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Impact of Silicon-enriched Fertilizer on Basal Stem Rot Disease in Palm Species Caused by *Ganoderma boninense*

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ABSTRACT

Silicon (Si) is the second most abundant element that encourages plant growth, particularly in higher plants. This research maximizes Si's stress-tolerance benefits for plants. Therefore, this study aimed to evaluate the impact of silicon-enriched fertilizer in reducing the impact of Basal Stem Rot (BSR) disease in palm species, suggesting a potential sustainable solution to this critical agricultural challenge. The study utilized the root-sitting technique on three-month-old palm seedlings grown under controlled nursery conditions. The T1 and T2 seedlings were untreated with silicon-enriched fertilizer. In contrast, the T3 seedlings were treated with 500g of silicon-enriched fertilizer. The T2 and T3 seedlings were further challenged with *G. boninense* PER 17 using the rubber woodblocks (RWBs) sitting technique during the nursery trial (10 months). Results revealed that disease incidence (DI) in oil palm (50.0%) and betel nut palm (44.4%) for T3 seedlings was significantly lower ($p \leq 0.05$) compared to T2 seedlings, both of which had a DI of 94.4%. The BSR DI in T3 seedlings was reduced by 52.63% in oil palm and 67.35% in betel nut palm. These findings suggest that treatment T3 offers protection against *G. boninense* infection in both palm species. The results demonstrated that treatment T3, involving silicon-enriched fertilizer, significantly reduced the progression of BSR disease in palm seedlings, highlighting its effectiveness as a disease management strategy.

Keywords: Basal stem rot, betel nut palm, *Ganoderma boninense*, oil palm, silicon

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INTRODUCTION

Basal stem rot (BSR) is a major disease affecting various palm species, particularly oil palm (*Elaeis guineensis*), in Southeast Asia and other tropical areas. The pathogen responsible, *Ganoderma boninense*, causes significant financial damage by leading to stem deterioration, lower fruit production, and, ultimately, the death of affected trees (Abubakar et al., 2022). Traditional strategies for managing this disease, such as chemical and cultural interventions, have had limited effectiveness, highlighting the need for more sustainable and successful solutions (Khoo & Chong, 2024).

Although not classified as an essential nutrient, silicon (Si) has gained attention for its positive role in enhancing a plant's resilience to various biotic and abiotic challenges. Research has demonstrated that fertilizers containing Si can strengthen plant defenses by increasing cell wall thickness, enhancing systemic resistance, and decreasing infections caused by fungal pathogens (Etesami et al., 2020). Numerous studies have explored the effects of Si on BSR in oil palms; further research is needed to address key gaps. Si has been widely shown to reduce diseases in various crops. However, its specific mechanisms and effectiveness against BSR caused by *G. boninense* in palm species, particularly in betel nut palm, remain underexplored. This lack of knowledge is critical because the betel nut palm may respond differently to Si compared to oil palm due to species-specific physiological and biochemical differences. Additionally, understanding Si's role across multiple palm species can provide broader insights into its potential as a sustainable disease management strategy. Recent investigations have highlighted Si as a valuable component for strengthening plant defenses against a variety of diseases (Debona et al., 2017). Fertilizers enriched with silicon have demonstrated effectiveness in reducing disease severity across numerous crops by fortifying cell walls, initiating biochemical defense responses, and enhancing overall plant vigor (Sarma et al., 2024).

The precise impact of Si on combating *G. boninense* in palm species remains underexplored. This study focuses on oil palm (*Elaeis guineensis* Jacq.) and betel nut palm (*Areca catechu*) because of their economic importance and vulnerability to BSR. Although the betel nut palm is not as extensively studied regarding BSR, its susceptibility to *Ganoderma* infections makes it a relevant subject for examining disease management strategies. This research concentrates on these two palm species to investigate both a globally important crop and a less frequently studied species, aiming to provide a wider understanding of controlling *G. boninense* across various palm types. Consequently, this study focuses on evaluating the extent to which Si mitigates the severity of the BSR disease.

MATERIALS AND METHODS

Study Site, Plant Materials and Growth Conditions

The study was conducted at an outdoor nursery in Ladang 2 (3°00'86.9"N, 101°70'44.7"E) at Universiti Putra Malaysia, Serdang, Selangor. This study used two palm species: the oil palm (*Elaeis guineensis* Jacq.) and the betel nut palm (*Areca catechu*). 3-month-old oil palm seedlings were collected from Federal Land Development Authority (FELDA) Agricultural Services, Sungai Tekam, Jerantut, Pahang, while 3-month-old betel nut palm seedlings were obtained from Kuala Pilah, Negeri Sembilan. All seedlings were implanted in black polybags (38 cm high × 46 cm in diameter) filled with soil from the 'Munchong' series. Soil for the study was sourced from the Universiti Putra Experimental Farm in Puchong, Selangor, and combined with organic compost from the Federal Land Consolidation and Rehabilitation Authority (FELCRA) in Seberang Perak, Malaysia. A mixture ratio of 3 parts soil to 1 part compost was used. The research site had a 30°C to 36°C temperature range, with relative humidity between 60% and 80%. During the experiment, seedlings were irrigated twice daily and fertilized monthly. Fertilizer application and routine operations were conducted in accordance with standard, approved nursery practices (Fairhurst et al., 2019). Control seedlings received NPK Blue fertilizer (12: 12: 17: 2 + TE) (YaraMila, Malaysia), while seedlings were treated with fertilizer enriched with silicon (6: 6: 8: 2 + Si) (Sigma-Aldrich, United States of America) (Table 1).

