat significantly delayed the latent period, reduced the AUDPC, and minimised lesion formation caused by *Fusarium* spp., reinforcing the evidence that Si physically impedes pathogen ingress (Sakr, 2022).

Assessment of disease severity further confirmed the suppressive effect of silicon on both foliar and internal root symptoms. Treatments with higher Si concentrations consistently exhibited lower foliar disease severity values throughout the assessment period compared with those of the untreated control. The divergence in the foliar symptom expression among the treatments from the early months of infection likely reflects differences in a host's physiological responses to root colonisation by *R. microporus*. As the pathogen initially infects a host and develops within its root tissues, foliar symptoms, such as leaf yellowing, wilting, and defoliation, emerge as secondary responses associated with impaired water and nutrient transport, often becoming visible before severe internal root decay is fully established (Suryanto *et al*., 2017; Go *et al*., 2021; Longsaward *et al*., 2023).

Likewise, in a field study on wheat blast, the foliar application of Si at the highest concentration (1.92 t·ha^{-1}) led to a 75.68% reduction in the AUDPC compared with that of the untreated control (Oliveira *et al.*, 2019). This result underscores a strong negative correlation between Si dosage and foliar disease severity, demonstrating the efficacy of Si in strengthening plant resilience against pathogenic stress. These findings reflect a broader consensus that Si is particularly effective in enhancing resistance under pathogen-challenged conditions rather than promoting growth under non-stressed conditions.

More critically, the silicon application substantially suppressed the internal root rot development in the rubber seedlings, with the highest silicon treatment exhibiting the greatest reduction in internal tissue damage. The finding is consistent with those of the research on disease severity in bananas through enhanced structural and biochemical defences. Silicon treatment has been shown to reduce the symptoms of Fusarium wilt in bananas by increasing the silicon deposition in roots and increasing the accumulation of phenolic compounds, which collectively contribute to structural reinforcement against pathogen invasion (Fortunato *et al*., 2012; Zakaria *et al*., 2024). Similarly, in sugarcane, silicon application enhanced resistance to the smut disease by promoting lignification and strengthening vascular tissues, thereby limiting pathogen proliferation (Deng *et al*., 2020). These studies support the role of silicon in reinforcing structural and biochemical defences that restrict pathogen development. Moreover, the results further indicate that although the highest Si concentration (S4) provided the strongest suppression of disease severity, the intermediate concentration (S3) also conferred substantial protection, albeit to a lesser extent. This suggests that even moderate levels of Si can offer meaningful disease suppression, while higher concentrations may be more effective in optimising resistance. Supporting this, recent experimental studies have demonstrated the efficacy of Si and various silicate compounds in mitigating root rot severity across different crops. For instance, in oil palm and ginseng, Si application significantly reduced disease severity (Najihah *et al*., 2015; Abbai *et al*., 2019; Mayzaitul-Azwa *et al*., 2025). Similarly, Abd-El-Kareem *et al.* (2019) reported that the use of silicon, potassium, sodium, and calcium silicates applied as soil amendments or foliar sprays markedly decreased the incidence and severity of black root rot in strawberry plants.

Taken together, these results reinforce the concept that Si functions both as a structural and physiological barrier to infection. Its multifaceted role in disease resistance spans mechanical fortification, modulation of phytohormonal signalling, and priming of inducible defence mechanisms. The consistent pattern of reduced disease incidence, lower AUDPC values, and suppressed root and foliar symptom expression across increased Si concentration strongly suggests that Si should be considered a key component in integrated disease management strategies, particularly for perennial crops susceptible to root pathogens, such as *H. brasiliensis*.

