Received: September 8, 2025 | Received in revised form: January 8, 2026 | Accepted: January 13, 2026 | Available online: January 23, 2026

JOURNAL OF APPLIED RESEARCH ON SCIENCE AND TECHNOLOGY
JARST
INSTITUTE OF RESEARCH AND DEVELOPMENT
RAJAMANGALA UNIVERSITY OF TECHNOLOGY THANYABURI
ISSN ONLINE: 2773-9473
https://ph01.tci-thaijo.org/index.php/rmutt-journal

Implication of calcium silicate in growth enhancement and alternaria leaf spot disease control in chinese cabbage

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ABSTRACT

Calcium silicate is an inorganic compound that strengthens plant cell walls, enhancing resistance to environmental stress and fungal pathogens. Moreover, it has been reported to promote plant growth and defense mechanisms through physiological and biochemical pathways. In this research, the efficacy of calcium silicate in promoting seed germination and seedling physiological development, as well as its potential for inhibiting fungal pathogens that cause leaf spot disease in Chinese cabbage (*Brassica rapa* subsp. *chinensis*) was investigated. The fungal pathogen was isolated from diseased Chinese cabbage in Phra Nakhon Si Ayutthaya Province, Thailand. Based on morphological identification and molecular techniques using PCR amplification of the ITS1-5.8S-ITS2 region, the pathogen was identified as *Alternaria brassicicola*, with an identity level of 98.00-100.00%. The effect of calcium silicate on seed germination was investigated at three different concentrations (1%, 2%, and 3%). The finding indicated that calcium silicate did not affect on seed germination at 72 hrs. All treatments showed that 100% germination. Moreover, the 3% calcium silicate presented the highest concentration for plant-induced, with seedlings at 28 days exhibiting an average height of 15.80 cm, an average of 7 roots per plant, and a mean root length of 5.43 cm, significantly greater than the control. For the possibility of fungal control using the poisoned food technique, calcium silicate at the highest concentration could inhibit mycelial growth by 28.21%. This research suggests that calcium silicate may be a potential growth-promoting agent for Chinese cabbage, especially for enhancing the root system, while also inhibiting fungal mycelium. Therefore, calcium silicate could be considered as an effective seed coating or soil amendment to protect seeds during early germination and seedling establishment.

Keywords: Alternaria brassicicola, Calcium silicate, Chinese cabbage, Fungal pathogen

INTRODUCTION

Calcium silicate (Ca_2SiO_4) is a source of nutrition containing calcium and silicon, which plays significant roles in plant growth and mechanical defense. Calcium is important for cell walls, membrane stabilization, and intracellular signaling, while silicon, though not classified as essential, improved tolerance against abiotic and biotic stresses [1]. Both element combinations revealed beneficial effects in enhancing plant vigor, photosynthetic efficiency, and resistance to pathogens [2]. In agricultural practices, calcium silicate has been employed to amend soils deficient in silicon, leading to improved crop yields and quality.

Calcium silicate application has illustrated benefits such as increased photosynthetic efficiency, enhanced root development, and induced plant defense mechanisms. In addition, the combination of calcium silicate into soil management strategies has been associated with the suppression of certain plant pathogens, suggesting its potential as a component in integrated disease management programs [3, 4].

Nevertheless, climate change has become a significant factor influencing soil health and pathogen dynamics. Rising global temperatures, changes in precipitation of soil patterns, and increased frequency of extreme weather events can alter soil microbial communities and promote the proliferation of soil-borne pathogens [5]. These changes may extend the geographic range and seasonal activity of pathogens, resulting in higher disease pressure on susceptible crops. Moreover, soil moisture and temperature

DOI: 10.60101/jarst.2026.263405

elevation can create conditions for fungal pathogens to thrive, complicating disease management in susceptible vegetable crops [6].

