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EXOGENOUS SILICON AND *PSEUDOMONAS FLUORESCENS* ALLEVIATE *MELOIDOGYNE JAVANICA* STRESS IN TOMATO PLANTS

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In this study, the biological control effects of the *Pseudomonas fluorescens* strain CHA0 were compared to those of silicon (Si), used as a chemical control agent, against *Meloidogyne javanica*, the causative agent of root-knot disease in tomato plants. Indicators such as the number of *M. javanica* galls, eggs, egg masses, and the enzymatic activities of peroxidase (POX) and phenylalanine ammonia-lyase (PAL) were analysed. Results showed a significant reduction in the numbers of galls, eggs, and egg masses produced by *M. javanica* on tomato plants treated with *P. fluorescens* CHA0 (applied as a soil additive) as well as with Si (applied as a root and foliar treatment). The enzymatic activities peaked on the fifth day post-inoculation with *M. javanica* and then gradually declined. The greatest increase in enzymatic activities was observed in the combined treatment with *M. javanica*, *P. fluorescens* CHA0, and Si (the N+B+SiO2 treatment). The use of *P. fluorescens* CHA0 and Si enhanced the defence-related enzyme activity in tomato plants against *M. javanica*. However, high concentrations of Si were shown to inhibit the growth of *P. fluorescens* CHA0.

Key words: tomato*, Meloidogyne javanica*, Si, *Pseudomonas fluorescens*, PAL, POX

The tomato (*Solanum lycopersicum* Mill.), belonging to the Solanaceae family, is not only the most important horticultural crop globally but also the primary model for studying fleshy-fruited dicotyledons (Saqib *et al.* 2020). Wildly cultivated as a vegetable in numerous countries (Amaresan *et al.* 2019), tomato production is severely impacted by plant pathogens, particularly nematodes, which substantially damage vital crops worldwide (Banerjee *et al.* 2017). Plant-parasitic nematodes (PPNs) are recognised as significant biotic stressors, causing considerable crop damage and yield losses globally, with annual economic impacts estimated at $173 billion (El Aimani *et al.* 2022). Tomato growth and development are especially vulnerable to root-knot nematodes (Khan *et al.* 2011). Plants infected with root-knot nematodes (*Meloidogyne* spp.) suffer from stunted growth and display characteristic symptoms of nutrient deficiency (Siddiqui & Akhtar 2007) as well as root galling (Olowe 2004). Biological control and the activation of plant defence mechanisms are two promising strategies for managing various

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phytopathogens, especially plant-parasitic nematodes. These eco-friendly approaches have drawn increasing attention (Sahebani & Gholamrezaee 2021).

Microorganisms in the rhizosphere can offer protection against pathogen invasion (Berendsen *et al.* 2012). Growth-promoting bacteria provide substantial protection against nematode diseases (Son *et al.* 2009). Similarly, certain chemical compounds may suppress phytopathogen populations and enhance plant resistance to pathogen-induced diseases (Dordas 2008). Nematode-infected plants generally exhibit foliar symptoms of nutrient deficiency, and fertiliser management can influence the growth and reproduction of nematodes (Li *et al.* 2010). Biological control is a safe alternative to pesticides in disease management and is expected to be free from toxic residual effects (Wyckhuys *et al.* 2013). Various microbial antagonists of root-knot nematodes have been identified, with their application significantly reducing nematode populations (Zhou *et al.* 2016). *Pseudomonas fluorescens* (UP61) is a biocontrol agent (BCA) commonly used against plant-parasitic nematodes (Höfte & Altier 2010). Alongside their suppressive effects on target pathogens, these BCAs also stimulate or activate plant defence mechanisms (Molinari & Leonetti 2019).

Approximately 70% of soil mass consists of silicon (Si), making it one of the most abundant elements in the Earth's crust (Okeke *et al.* 2023). Many plants, particularly grasses and sedges, benefit from silicon exposure, leading to a range of positive effects (Rajput *et al.* 2021). Silicon (Si) is a beneficial element for various plant species under certain environmental conditions (Chanchal Malhotra *et al.* 2016). Recently, increasing attention has been directed towards the role of Si in enhancing plant resistance to both abiotic and biotic stresses (Chanchal Malhotra *et al.* 2016; Bakhat *et al.* 2018). It is well established that Si can strengthen plant defence mechanisms against various phytopathogens (Wang *et al.* 2017).

However, no research has been conducted to investigate the combined effect of silicon (Si) and potential biological agents on *Meloidogyne javanica* CHA1 infection in root-knot nematodes. Therefore, this study aimed to examine how *P. fluorescens* CHA0 (a biotic agent) and Si (an abiotic agent) may influence nematode-infected tomato plants.