Table 1
Characteristics of fertilizer enriched with silicon

Selected features	Unit	Value
Potential of hydrogen	-	5.23
Total Carbon	%	7.37
Total Nitrogen	%	6.25
Phosphorus oxide	%	6.56
Potassium oxide	%	8.54
Calcium oxide	%	9.77
Magnesium oxide	%	1.98
Silicone oxide	%	4.06
Available Copper	mg/kg	3.12
Available Iron	mg/kg	53.62
Available Zinc	mg/kg	5.66
Available Manganese	mg/kg	597.88

Maintenance of *Ganoderma boninense* PER 71 Isolates

The *G. boninense* PER 71 isolate was obtained from the Malaysian Palm Oil Board (MPOB), Bangi, Selangor. This strain was subcultured onto Potato Dextrose Agar (PDA) (Oxoid, USA) and maintained at room temperature of 28°C for 7 to 8 days (Surendran et al., 2021).

Preparation of Rubber Wood Blocks

Following the guidelines by Idris et al. (2006), 108 rubber wood blocks (RWBs) were made from fresh *Hevea brasiliensis* wood, each with dimensions of 6.0 cm by 6.0 cm by

6.0 cm. Each RWB was washed under running water and placed in a double-layered, heat-resistant polypropylene bag measuring 10.0 cm × 32.0 cm. The sample was autoclaved at 103.4 kPa and 121°C for 30 min. Following sterilization, 100 mL of molten malt extract agar (MEA) (Oxoid, USA) was added to each bag to provide supplementary nutrients for the growth of *G. boninense*. The bags were knotted with raffia string and autoclaved again in the mentioned circumstances. After sterilization, the bags were turned 360° to ensure the rubber wood blocks were completely coated with the MEA before they solidified. The preparation of *G. boninense* inoculum on RWBs involved placing a small piece from a 7- to 9-day-old pure culture of *G. boninense*, grown on PDA and obtained using a 10 mm in diameter core borer, onto the surface of each autoclaved RWB. This process was performed in a laminar flow hood to prevent contamination, and the bags were immediately sealed with a rubber band. The inoculated RWBs were then incubated in a dark cabinet at 27±2°C for approximately 10 to 12 weeks until fully colonized by the *G. boninense* mycelium.

Artificial Inoculation of Palm Seedlings Using Rubber Wood Blocks Infected with *G. boninense PER 71*

The inoculation procedure followed the method described by Idris et al. (2006). A nursery study was conducted using 18 blocks in a randomized complete block design (RCBD) with 3 sub-replications. Seedlings in T1 (negative control) were planted in polybags without *G. boninense* infection. In treatments T2 and T3, the seedlings were placed directly on the RWBs, ensuring their roots were in contact with the *G. boninense*-infected inoculum. After placement, the seedlings were covered with topsoil according to their respective treatments (Table 2). Seedlings were treated with silicon-enriched fertilizer and artificially infected with *G. boninense* over 10 months through the application of 10 doses, each consisting of 50 g per month. This process resulted in 500 g of silicon-enriched fertilizer per seedling, with rubber wood blocks (RWBs) serving as the inoculation medium.

Table 2
Treatments for basal stem rot in oil palm and betel nut palm seedlings

Treatment	Description
T1	Seedlings without treatment or infection (negative control).
T2	Seedlings left untreated but exposed to artificial infection with *G. boninense* (positive control).
T3	Seedlings were given silicon-enriched fertilizer and artificially infected with *G. boninense* (10 doses, 50 g per month, totaling 500 g per seedling).

Disease Incidence

The progression of disease in palm seedlings was tracked bi-monthly using a quantitative indicator known as disease incidence (DI), which reflects the number of seedlings exhibiting

visible symptoms, such as yellowing or necrosis of leaves, with or without white fungal growth or the presence of fruiting bodies. The DI was calculated using the equation formulated by Priwiratama et al. (2020):

$$\text{Disease incidence } (\%) = \left[\left(\frac{\text{Seedlings infested number}}{\text{Total number of seedlings assessed}}\right) \times 100\right]$$

A curve depicting disease progression was derived from the disease incidence measurements. A decrease in disease incidence compared to the control would suggest higher treatment efficacy in disease management. The progression of the disease was evaluated using the area under the disease progress curve (AUDPC), as described by Kamu et al. (2021).

$$\text{The area under the disease progress curve} = \sum_{i}^{n-1}\left[\left(\frac{Y_i - Y_{i+1}}{2}\right)(t_{i+1} - t_i)\right]$$

Where, n = assessment time number, Y = disease incidence and t = time.

Kamu et al. (2021) obtained the curve slopes by transforming the DI data using the monomolecular model (Monit).

Disease Severity Index

The progression of BSR disease in palm seedlings was evaluated using the disease severity index (DSI), which measures the total area or extent of disease in plant tissue (Rakib et al., 2015). The DSI was determined based on the seedlings' external and internal symptoms. The foliar disease severity index (DSFI) was assessed using a scale from 0 to 5, reflecting the severity of leaf symptoms (Table 3). *Ganoderma* selective medium (GSM) was used to confirm the presence of *G. boninense* in the palm tissue (Idris et al., 2006; Rees et al., 2009).