Chinese cabbage (*Brassica rapa* subsp. *chinensis*), commonly known as bok choy, is a leafy vegetable of significant economic importance, particularly in Asian countries. However, the cultivation process challenges including abnormal seed germination, weak root systems, and susceptibility to diseases such as leaf spot caused by genus *Alternaria* [7]. This pathogen can infect seeds and seedlings, leading to pre- and post-emergence damping-off and significant yield loss [8]. In addition, early initial root growth performs the plant more vulnerable to attack from biotic and abiotic stress, particularly non-optimal field conditions. Early-stage infections and poor root development can disrupt plant establishment, limiting the crop's ability to take up water and nutrients. [9]. These factors collectively weaken plant vigor and can increase plants' chemical inputs, raising issues related to environmental safety and sustainable crop production. Additionally, environmental stresses, including variations in soil moisture and temperature fluctuations, can enhance the virulence of soil-borne pathogens, leading to increased risk to seedling survival and crop productivity [10, 11].

Fungicide chemicals are widely used as the primary control strategies against disease. Although effective, these agents are a cause of environmental pollution as well as threats to both human health and the development of fungicide-resistant pathogen strains [12]. Hence, there is an increasing requirement for sustainable treatments that can enhance plant defense and reduce the application of chemicals. One of the capable strategies may be calcium and silicon compounds (e.g., calcium silicate), which have revealed an improvement in germination, seedling vigor, and control of pathogens [13]. Recent technological advances in seed treatments have also included the use of nanomaterials and mineral coatings to enhance seed performance under stress [14]. More research has shown that seed priming with calcium silicate can improve water uptake, accelerate enzymatic activation during germination, and promote early root elongation [15].

These physiological enhancements may contribute to stronger seedlings with increased resistance to early-season diseases, including those caused by *Alternaria* spp. [16]. In the present, calcium silicate is one of the most promising candidates for sustainable crop management practices. This study aims to investigate the efficacy of calcium silicate in enhancing seed germination, promoting physiological growth parameters, and potentially inhibiting the fungal pathogens in Chinese cabbage. This research will seek to develop a practical and environmentally safe strategy that enhances early-stage plant development while contributing to disease suppression.

MATERIALS AND METHODS

1. Fungal isolation

Chinese cabbage showing brown leaf spot symptoms with distinct concentric rings and dark brown lesion margins was collected from a private plantation in Phra Nakhon Si Ayutthaya, Thailand. Fungal isolation using the tissue transplanting method with symptomatic tissues (5×5 mm) was performed. The tissues were cut and surface-sterilized in 1.2% sodium hypochlorite solution for 3 min., then rinsed with sterile distilled water 2-3 times. The tissue was wiped and allowed to air dry, placed on the surface of potato dextrose agar (PDA) contained with streptomycin sulfate at a concentration of 200 ppm, then incubated at 25°C under a 12 hrs. with light 12 hrs. dark photoperiod for 5 days to induce mycelial and reproductive structure development.

The fungus was purified using a single spore isolation technique on water agar (WA), then spore suspension at a concentration of 1×10^8 spores/mL from a pure culture was inoculated onto 21-day-old *Brassica chinensis* seedlings to confirm the pathogen's infectivity and its ability to induce disease symptoms. Purified mycelia were transferred onto potato carrot agar (PCA) kept at 14°C for further study [17].

2. Morphological, molecular identification and Phylogenetic tree

Petri dishes containing 15 mL of PDA mixed with 200 ppm streptomycin sulfate were inoculated with a 5-mm diameter core taken from the edge of an actively growing 5-day old culture, then incubated at 25°C under a photoperiod of 12 hrs. light/12 hrs. dark. Colony diameter of a five-replicate culture was recorded at day 5. Also, 30 conidia were randomly selected from each replicate to measure their length and width at day 5 under an Olympus CX31 binocular compound microscope at 400x magnification with Olympus CellSens standard software version 1.16.

The fungal genomic DNA was prepared and extracted following Rattanakreetakul et al. [18] and using the kit "DNA Secure Plant Kit" (Tiangen, Co., Ltd., Beijing, China) following the manufacturer's instructions. The internal transcribed spacer (ITS) region was amplified using the primer ITS1 (5′-TCC GTAGGTGAACCTG CGG-3′) and ITS4 (5′-TCCTCCGCTT ATTGATATGC-3′) [19] following Bincader et al. [17]. PCR was carried out using the PCR thermal cycler (Sensoquest GmbH, Göttingen, Germany) under the following conditions: pre-denaturation at 94°C for 5 min; 30 cycles of denaturation at 94°C for 1 min, annealing at 56°C for 1 min, and extension at 72°C for 1 min; and a final extension step of 72°C for 5 min. PCR products were rechecked and separated by 1.2% agarose gel electrophoresis, then performed at ATGC Co., Ltd., in Pathum Thani, Thailand, for nucleotide sequencing analysis.