CONCLUSION

The results of this study clearly demonstrate the potential of Si application in suppressing the white root disease caused by *R. microporus* in rubber seedlings. A dose-dependent response was observed, with higher Si concentrations consistently associated with reduced disease incidence, severity, and progression. The disease suppressive effect of Si appears to be primarily linked to passive defence mechanisms, as reflected by improvements in girth increment and root biomass, which may delay pathogen invasion and restrict disease development. Enhanced root system development likely improved physical resistance and tolerance against infection, rather than directly inhibiting pathogen activity. However, a longer evaluation period may be required to fully elucidate the effect of Si on trunk girth development in perennial woody crops, such as rubber. Importantly, the results indicate that all Si-treated seedlings performed better than untreated controls, suggesting that Si fertilisation can be applied progressively, beginning at the nursery stage and continuing through young to mature rubber plants, to enhance disease resilience. Therefore, Si fertilisation represents a sustainable and practical strategy for integrated disease management in *H. brasiliensis*.

ACKNOWLEDGEMENTS

The authors would like to express their sincere gratitude to the Public Service Department of Malaysia for the scholarship awarded to the first author under the postgraduate study sponsorship scheme. Special thanks are also extended to the Rubber Industry Smallholders Development Authority for the continuous support and facilitation throughout the research period.

ETHICAL STATEMENT

Not applicable.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

REFERENCES

Abbai, R., Kim, Y.J., Mohanan, P., El-Agamy Farh, M., Mathiyalagan, R., Yang, D.U., Rangaraj, S., Venkatachalam, R., Kim, Y.-J. & Yang, D.C. 2019. Silicon confers protective effect against ginseng root rot by regulating sugar efflux into apoplast. Scientific Reports, 9(1): 18259. https://doi.org/10.1038/s41598-019-54678-x

Abdullah, F., Ilias, G.N.M., Nelson, M., Nur Ain Izzati, M.Z. & Umi Kalsom, Y. 2003. Disease assessment and the efficacy of *Trichoderma* as a biocontrol agent of basal stem rot of oil palm. Research Bulletin Science Putra, 11: 31–33.

Abd-El-Kareem, F., Elshahawy, I.E. & Abd-Elgawad, M.M. 2019. Management of strawberry leaf blight disease caused by *Phomopsis obscurans* using silicate salts under field conditions. Bulletin of the National Research Centre, 43: 1. https://doi.org/10.1186/s42269-018-0041-2

Ahammed, G.J. & Yang, Y. 2021. Mechanisms of silicon-induced fungal disease resistance in plants. Plant Physiology and Biochemistry, 165: 200–206. https://doi.org/10.1016/j.plaphy.2021.05.031

Ashfaq, W., Brodie, G., Fuentes, S., Pang, A. & Gupta, D. 2024. Silicon improves root system and canopy physiology in wheat under drought stress. Plant and Soil, 502: 279–296. https://doi.org/10.1007/s11104-023-06202-4

Association of Natural Rubber Producing Countries. 2023. Natural rubber trends & statistics—December 2023 [WWW Document]. URL https://www.anrpc.org (accessed 08.17.25).

Breton, F., Hasan, Y., Lubis, Z. & de Franqueville, H. 2006. Characterization of parameters for the development of an early screening test for basal stem rot tolerance in oil palm progenies. Journal of Oil Palm Research, Special Issue April 2006: 24–36.

Campbell, C.L. & Madden, L.V. 1990. Introduction to Plant Disease Epidemiology. John Wiley and Sons, Hoboken. 728 pp.

Chiang, K.S., Liu, H.I. & Bock, C. 2017. A discussion on disease severity index values. Part I: Warning on inherent errors and suggestions to maximise accuracy. Annals of Applied Biology, 171(2): 139–154. https://doi.org/10.1111/aab.12362

Chong, I.Q., Azman, E.A., Ng, J. ., Ismail, R., Awang, A., Hasbullah, N.A., Murdad, R., Ahmed, O.H., Musah, A.A., Alam, M.A., Awang Besar, N., Tajidin, M.E. & Jalloh, M. B. 2022. Improving selected chemical properties of a paddy soil in Sabah amended with calcium silicate: A laboratory incubation study. Sustainability, 14(20): 13214. https://doi.org/10.3390/su142013214

Deng, Q., Wu, J., Chen, J. & Shen, W. 2020. Physiological mechanisms of improved smut resistance in sugarcane through application of silicon. Frontiers in Plant Science, 11: 568130. https://doi.org/10.3389/fpls.2020.568130

Emerald Harvest. 2024. Understanding silicon supplements: The difference between potassium, sodium, and calcium silicates [WWW Document]. URL https://emeraldharvest.co/sources-of-soluble-silicon/ (accessed 08.17.25).