Table 3
Disease severity index of foliar

Disease class	Associated signs and symptoms of infection
0	A healthy plant with vibrant green leaves and no signs of fungal growth anywhere on the plant.
1	1–3 yellowing leaves, with no fungal growth observed on any part of the plant.
2	Presence of fungal growth, with or without yellowing leaves.
3	More than three yellowing leaves, along with dead or necrotic leaves, with or without fungal growth on the plant.
4	At least 50% of the leaves show severe yellowing or necrosis, with or without fungal growth.
5	The plant is dead, with or without visible fungal growth.

Note. Adapted from Rakib et al. (2015)

After the experiment (10 months after artificial infection with *G. boninense* PER 71), the palm seedlings were destructively sampled by carefully uprooting, longitudinally sectioning, and visually examining them for internal symptoms. The bole (DSIB) and roots (DSIR) disease severity index were evaluated according to a disease classification scale ranging from 0 to 4, as outlined in Table 4.

Table 4
Disease severity index of bole and disease severity index of root at oil palm and betel nut palm

Class	Associated signs and symptoms of infection
0	0% (healthy bole or root tissues)
1	Up to 25% (decay in bole or root tissues)
2	25–50% (decay in bole or root tissues)
3	51–75% (decay in bole or root tissues)
4	More than 75% (decay in bole or root tissues)
5	100% (complete decay of bole or root tissues)

Note. Adapted from Rakib et al. (2015)

The DSIF, DSIB, and DSIR were calculated using the following formulas revised from Rakib et al. (2015):

$$\text{Disease severity index of foliar / bole / root} = \left(\frac{\sum (\text{Disease class} \times \text{Number of seedlings for each disease class})}{\sum (\text{Total number of replicates} \times 5)}\right) \times 100$$

Where five is the constant indicating the highest assessment class. The number of seedlings that died due to BSR should be recorded regularly, typically throughout 6 to 12 months, depending on the growth stage of the seedlings.

Dead Seedlings

Dead seedlings were recognized by complete necrosis, defoliation, and stem collapse (Noor Azmi, 2020). A severity index can be assigned based on visual scoring of symptoms, ranging from healthy (0) to dead (5), following established disease rating scales (Rakib et al., 2015).

$$\text{Dead seedlings (\%)} = \left(\frac{\text{Number of Dead Seedlings}}{\text{Total Number of Seedlings}} \times 100\right)$$

Re-isolation of the pathogen from the decayed basal stem tissues was essential to confirm that the seedlings died due to *G. boninese*. The infected tissues were cultured on *Ganoderma* selective media (GSM) to isolate and identify *G. boninense* under a microscope based on its characteristic morphology (Idris et al., 2020).

Measurements by SEM and TEM

The measurement of silica bodies and their deposition were carried out using scanning electron microscopy (SEM) and transmission electron microscopy (TEM), following the

method described by Zhang et al. (2013). Fresh root samples were cut into 21 cm³ sections for SEM observation (S-4000, Hitachi Co. Ltd., Japan) and 21 mm³ sections for TEM (HT7800 RuliTEM, Hitachi High-Tech, Japan). Images captured under both microscopes revealed silica bodies (SB) and silica layers (SL) in the root tissues.

Statistical Analysis

Statistical analysis was performed using one-way analysis of variance (ANOVA). Any significant difference was further analyzed using the least significant difference (LSD) post-hoc analysis at $p \leq 0.05$. All statistical analysis was performed using the Statistical Analysis System (SAS) 9.2 software.

RESULTS

Disease Incidence

A notable difference in treatment interactions was observed over time, with statistical significance at $p \leq 0.05$. The disease index (DI), determined by leaf symptoms, was substantially lower in the T3 group treated with silicon-enriched fertilizer compared to the T2 seedlings (Figure 1). A reduced DI value indicated disease suppression. No DI was found for T3 seedlings at four months. This indicated that the seedlings in treatment T3 had gradually reduced the development of BSR disease symptoms. Disease symptoms in the seedlings treated with T3 began to appear six months after inoculation with *G.*