DOI: 10.60101/jarst.2026.263405

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The nucleotide sequence was generated with multiple alignments performed using the Clustal W alignment routine [20]. The phylogenetic tree was created using the maximum parsimony [21], and the confidence of the groupings was determined by bootstrap analysis [22], with 1,000 replications to test the significance of the trees. Analysis of the sequence data was performed by the MEGA version X software program [23] to generate a phylogenetic tree.

3. Efficacy of calcium silicate on seed germination

The efficacy of calcium silicate in promoting seed germination of Chinese cabbage (hybrid cultivar Chan Jao F1 obtained from a commercial seed supplier) was evaluated using the blotter method. Seeds were soaked in calcium silicate solutions at three different concentrations (1%, 2%, and 3%, w/v) for 6 hr, while sterile distilled water was used as the control. Germination percentage were recorded at 24, 48, and 72 hrs. Calculation was described as follows:

$$Germination\ percentage\ (\%) = \left[\frac{Total\ of\ seed\ germination}{Total\ of\ seed}\right] \times 100 \quad (1)$$

The experiment was arranged in a completely randomized design (CRD), with 7 replications per treatment. Statistical analysis was performed using R software (version 3.6.2). Mean comparisons were conducted using the Least Significant Difference (LSD) method at a significance level of $P \leq 0.05$.

4. Effect of calcium silicate on controlling fungal pathogen in vitro

Fungal pathogen was cultured on PDA and incubated at 25°C under a 12-hrs. light/12 hrs. dark photoperiod for 5 days. A 6-mm diameter mycelial plug was cut from the edge of colony margin using a 6-mm cork borer and transferred onto PDA media amended with calcium silicate at 3 different concentrations, then incubated under the same conditions. Colony diameter was measured for 5 days. The experiment was arranged in a completely randomized design (CRD) with seven replications. Data were statistically analyzed using R software (version 3.6.2). Treatment means were compared using the Least Significant Difference (LSD) method at a significance level of $P \leq 0.05$. The diameter of fungal colonies was calculated using the following formula:

$$Colony\ diameter\ (cm) = \left[\frac{Diameter\ on\ asix\ X + Diameter\ on\ asix\ Y}{2}\right] \quad (2)$$

$$Percentage\ of\ inhibition = \left[\frac{Control - Treatment}{Control}\right] \times 100 \quad (3)$$

5. Calcium silicate efficacy on growth development

A field experiment was conducted in the greenhouse (28±2°C; 70-80% RH) at Division of Plant Science, Faculty of Agricultural Technology and Agro-Industry, Rajamangala University of Technology Suvarnabhumi, Phra Nakhon Si Ayutthaya, Thailand. The efficacy of calcium silicate was evaluated using seedlings obtained from the seed germination experiment above. The seedlings were transplanted into 6-inch nursery pots filled with peat moss sterilized by autoclaving at 121°C and 15 psi for 20 min. The sterilization process was repeated after 24 hrs. to ensure complete disinfection. Experiments were treated with calcium silicate solutions at three concentrations and sterile distilled water used as the control. The solutions were applied every 7 days (no other nutrients or fertilizers were added). Plant height, root length, and the number of roots were recorded weekly for 30 days (describe by Bejarano-Herrera et al. [24]. The experiment was arranged in a completely randomized design (CRD) with ten replications per treatment. Data were analysed using R software (version 3.6.2). Mean comparisons were performed using the Least Significant Difference (LSD) method at a significance level of $P \leq 0.05$.