Fauteux, F., Rémus-Borel, W., Menzies, J. G. & Bélanger, R. R. 2005. Silicon and plant disease resistance against pathogenic fungi. FEMS Microbiology Letters, 249(1):1–6. https://doi.org/10.1016/j.femsle.2005.06.034

Fortunato, A.A., Rodrigues, F.Á., Baroni, J.C.P., Soares, G.C.B., Rodriguez, M.A.D. & Pereira O.P. 2012. Silicon suppresses Fusarium wilt development in banana plants. Journal of Phytopathology, 160(11–12): 674–679. https://doi.org/10.1111/jph.12005

Fraysse, F., Pokrovsky, O.S., Schott, J. & Meunier, J.-D. 2009. Surface chemistry and reactivity of plant phytoliths in aqueous solutions. Chemical Geology, 258(3–4): 97–206. https://doi.org/10.1016/j.chemgeo.2008.10.003

Go, W.Z., Chin, K.L., H'ng, P.S., Wong, M.Y., Luqman, C.A., Surendran, A., Tan, G.H., Lee, C.L., Khoo, P.S. & Kong, W.J. 2021. Virulence of *Rigidoporus microporus* isolates causing white root rot disease on rubber trees (*Hevea brasiliensis*) in Malaysia. Plants, 10(10): 2123. https://doi.org/10.3390/plants10102123

Greger, M., Landberg, T. & Vaculík, M. 2018. Silicon influences soil availability and accumulation of mineral nutrients in various plant species. Plants, 7(2): 41. https://doi.org/10.3390/plants7020041

Idris, A.S., Kushairi, D., Ariffin, D. & Basri, M.W. 2006. Technique for inoculation of oil palm germinated seeds with *Ganoderma*. MPOB Information Series, June 2006: 314.

Ilias G.N.M. 2000: *Trichoderma* and its efficacy as a bio-control agent of basal stem rot of oil palm (*Elaeis guineensis* Jacq.). (Ph.D.) Universiti Putra Malaysia.

Jones, L.H.P. & Handreck, K.A. 1967. Silica in soils, plants and animals. Advances in Agronomy, 19: 107–149. https://doi.org/10.1016/S0065-2113(08)60734-8

Khairulmazmi, A., Juraimi, A. S., Uddin, M. K. & Hasan, M. M. 2020. Pesticide and fungicide calculation. In: Basic Calculations in Agriculture. M.K. Uddin, A.S. Juraimi & M.P. Anwar (Eds.). Universiti Putra Malaysia Press, Serdang. pp. 113–128.

Kovács, S., Kutasy, E. & Csajbók, J. 2022. The multiple roles of silicon nutrition in alleviating environmental stresses in sustainable crop production. Plants, 11(9): 1223. https://doi.org/10.3390/plants11091223

Kumar, A., Choudhary, A., Kaur, H., Singh, K., Guha, S., Choudhary, D.R., Sonkar, A., Mehta, S. & Husen, A. 2025. Exploring the role of silicon in enhancing sustainable plant growth, defense system, environmental stress mitigation and management. Discover Applied Sciences, 7(5): 406.