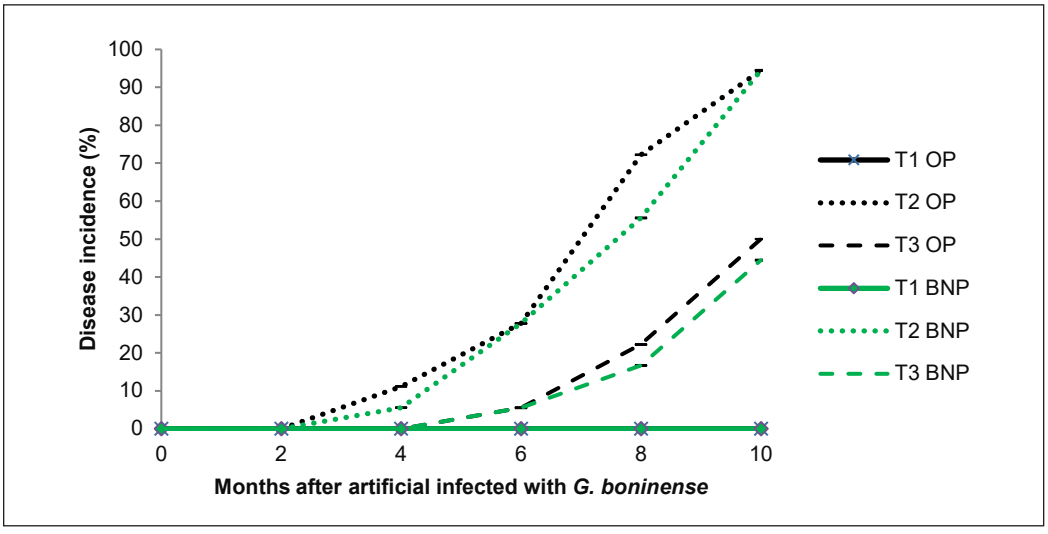

Figure 1. The incidence of basal stem rot occurrence in oil palm and betel nut palm seedlings for ten months following artificial inoculation with *G. boninense*

Note. OP = oil palm and BNP = betel nut palm. Data are presented as means ± standard error, with statistical analysis using the least significant difference test ($p \leq 0.05$)

boninense. The disease symptoms in oil palm seedlings gradually increased thereafter, with a DI of 50.00% at ten months of observation. In contrast, the disease symptoms in betel nut palms gradually increased subsequently, with a DI of 44.44% at ten months of observation. The findings indicated that the use of silicon-enriched fertilizer offered an effective degree of disease management. Symptoms of the disease appeared much earlier in T2-treated seedlings, starting four months post-infection with *G. boninense*. As anticipated, after ten months of evaluation, the untreated control group (T2) of oil palm and betel nut palm seedlings exhibited the highest disease incidence (DI) of 94.44%. However, while the foliar symptoms were evident, they did not reveal the extent of damage affecting the roots and bole region.

Area Under Disease Progress Curve and Disease Reduction

The disease incidence (DI) of oil palm and betel nut palm seedlings was analyzed using the area under the disease progress curve (AUDPC) to evaluate the severity of the disease in each treatment (Table 5). The AUDPC offers a quantitative measure of disease intensity over time, facilitating comparisons between different disease management approaches. The calculation was made using the DI derived from the classification of leaf symptoms. In treatment, T3, oil palm and betel nut palm seedlings treated with silicon-enriched fertilizer showed a marked reduction in AUDPC, with values of 150.00 unit² and 88.89 unit², respectively, ten months post-infection with *G. boninense.* Based on the AUDPC, it was clear that treatment T3 was the most effective in slowing the progression of BSR disease. As anticipated, disease reduction was significantly higher in treatment T3 for both palm seedlings, with decreases of 52.62% in oil palm and 67.35% in betel nut palm. The highest AUDPC values were observed in the T2 treatment, with oil palm seedlings showing 316.66 unit² and betel nut palm 272.22 unit², indicating greater susceptibility to the disease.

Table 5
The area under disease progress curve and disease reduction of oil palm and betel nut palm seedlings at 10 months following artificial inoculation with G. boninense *PER 71*

	Oil palm seedlings			**Betel nut palm seedlings**		
Treatment	T1	T2	T3	T1	T2	T3
Area Under Disease Progress Curve (unit²)	0.00	316.66	150.00	0.00	272.22	88.89
Disease Reduction (%)	-	-	52.63	-	-	67.35

Disease Severity Index of Foliar

Significant differences existed between the treatment interaction and month at $p \leq 0.05$. For oil palm and betel nut palm seedlings, the DSI, derived from observable leaf symptoms, was considerably lower in the T3 seedlings treated with silicon-enriched fertilizer (Figure

2). A lower disease severity index of foliar (DSIF) indicated success in suppressing the onset of BSR disease infection development in oil palm seedlings. There was a total absence of symptoms in treatment T3 at four months. However, the disease progression in oil palm and betel nut palm seedlings gradually increased with a DSIF of 37.50% and 52.78%, respectively, at ten months of observation. The percentage of DSIF recorded in treatment T3 for both seedlings was significantly lower than the T2 seedlings. Visible disease symptoms in the T2 seedlings emerged as early as four months into the study. By the tenth month, T2 seedlings of oil palm and betel nut palm recorded external DSFI values of 86.11% and 87.50%, respectively.