RESULTS AND DISCUSSION

1. Fungal isolation and morphological characteristics

The fungal isolate obtained from Chinese cabbage showing brown leaf spot symptoms, dark brown margins, and concentric ring patterns from private plantation in Phra Nakhon Si Ayutthaya Province (Figure 1A). Morphological characteristics was consistent with *Alternaria* spp., as previously described by Pongpisutta et al. [12]. When cultured on PDA, the colony appeared olive green to gray with a smooth white margin and moderately raised mycelia on the medium (Figure 1B). Microscopic examination at 400× magnification indicated that the all isolate produced dictyospores (conidia) measuring approximately 6.15-9.51 × 16.98-48.64 µm. The conidia were light brown, with mostly smooth walls, although roughened walls were occasionally observed in older spores. The conidia were typically obclavate, 2-5 transverse septa, with an apical beak that was pale brown and short, and a rounded base. Conidia were observed in branched chains of approximately 7-15 spores, light brown conidiophores. Additionally, proliferation of conidia cells into new conidiophores and the emergence of new conidia from the conidial apex were frequently observed (Figure 1C-1D).

Based on the morphological features described above and comparison with descriptions in Illustrated Genera of Imperfect Fungi [25], the isolate was identified as *Alternaria brassicicola*. This fungal pathogen has been reported to infect a wide range of host plants, specifically Brassicaceae family such as cabbage, Chinese cabbage, and broccoli, as well as other economically important crops including lettuce, tomato, and sunflower. Furthermore, *A. brassicicola* is known to occur in a saprophytic stage and may act as a secondary infection in some cases [26, 27, 28].

DOI: 10.60101/jarst.2026.263405

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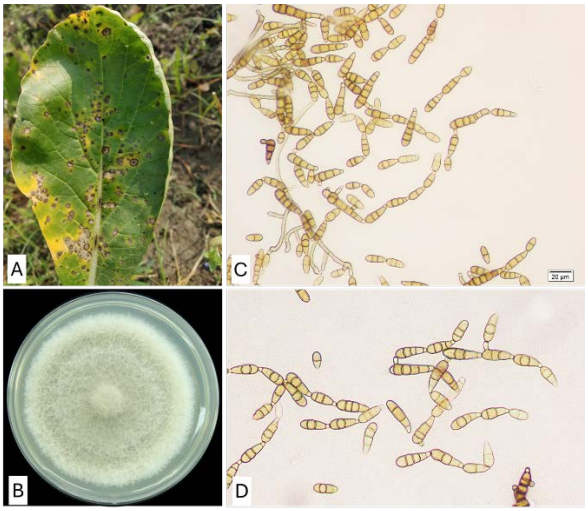

Figure 1 Fungal isolation used in this study. Leaf spot disease on Chinese cabbage (A); Colony characteristics of fungal cultured on PDA and incubated at 25°C under a 12-hrs. light/12 hrs. dark photoperiod for 5 days (B); and conidia characteristics of the fungus observed under a light microscope at 20× magnification (C-D).

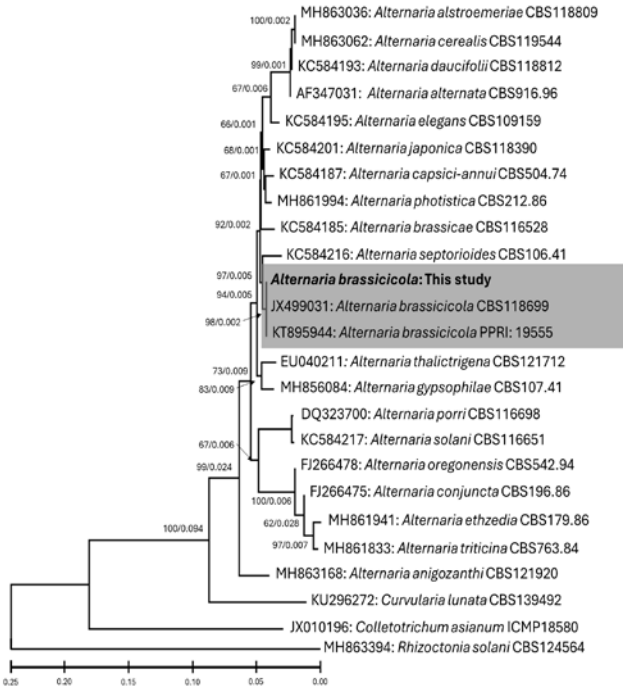

Figure 2 Neighbor-Joining tree constructed based on ITS sequences of Alternaria species, including ex-type or epitype sequences. Bootstrap values greater than 10% are indicated above the nodes. Strains isolated in this study are highlighted in bold.