Lisztes-Szabó, Z., Filep, A.F., Csík, A., Pető, Á., Kertész, T.G. & Braun, M. 2020. pH-dependent silicon release from phytoliths of Norway spruce (*Picea abies*). Journal of Paleolimnology, 63: 65–81. https://doi.org/10.1007/s10933-019-00103-2

Longsaward, R., Pengnoo, A., Kongsawadworakul, P., & Viboonjun, U. 2023. A novel rubber tree PR-10 protein involved in host-defense response against the white root rot fungus *Rigidoporus microporus*. BMC Plant Biology, 23(1): 1–21. https://doi.org/10.1186/s12870-023-04149-3

Ma, J. F. & Yamaji, N. 2006. Silicon uptake and accumulation in higher plants. Trends in Plant Science, 11(8): 392–397. https://doi.org/10.1016/j.tplants.2006.06.007

Ma, J. F. & Yamaji, N. 2015. A cooperative system of silicon transport in plants. Trends in Plant Science, 20(7): 435–442. https://doi.org/10.1016/j.tplants.2015.04.007

Mayzaitul-Azwa, N.J., Shuhada, N.M.T., Hanafi, M.M. & Nurul Huda, A. 2025. Impact of silicon-enriched fertilizer on basal stem rot disease in palm species caused by *Ganoderma boninense*. Pertanika Journal of Tropical Agricultural Science, 48(3): 973–990. https://doi.org/10.47836/pjtas.48.3.18

Najihah, N.I., Hanafi, M.M., Idris, A.S. & Hakim, M.A. 2015. Silicon treatment in oil palms confers resistance to basal stem rot disease caused by *Ganoderma boninense*. Crop Protection, 67: 151–159. https://doi.org/10.1016/j.cropro.2014.10.004

Oliveira, T.B., Aucique-Pérez, C.E. & de Ávila Rodrigues, F. 2019. Foliar application of silicon decreases wheat blast symptoms without impairing photosynthesis. Bragantia, 78(3): 423–431. https://doi.org/10.1590/1678-4499.20180379

Orzoł, A., Cruzado-Tafur, E., Gołębiowski, A., Rogowska, A., Pomastowski, P., Górecki, R.J., Buszewski, B., Szultka-Młyńska, M. & Głowacka, K. 2023. Comprehensive study of Si-based compounds in selected plants (*Pisum sativum* L., *Medicago sativa* L., *Triticum aestivum* L.). Molecules, 28(11): 4311. https://doi.org/10.3390/molecules28114311

Pavlović, J., Kostić, L., Bosnić, P., Kirkby, E.A. & Nikolić, M. 2021. Interactions of silicon with essential and beneficial elements in plants. Frontiers in Plant Science. 12: 697592. https://doi.org/10.3389/fpls.2021.697592

Ramírez-Olvera, S.M., Trejo-Téllez, L.I., Gómez-Merino, F.C., Ruíz-Posadas, L.D.M., Alcántar-González, E.G. & Saucedo-Veloz, C. 2021. Silicon stimulates plant growth and metabolism in rice under conventional and osmotic stress conditions. Plants, 10(4): 777. https://doi.org/10.3390/plants10040777

Raturi, G., Sharma, Y., Rana, V., Thakral, V., Myaka, B., Salvi, P., Singh, M., Dhar, H. & Deshmukh, R. 2021. Exploration of silicate solubilizing bacteria for sustainable agriculture and silicon biogeochemical cycle. Plant Physiology and Biochemistry, 166: 827–838. https://doi.org/10.1016/j.plaphy.2021.06.039

Richmond, K.E. & Sussman, M. 2003. Got silicon? The non-essential beneficial plant nutrient. Current Opinion in Plant Biology, 6(3): 268–272. https://doi.org/10.1016/S1369-5266(03)00041-4

Sabir, A., Waraich, E.A., Ahmad, M., Hussain, S., Asghar, H. N., Haider, A., Ahmad, Z. & Bibi, S. 2024. Silicon-mediated improvement in maize (*Zea mays* L.) resilience: Unrevealing morpho-physiological, biochemical, and root attributes against cadmium and drought stress. Silicon, 16: 3095–3109. https://doi.org/10.1007/s12633-024-02907-y

Sakr, N. 2022. Silicon reduces the severity of *Fusarium* infection on young wheat parts *in vitro*. The Open Agriculture Journal, 16: e187433152207260. https://doi.org/10.2174/18743315-v16-e2207260