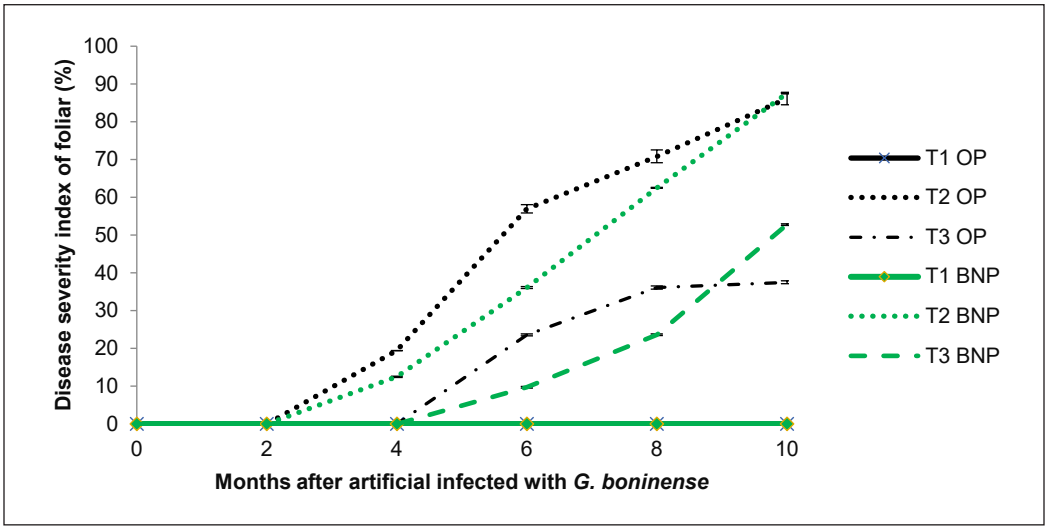

Figure 2. Foliar disease severity index of oil palm and betel nut palm seedlings ten months after artificial inoculation with *G. boninense*
Note. OP = oil palm and BNP = betel nut palm. Data are presented as means ± standard error, with statistical analysis using the least significant difference test ($p \leq 0.05$)

Bole and Root Disease Severity Index

There was a statistically significant difference ($p \leq 0.05$) between treatments T1 and T2 concerning the disease severity indices for the bole (DSIB) and roots (DSIR) (Figure 3). Treatment T2 in oil palm and betel nut palm seedlings exhibited the highest disease severity index of roots (DSIR), with 38.89% and 70.83% of the primary roots showing brown discoloration, compared to 20.83% and 30.56% in treatment T3 seedlings, respectively (Figures 4A and 4B). When evaluating bole decay and disease severity, it was found that using silicon-enriched fertilizer in T3 treatment led to the lowest disease severity index of the bole (DSIB) in oil palm seedlings, recorded at 6.94%. This was significantly lower than the 26.39% DSIB observed in the treatment T2 seedlings. The same trend was

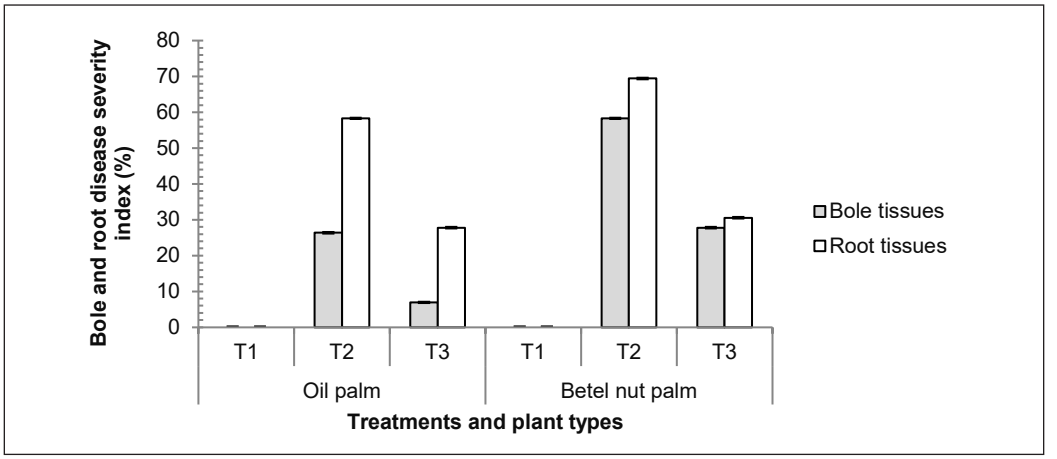

Figure 3. Bole and root disease severity index of oil palm seedlings ten months after artificial inoculation with *G. boninense*
Note. OP = oil palm and BNP = betel nut palm. Data are presented as means ± standard error, with statistical analysis using the least significant difference test ($p \leq 0.05$)

also recorded in betel nut palm seedlings for treatment T3 (27.78%) compared to treatment T2 (66.67%). Brown lesions, characterized by an irregular, darker zone, were observed in longitudinal sections of the infected boles (Figures 4C and 4D). The results suggest that treatment T3 effectively hindered the penetration and dissemination of *G. boninense* within the vascular tissues of the seedlings.

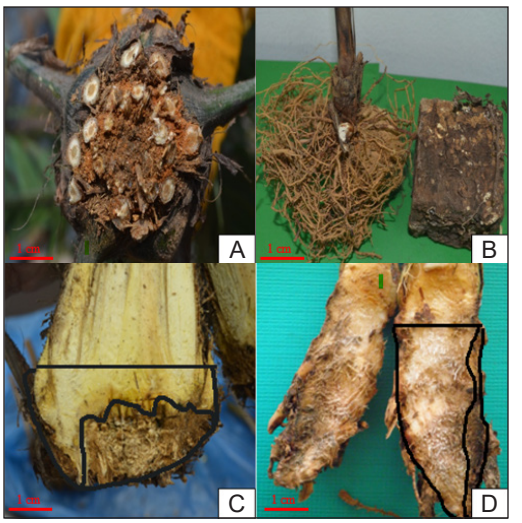

Figure 4. Decay of primary roots and bole resulting from *G. boninense* infection. (A) Primary roots of oil palm, (B) primary roots of betel nut palm, (C) bole of oil palm, and (D) bole of betel nut palm. The black lines in Figures 4C and 4D depict the area decay of primary roots and the bole