3.2 Molecular analysis

The identification of fungal species using molecular techniques served as a reliable method to confirm the accuracy of the fungal strains obtained. The molecular data supported the morphological observations and ensured precise taxonomy of the fungi. The finding indicated that PCR amplification of the ITS1-5.8S-ITS2 region using ITS4/ITS5 primers showed a PCR product of approximately 550 bp. Nucleotide sequence analysis and comparison with the GenBank database revealed a high similarity to *Alternaria brassicicola*, with percent identity ranging from 98.41% to 98.61% and query coverage ranging from 98.00% to 100.00%. Based on the phylogenetic analysis using the Neighbor-Joining method, the fungal isolate was clustered within the same clade as *A. brassicicola* isolates CBS118699 (accession no. JX499031) and PPRI:19555 (accession no. KT895944), with a bootstrap value of 98% (Figure 2). It was clearly separated from *A. brassicae* isolated CBS116528 (accession no. KC584185) and *A. alternata* isolated CBS916.96 (accession no. AF347031), a known pathogen of *Brassica* and lettuce plants, which formed a distinct clade with a bootstrap value of more than 90%. In addition, the fungal study was also clearly separated from *A. septorioides* isolate CBS106.41 (accession no. KC584216), a morphologically similar species that causes comparable disease symptoms in plants [26, 28].

The internal transcribed spacer (ITS) region of ribosomal DNA has been regarded as the universal DNA barcode for fungi due to its high variability and broad applicability across diverse fungal taxa. Nowadays, advancements in molecular systematics have underscored the benefits of incorporating additional genetic markers to enhance phylogenetic resolution. Phylogenetic tree analyses, which combine sequences from loci such as the large subunit (*LSU*) rRNA, RNA polymerase II subunit (*RPB2*), translation elongation factor 1-alpha (*TEF-1α*), and glyceraldehyde-3-phosphate dehydrogenase (*GAPDH*), have been effective in identifying species level and uncovering novel taxa. For instance, Zhu et al. [29] used the multi-sequence approach to identify a new genus, *Heteroxylaria*, within the family Xylariaceae, highlighting the ability to resolve complex taxonomic relationships. Moreover, the combination of deep learning techniques with molecular data has also further refined fungal classification. Moreover, the integration of deep learning techniques with molecular data has further refined fungal classification. The research of Liu et al. [30] developed FungiLT, a deep learning model combining BiLSTM and Transformer architectures, which achieved a species-level classification accuracy of 98.77% using ITS sequences. This approach presents the potential of combining computational tools with molecular data to improve identification accuracy, especially when dealing with large-scale sequencing datasets.

In our research, while ITS sequencing provided a foundational framework for fungal identification, the addition of multiple gene regions significantly enhanced the resolution and reliability of species diagnosis. This multi-locus strategy is important when

DOI: 10.60101/jarst.2026.263405

distinguishing among morphologically similar or closely related species, where single-locus analyses may fall short. So, multiple genetic markers not only corroborate morphological assessments but also ensure a more robust and accurate taxonomic classification [12, 17, 18, 31, 32].

3.3 Efficacy of calcium silicate on seed germination

The effectiveness of calcium silicate in promoting seed germination of *Brassica rapa* subsp. *chinensis* was investigated under laboratory conditions using the blotter method. Seeds were soaked in calcium silicate solutions at three different concentrations (1%, 2%, and 3%) and then incubated to monitor germination responses over 72 hrs. period. The first 24 hrs. investigation, germination percentage from 93.33% to 96.67%, with no statistically significant differences observed among the treatments. At 48 hrs., all treatments showed a 96.67% similar of germination percentage, indicating a continued and uniform germination response across the concentration levels. Finally for 72 hrs., complete germination (100%) was observed in all treatments. This result suggests that calcium silicate at all concentrations did not inhibit germination and may support early seedling development. These findings suggest potential for calcium silicate application in enhancing seed performance (Table 1).