Schaller, J., Puppe, D., Kaczorek, D., Ellerbrock, R. & Sommer, M. 2021. Silicon cycling in soils revisited. Plants, 10(2): 295. https://doi.org/10.3390/plants10020295

Shaikh Abd Hadi, S.M.H., Zakaria, L., Mohamed Sidique, S.N., Mohmad Mahyudin, M., Berahim, Z., Idris, M.A. & Mohamed Nor, N. M. I. 2022. Silicon mediates the changes in physiological performance, nutrient uptake, root colonization morphology and secondary metabolite activity in rubber rootstock seedlings (*Hevea brasiliensis*) inoculated with *Rigidoporus microporus*. Plant Pathology, 71(9): 1956–1968. https://doi.org/10.1111/ppa.13621

Shabbir, I., Abd Samad, M.Y., Othman, R., Wong, M.Y., Sulaiman, Z., Jaafar, N.M. & Bukhari, S.A.H. 2020. White root rot disease suppression in rubber plant with microbial co-inoculants and silicon addition. Rhizosphere, 15: 100221. https://doi.org/10.1016/j.rhisph.2020.100221

Singh, P., Kumar, V., Sharma, J., Saini, S., Sharma, P., Kumar, S., Sinhmar, Y., Kumar, D. & Sharma, A. 2022. Silicon supplementation alleviates the salinity stress in wheat plants by enhancing the plant water status, photosynthetic pigments, proline content and antioxidant enzyme activities. Plants, 11(19): 2525. https://doi.org/10.3390/plants11192525

Suryanto, D., Munthe, R.A., Nurwahyuni, I. & Munir, E. 2017. An assay on potential of local *Trichoderma* spp. to control white root rot disease caused by *Rigidoporus microporus* in rubber plant stump. Journal of Pure & Applied Microbiology, 11: 717–723. https://doi.org/10.22207/JPAM.11.2.10

Tripathi, P., Subedi, S., Khan, A. L., Chung, Y.-S. & Kim, Y. 2021. Silicon effects on the root system of diverse crop species using root phenotyping technology. Plants, 10(5): 885. https://doi.org/10.3390/plants10050885

Wang, L., Dong, M., Zhang, Q., Wu, Y., Hu, L., Parson, J. F., Eisenstein, E., Du, X. & Xiao, S. 2020. Silicon modulates multi-layered defense against powdery mildew in *Arabidopsis*. Phytopathology Research, 2: 7. https://doi.org/10.1186/s42483-020-00048-9

Wang, M., Gao, L., Dong, S., Sun, Y., Shen, Q. & Guo, S. 2017. Role of silicon on plant–pathogen interactions. Frontiers in Plant Science, 8: 701. https://doi.org/10.3389/fpls.2017.00701

Wang, L., Gao, Y., Jiang, N., Yan, J., Lin, W., & Cai, K. 2022. Silicon controls bacterial wilt disease in tomato plants and inhibits the virulence-related gene expression of *Ralstonia solanacearum*. International Journal of Molecular Sciences, 23(13): 6965. https://doi.org/10.3390/ijms23136965

Yan, G.-C., Nikolic, M., Ye, M.-J., Xiao, Z.-X. & Liang, Y.-C. 2018. Silicon acquisition and accumulation in plant and its significance for agriculture. Journal of Integrative Agriculture, 17(10): 2138–2150. https://doi.org/10.1016/S2095-3119(18)62037-4

Zakaria, M. A. T., Sakimin, S. Z., Ismail, M. R., Ahmad, K., & Kasim, S. (2024). Growth Enhancement and Resistance of Banana Plants to Fusarium Wilt Disease as Affected by Silicate Compounds and Application Frequency. Plants, 13(4): 542. https://doi.org/10.3390/plants13040542

Zhao, D., Xu, C., Luan, Y., Shi, W., Tang, Y. & Tao, J. 2021. Silicon enhances stem strength by promoting lignin accumulation in herbaceous peony (*Paeonia lactiflora* Pall.). International Journal of Biological Macromolecules, 190: 769–779. https://doi.org/10.1016/j.ijbiomac.2021.09.016