Dead Seedlings

For both oil palm and betel nut palm seedlings, there was a notable difference ($p \leq 0.05$) in the count of dead seedlings (DS) between treatments T1 and T2 (Figure 5). Silicon-enriched fertilizer was deemed effective in controlling BSR infection, as it significantly reduced the number of DS in both oil palm and betel nut palm seedlings. Ten months after being artificially infected with *G. boninense*, the DS in the T3 seedlings of oil palm and betel nut palms in treatment were 11.11 and 5.56%, respectively. In contrast, treatment T2 for oil palm seedlings showed a DS

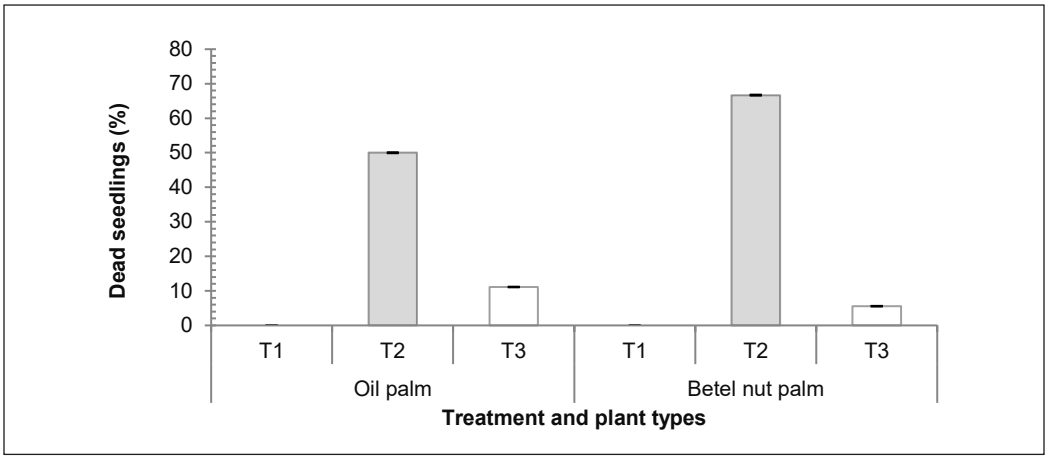

Figure 5. Mortality of oil palm and betel nut palm seedlings due to *G. boninense* infection, measured ten months after inoculation

Note. The different colours represent different treatments. OP = oil palm and BNP = betel nut palm. Data are presented as means ± standard error, with statistical analysis using the least significant difference test ($p \leq 0.05$)

of 50.00% at ten months after artificial infection with *G. boninense*. However, treatment T2 seedlings showed a DS of 66.67% at ten months after artificial infection with *G. boninense.*

Measurement by SEM and TEM

The Scanning Electron Microscope (SEM) images from this analysis showed that silicon accumulated as silica bodies in the plants' roots (Figure 6). A dense silicon layer was also observed in the plant roots' endodermal cell wall diagram (Figure 7).

DISCUSSION

This research evaluated the effectiveness of silicon-enriched fertilizer on palm seedlings exposed to *G. boninense* PER 71, the pathogen responsible for BSR. Lower disease incidence (DI), area under the disease progress curve (AUDPC), disease severity indices for foliar (DSIF), root (DSIR), and bole (DSIB), as well as fewer dead seedlings (DS) and higher disease reduction (DR) in T3-treated seedlings compared to the T2 positive control, highlight that fertilization with nutrient enhancement is a key cultural management strategy for controlling *Ganoderma* infections in palm seedlings. Consistent with the findings of this research, Rebitanim et al. (2020) also reported a 77.78% decrease in BSR disease incidence in seedlings treated with GanoCare®, a fertilizer containing beneficial elements, with a notable reduction in dead seedlings to 6.67%, in contrast to 93.33% in untreated samples. Therefore, it is necessary to maintain nutrient availability in palm seedlings with fertilizers. This study demonstrated that nutrient supplementation with silicon-enriched

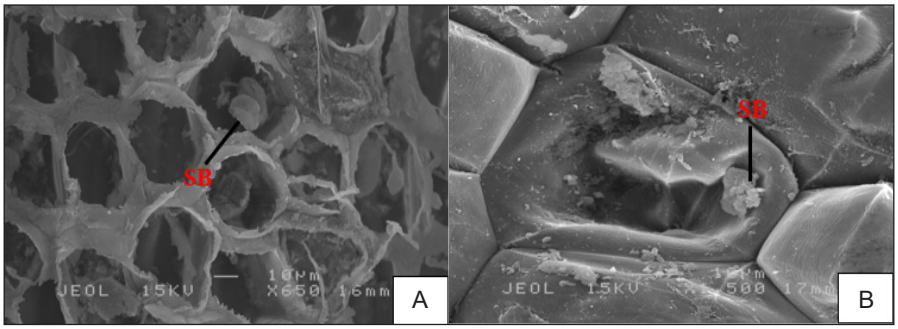

Figure 6. Silica bodies deposition in palm roots. Betel nut palm (A) and oil palm (B). Silica bodies are detected by scanning electron microscopy energy. Magnification = 10 µm × 600 (A) and 10 µm × 1,500 (B).
Note. SB = Silica bodies