Table 1 Germination percentage of Chinese cabbage seeds soaked in calcium silicate solutions at three different concentrations (1%, 2%, and 3%) over a period of 24 to 72 hrs.

Treatments	Germination percentage (%)[1/]		
	Day 1	Day 2	Day 3
Control	93.33 ±11.54[a]	96.67 ±5.77[a]	100.00 ±0.00[a]
1% Calcium silicate	93.33 ±11.54[a]	96.67 ±5.77[a]	100.00 ±0.00[a]
2% Calcium silicate	96.67 ±5.77[a]	96.67 ±5.77[a]	100.00 ±0.00[a]
3% Calcium silicate	93.33 ±5.77[a]	96.67 ±5.77[a]	100.00 ±0.00[a]
C.V. (%)	9.6942	5.9726	4.2633
F-test	NS	NS	NS
MSE	83.33	33.33	1.81

[1/] Column values followed by the same letter are not significantly different ($P \leq 0.05$)

4. Effect of calcium silicate on controlling fungal pathogen in vitro

The effectiveness of calcium silicate to inhibit the fungal mycelium, the causal agent of leaf spot disease in Chinese cabbage, was evaluated using the poisoned food technique. The results indicated that at 1 day after inoculation, calcium silicate at concentrations of 2% and 3% exhibited the lowest fungal mycelial growth, with colony diameters of 2.25 cm. In comparison, the control and the 1% calcium silicate treatment resulted in colony diameters of 3.00 cm, respectively.

However, statistical analysis indicated no significant differences between the treatments and the control. After 3 days of inoculation, calcium silicate at 3% and 2% concentrations could inhibit fungal mycelium, with colony diameters of 3.25 cm and 3.63 cm, respectively. In contrast, the 1% calcium silicate and the control exhibited colony diameters of 4.75 cm and 4.88 cm, respectively.

Likewise, at 5 days after inoculation, the results showed the 3% calcium silicate significantly reduced mycelial growth, showing a colony diameter of 7.00 cm, while 2% and 1% calcium silicate had colony diameters of 7.50 cm and 9.50 cm, respectively, whereas the control showed a colony diameter of 9.75 cm. (Table 2).

Table 2 Efficacy of calcium silicate solutions at three different concentrations (1%, 2%, and 3%) in inhibiting the mycelial growth of *Alternaria brassicicola*, the causal agent of leaf spot disease in Chinese cabbage (*Brassica rapa* subsp. *chinensis*), measured at 1, 3, and 5 days of incubation.

Treatments	Colony Diameter (cm) [1/]		
	Day 1	Day 3	Day 5
Control	3.00±0.4[a]	4.88±0.64[a]	9.75±0.50[a]
1% Calcium silicate	3.00±0.4[a]	4.75±0.48[a]	9.50±0.41[a]
2% Calcium silicate	2.25±0.50[a]	3.63±0.63[b]	7.50±0.58[b]
3% Calcium silicate	2.25±0.87[a]	3.25±0.29[b]	7.00±1.08[c]
C.V. (%)	2.1994	1.2856	4.2041
F-test	NS	**	***
MSE	0.33	0.28	0.47

[1/] Column values followed by the same letter are not significantly different ($P < 0.05$)

DOI: 10.60101/jarst.2026.263405

At the present, the research demonstrates the potential of calcium silicate as an effective agent to inhibit fungal mycelium of *A. brassicicola* on Chinese cabbage, particularly at higher concentrations (2% and 3%). The concentration of inhibition aligns with the previous studies indicating the role of silicon-based compounds in enhancing plant resistance and suppressing fungal pathogens. [33, 34].