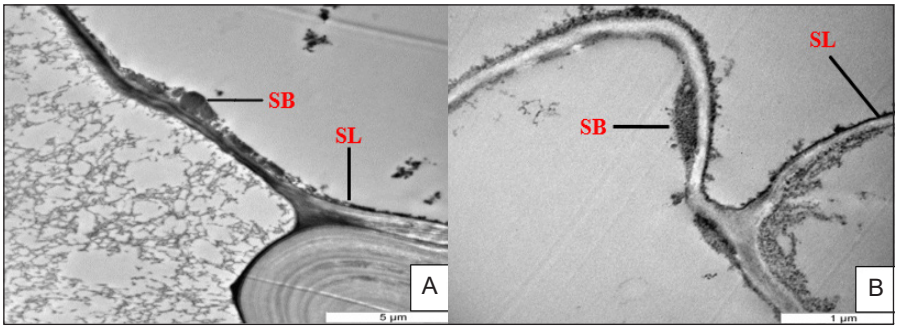

Figure 7. Si deposition in endodermis of palm roots cell wall. Betel nut palm (A) and oil palm (B). The blackened area represents the location of Si deposition. Silica is detected by transmission electron microscopy. Magnification A= 5 µm and B = 1 µm
Note. SB = Silica bodies; SL = silica layer

fertilizer enhanced the resistance of oil palm seedlings to the physical damage caused by *G. boninense*, as well as in betel nut palm seedlings. It is well-documented that silicon-enriched fertilizers contain advantageous elements that effectively lower infection rates. Recent research continues to support the use of silicon-based fertilizers in boosting plant health and disease resistance (Ma, 2021; Ning et al., 2014). Silicon is vital in strengthening plant structure, reinforcing cell walls, and triggering various defense mechanisms against biotic stress factors. This has been particularly noted in crops such as rice, wheat, and oil palm, where silicon application has been associated with better resistance against fungal infections and other pathogens.

This study's findings revealed a significant link between silicon-enriched fertilizer use and silicification initiation in the roots of palm seedlings treated with this fertilizer. Elevated silicon concentrations in the root tissues improved resistance to *G. boninense*. Two primary theories explain silicon's role in plant resistance: It creates a physical barrier to hinder fungal entry and enhances physiological defenses through biochemical

processes (Brunings et al., 2021; Ranjan et al., 2021). An amplified number of silicified bulliform cells in the root epidermis cell walls is suggested to be a physical barrier, preventing *G. boninense* penetration. This barrier is related to lignin-carbohydrate complexes bound to silicon in the epidermal cell wall (Carré-Missio et al., 2021; Lux et al., 2020). Liang et al. (2015) further supported this physical barrier concept by showing that silicon-organic molecule complexes in the epidermal cell walls enhance plant resistance to fungal degradation enzymes. A higher disease reduction (DR) percentage in palms supplemented with silicon-enriched fertilizer suggests that sufficient silicon content slows disease progression by strengthening the cell wall, making it more resistant when *G. boninense* attempts to invade. The creation of a-Si cuticle double layer is a physical barrier to restrict pathogen penetration, as revealed in various research, including novel findings on Si deposition in epidermal cells (Kim et al., 2002; Ma & Yamaji, 2006). These observations are consistent with SEM and TEM analysis, which identified a silicon layer on the outer cell wall of root epidermal cells in palm seedlings that received silicon-enriched fertilizer treatment. The Si-cuticle layer may act as a physical barrier that reduces NH_4-N volatilization from leaf surfaces, thereby suppressing potential nutrient sources for pathogens (Bhardwaj et al., 2023).

The second theory posits that disease suppression is related to the stimulation and buildup of defense mechanisms, such as phenolics and phytoalexins, which are closely tied to the activity of P-R genes (Boudet, 2000; Del Río et al., 2001). This hypothesis is supported by Rodrigues et al. (2003), who found that silicon application in rice led to the buildup of osmophilic materials in epidermal cells, thereby increasing resistance to the fungus *M. grisea*. Si can impede fungal hyphae penetration by promoting the buildup of an antifungal chemical, flavonoid, which can damage fungal cell walls (Alvarez & Datnoff, 2001; Brescht et al., 2004). This study demonstrates that *G. boninense* effectively infects palm seedlings through artificial inoculation using a placement method, where infection mainly happens when healthy palm roots encounter fungal inoculum-containing debris. Further, it was predicted that *G. boninense* would infect the root cell wall by making holes through all cell wall layers. This indicated simultaneous wood deterioration with the infection-producing enzymes that can break down cell wall layers. Recent studies have confirmed that different *Ganoderma* species cause concurrent degradation of plant cell walls. Comparable wood decay patterns have been observed in *Laurelia Filipina* and date palm wood infected by *G. colosseum* (Adaskaveg et al., 1991; Agosin, 1990). This degradation is primarily due to the critical function of carbohydrate-active enzymes (CAZymes), especially cell wall degrading enzymes (CWDEs), which are essential for *Ganoderma* species to break down lignin and cellulose, enabling pathogen infiltration (Ramzi et al., 2019).