Silicon amendments, including compounds such as calcium silicate, have been recognized for their role in enhancing plant structural defenses, especially the accumulation of silica within the plant cell wall. Cell walls are rigid and form a physical barrier that hinders fungal penetration and limits pathogen colonization [33]. Moreover, silicon has been reported to modulate plant immune responses by inducing systemic acquired resistance (SAR). This process involves the upregulation of defense-related enzymes, such as phenylalanine ammonia-lyase, peroxidases, and polyphenol oxidases, as well as the activation of antioxidant pathways that mitigate oxidative stress caused by pathogen infection [34]. Collectively, these mechanisms contribute to the reduction of pathogen virulence and enhance the overall resilience of the plant against a broad spectrum of biotic stresses.

Comparable research on *Alternaria* species showed that silicon treatments significantly reduced mycelial growth and lesion development in various host plants [34, 35]. These studies corroborate the inhibitory effects observed in our experiments, particularly enhanced efficacy at 3% calcium silicate concentration.

5. Calcium silicate efficacy on growth development

The efficacy of calcium silicate on the physiological development of Chinese cabbage was investigated. The application of calcium silicate significantly influenced seedling growth. After 7 days cultivation, seedlings treated with the highest concentration (3%) could exhibit the greatest growth, with an average height of 2.23 cm. followed 2% and 1% calcium silicate with average heights of 1.98 cm and 1.70 cm, respectively.

At 14 days, the results indicated that seedlings treated with 3% calcium silicate reached the highest average height of 7.68 cm, followed by 2% and 1% concentrations, which average heights of 6.53 cm and 5.58 cm, respectively. (Control is average heights of 4.78 cm) (Table 2).

Similarly, at 21 and 28 days after plantation, 3% calcium silicate showed the greatest height, with mean values of 12.70 cm and 15.80 cm., while seedling were treated with 2% and 1% concentrations showing 11.30 cm and 10.30 cm at day 21, and 14.05 cm and 13.70 cm at day 28, respectively (Table 3; Figure 3).

Table 3 Efficacy of calcium silicate solutions at three different concentrations (1%, 2%, and 3%) in promoting the growth and development of Chinese cabbage seedlings.

Treatments	Plant height (cm) [1/]			
	7 Day	14 Day	21 Day	28 Day
Control	1.70 ±0.53^{b}	4.78 ±1.11^{c}	8.48 ±0.78^{c}	11.08 ±1.32^{b}
1% Calcium silicate	1.70 ±0.36^{b}	5.58 ±0.45b^{c}	10.30 ±0.80^{b}	13.70 ±0.82^{a}
2% Calcium silicate	1.98 ±0.32^{a}	6.53 ±0.98^{ab}	11.30 ±0.91^{b}	14.05 ±1.62^{a}
3% Calcium silicate	2.23 ±0.30^{a}	7.68 ±0.85^{a}	12.70 ±0.74^{a}	15.80 ±1.44^{a}
C.V. (%)	20.0356	14.3667	7.5621	9.7644
F-test	*	**	***	**
MSE	0.15	0.78	0.65	1.78

[1/] Column values followed by the same letter are not significantly different ($P \leq 0.05$)

Table 4 Efficacy of calcium silicate solutions at three different concentrations (1%, 2%, and 3%) on root development of 28-day-old Chinese cabbage seedlings.

Treatments	Number of Root (Root) [1/]	Length of Root (cm) [1/]
Control	5.00±1.26^{b}	2.28±0.75^{C}
1% Calcium silicate	6.00±0.96^{ab}	4.23±0.40^{b}
2% Calcium silicate	6.00±0.82^{ab}	4.40±0.58^{b}
3% Calcium silicate	7.00±1.00^{a}	5.43±0.68^{a}
C.V. (%)	18.5567	15.1745
F-test	**	***
MSE	1.04	0.38

[1/] Column values followed by the same letter are not significantly different ($P \leq 0.05$)

DOI: 10.60101/jarst.2026.263405

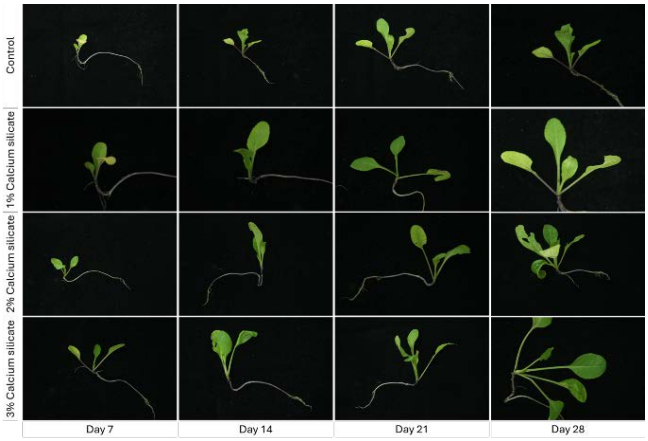

Figure 3 Efficacy of calcium silicate solutions at three different concentrations in promoting the growth of Chinese cabbage seedlings at 7, 14, 21, and 28 days after incubation.

Root development corresponded with the observed stem growth patterns. The highest calcium silicate concentration (3%) enhanced root growth and root number, with seedlings developing up to 7 roots per plant and an average root length of approximately 5.43 cm. In comparison, seedlings treated with 2% and 1% calcium silicate had an average of 6 roots per plant. The control seedling showed an average root number of 5 roots per plant and average root lengths of 4.40 cm and 4.23 cm, respectively, compared to the control's average root length of 2.28 cm (Table 4; Figure 3).

These findings align with recent studies highlighting the role of silicon, especially in the solution of calcium silicate, as a beneficial element enhancing plant growth and environmental stress tolerance. The research of Zargar et al. [36] indicated that silicon application can improve root architecture and biomass accumulation in vegetable plant by modulating nutrient uptake and stress resistance mechanisms.

Moreover, the research of Li et al. [37] reported calcium silicate enhanced growth and physiological performance in *Brassica* crops treated with silicon amendments, attributing the effects to improved cell wall inflexibility and antioxidant capacity. Furthermore, the observation of root elongation and root numbers correspond with findings by Eichi et al. [38], who noted silicon's role in stimulating root system development, which enhances water and nutrient absorption.

Moreover, silicon supplementation enhances photosynthetic efficiency and reduces reactive oxygen in vegetable crops. Therefore, the seedling height and root system development, as shown in this study, likely reflect the combined physiological benefits of calcium and silicon supplied by calcium silicate, supporting the plant's developmental processes [33].

CONCLUSIONS

The results of this study indicated that calcium silicate did not have a significant effect on seed germination of Chinese cabbage. This suggests that calcium silicate is not directly involved in the seed germination process. Moreover, other factors such as moisture availability, seed quality, and environmental conditions may play a more critical role in influencing germination.

However, calcium silicate was found in seedling growth, especially at higher concentrations (3%), which enhance seedling height, root number, and root length. These results are consistent with previous studies demonstrating that calcium silicate promotes plant cell development and strengthens the root system, resulting in longer and more extensively branched roots. In the case of fungal control, calcium silicate has shown potential in inhibiting the fungal pathogen *Alternaria brassicicola*, causal agent leaf spot disease in Brassicaceae crops.

The inhibitory mechanism may be associated with alterations in soil conditions that reduce spore distribution, as well as the induction of systemic acquired resistance (SAR), a natural plant defense response. Therefore, the application of calcium silicate represents a promising strategy to improve plant growth performance, enhance crop quality, and contribute to environmentally friendly disease control. This approach aligns with the goals of sustainable agricultural practices for long-term productivity and ecosystem health.

DECLARATION OF AI AND AI-ASSISTED TECHNOLOGIES IN THE WRITING PROCESS

The authors used Grammarly to check spelling and grammar during the preparation of this manuscript. The authors take full responsibility for the content of the publication and performed all necessary reviews and revisions after using this tool.

ACKNOWLEDGEMENT

The authors thank the Research and Development Institute of Rajamangala University of Technology Suvarnabhumi, Phra Nakhon Si Ayutthaya, Thailand for funding research under Frontier Research project [Grant No. R66202009] and we would like to thank Program in Plant Science, Faculty of Agricultural Technology and Agro-Industry, Rajamangala University of Technology Suvarnabhumi, for the molecular equipment in this research.

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DOI: 10.60101/jarst.2026.263405

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