Initial findings showed that adding silicon-enriched fertilizer enhanced the synthesis and deposition of silicon in root cell walls, leading to an increase in silicification. Cell wall destruction occurred in discrete areas with elevated lignin content, including the central lamella region. Effective silicification requires high concentrations of silicon cells and bodies in the middle lamella and cell wall corners, which are crucial regions for this process (He et al., 2013; Ma et al., 2006). Recent studies have shown that silicon accumulates in the intracellular spaces (ICS) between the cortical cells of *Molinia caerulea* (purple moor grass) roots, confirming its role in enhancing plant structural defenses (He et al., 2013; Ma et al., 2006). These findings reveal that Si is concentrated in essential locations like the ICS, reinforcing the plant's tolerance to environmental challenges.

Applying silicon-enriched fertilizer appears to be an effective method for managing BSR disease caused by *G. boninense*, comparable to fungicides, with the added potential of lowering the number of fungicide treatments or reducing the necessary active ingredient quantities (Fabricio et al., 2005). Additionally, the organic content in the specially formulated fertilizer provides several benefits, including improving soil structure, increasing soil pH, and boosting nutrient absorption in palm seedlings. These effects help minimize the likelihood of *G. boninense* adhering to the root cell wall, thus promoting the general health of the palm seedlings. The findings indicate that silicon-enriched fertilizer enhanced disease resistance, improved nutrient availability, and correct imbalances of key elements affecting palm growth and resilience against disease. Therefore, it will impact infection and pathogen sporulation.

Research findings confirmed the presence and accumulation of silica bodies in palm roots and a thick double layer of silicon in the cuticle of the endodermal cell walls in palm roots. These results were similarly supported by earlier research, which showed that Si deposition in the roots was a unique multifunctional plant component that worked as the soil environment's frontline (Lux et al., 2020). The unique attributes of this organ highlight certain features, like its cooperative interaction with soil microorganisms and specific morphological traits absent in other parts of the plant, such as Casparian bands in the endodermis and exodermis (Lux et al., 2020).

The study showed that applying Si-enriched fertilizer (treatment T3) altered root cell wall structure, thus increasing cell wall extensibility and improving plant resilience. The buildup of silicon in palm roots increases disease resistance by fortifying cell walls through crosslinking mechanisms like lignification (Currie & Perry, 2009). However, silica deposition is more energy-efficient than lignification, offering a cost-effective method for improving mechanical rigidity (Kumar et al., 2017). Despite these advantages, the precise interaction between silicification and lignification in roots is still not fully understood. Previous investigations by Gopal et al. (2005) demonstrated that coconut palms (*Cocos nucifera*) infected by root wilt phytoplasma altered the rhizosphere by

secreting chemicals that promoted beneficial microorganisms, including nitrogen-fixers, silicate solubilizers, and actinomycetes. This reduced harmful microorganisms and boosted silicon intake, boosting palm growth and production. The results indicate that silicon-enriched fertilizer (treatment T3) increased disease tolerance, reducing infection and pathogen sporulation.

CONCLUSION

The study demonstrates that silicon-enriched fertilizer (T3) substantially lowers the risk of *G. boninense* infection in palm seedlings by enhancing their disease resistance. Research indicates that silicon-enriched fertilizer (T3) can serve as a powerful tool for disease management, significantly reducing DI ($p \leq 0.05$) by 52.63% in oil palm and 67.35% in betel nut palm while delaying the onset of BSR. This fertilizer contains beneficial elements such as silicon (Si), which may influence the ultrastructure of palm roots and shoots by thickening cell walls. Silicon strengthens these structures, creating a physical barrier that limits the penetration of *G. boninense* hyphae. Additionally, it may stimulate the production of antifungal compounds that degrade fungal cell walls. As a result, these changes in root structure effectively restrict fungal movement toward the stem, thereby delaying the development of BSR and demonstrating increased tolerance in Si-treated plants.

Further research is essential to uncover the mechanisms involved in silicon (Si) uptake, translocation, and accumulation across various plant species. Investigating the expression and localization of Si transporter genes is particularly recommended to better understand genotypic differences in Si accumulation. Additionally, one of the least understood areas is how Si influences plants under combined stress conditions. Plants are subjected to multiple stressors in natural environments, including extreme temperatures, water scarcity, and salinity. Exploring these processes should be a key focus of future studies to enhance knowledge of plant adaptation to adverse conditions. Practical field trials of Si application in economically significant crops are also recommended to evaluate its real-world benefits.

Although the precise functions of Si in plants remain unclear, evidence suggests it plays a beneficial role, particularly in enhancing resistance to fungal pathogens. However, this hypothesis has yet to be definitively proven, as quantitative data supporting the mechanical barrier hypothesis is still lacking. Addressing this gap is critical for developing effective agricultural strategies. Recent studies have demonstrated the role of silicon-enriched fertilizers in promoting growth in both oil palm and betel nut palm species. However, these studies often face limitations in observing long-term effects, highlighting the need for extended research periods. Future applications of Si fertilizers are likely to contribute to greater biomass accumulation, including increased grain yields. A genetic approach could provide valuable insights into the mechanisms of Si action in palms, further

advancing our understanding. Moreover, evaluating the potential of Si fertilizers to reduce agricultural costs while delivering environmental benefits is vital. Developing optimized management practices for Si applications should be a priority for future research, ensuring its effectiveness and sustainability in agriculture.

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