MATERIAL AND METHODS

Pathogen sampling

Soil and root samples were collected from the rhizosphere of tomato in fields infested with root-knot nematodes in Pishva-Varamin, Tehran Province, Iran. A single egg mass was used to establish a population of plant-parasitic nematodes on the tomato plants. Based on morphological and morphometric characteristics, the nematode species was identified as *M. javanica* (Eisenback & Triantaphyllou 1991).

Egg extraction and second-stage juveniles

The egg masses of *M. javanica* collected from tomato roots were vigorously shaken with 200 mL of 0.5% sodium hypochlorite (NaOCl) in a blender bottle for 1 minute (Ansari *et al.* 2002). The eggs were then cleaned using a 200 mesh (75 μm) sieve, rinsed with water, collected on a 500 mesh (26 μm) sieve, and transferred to distilled water to create an egg suspension.

Extraction of juveniles

The root-knot nematode *M. javanica* was cultivated on tomato plants, and second-stage juveniles (J2) were extracted from the roots using the tray method (Whitehead & Hemming 1965). More than 400 second-stage juveniles were obtained and stored at 15°C for no longer than five days.

Bacterial strain

The bacterial strain *P. fluorescens* CHA0 used in this study (obtained from the College of Agriculture and Natural Resources, University of Tehran, Iran) was routinely cultured in nutrient yeast broth, comprising 25 g of nutrient broth (High Media, India), 5 g of yeast extract (High Media, India), and distilled water. The bacteria were agitated in the nutrient broth for 48 hours on a shaker at 150 rpm and then centrifuged at 4500 × g for 10 minutes. Subsequently, the bacterial cells were separated from the medium and washed with sterilized water. Finally, a bacterial suspension was prepared at a concentration of 10^9 CFU/mL (Thompson *et al.* 1996).

Silicon

Soluble Si fertiliser ($SiO_2 \geq 99.8\%$, granule diameter 10 – 20 nm, pH 4 – 6) acquired from Merck Company (Darmstadt, Germany) was stored in sealed plastic containers until usage. Si at 3 mM concentration had no adverse impact on the *P. fluorescens* CHA0 strain used in the greenhouse experiments. In this study, Si with concentrations of 1, 2, 3, 4, 5, 6, and 7 mM were prepared for *in vitro* analysis.

Plant materials

Seeds of tomato plants susceptible to *M. javanica* were cultivated in an environmentally controlled growth chamber. The seeds were sterilised using 0.85% sodium hypochlorite, washed three times with sterile $MgSO_4$ (0.1 M), and dried in a laminar flow hood. The seeds were then planted in plastic pots with a diameter of 15 cm, each containing a 1 kg sterilised mixture of field soil, leaf compost, and sand in a ratio of 1:2:2 (one seedling per pot). The soil was autoclaved on two successive days at 121°C for 1 hour. For in vivo analysis, the plants were subjected to the 4 – 6 leaf stage

In vitro tests

Determination of the effect of silicon on the growth rate of P. fluorescens CHA0

Various amounts of silicon were used to prepare a 0.3 mL volume of medium containing 0.325 g of powder for different treatments. Distilled water was then added to achieve a final volume of 25 mL. Once the solution was diluted and made uniform, each silicon concentration was distributed into four tubes, each with a volume of 10 mL, and autoclaved. Subsequently, 1 mL of *P. fluorescens* suspension at a concentration of 10^9 CFU was added to each tube, which was then placed on a shaker at 120 rpm for 24 hours. The following day, the tubes were centrifuged at 3,500 rpm for 6 minutes at 25°C. In the next step, the precipitate was mixed with 1 mL of sterilised distilled water, and the absorbance of the samples was measured at 590 nm using a spectrophotometer to determine the population density

Determination of silicon and P. fluorescens CHA0 effects on M. javanica

The soil in pots containing seedlings at the 4 – 6 leaf stage was drenched with 30 mL of *P. fluorescens* CHA0 suspension and 25 mL of 3 mM silicon. After 24 hours, the plants were infected with approximately 2,000 freshly hatched second-stage juveniles. The number of larvae was determined randomly in 1 mL of the larval suspension, after which the total larval suspension was diluted. The plants were then introduced into three holes around the roots in each pot.

The experiment consisted of 12 treatments:

1. Control plants: Plants treated with sterilized distilled water.
2. N: Plants treated with *M. javanica*.
3. SiO_2 (SD): Plants treated with Si (25 mL at 3 mM concentration, the soil drenching method).
4. SiO_2 (LS): Plants treated with Si (25 mL at 3 mM concentration, the leaf spray method).
5. B: Plants treated with *P. fluorescens* CHA0 (25 mL at 10^9 CFU, the soil drenching method).
6. N + SiO_2 (SD): Plants treated with Si (25 mL at 3 mM concentration, the soil drenching method) + *M. javanica*.
7. N + SiO_2 (LS): Plants treated with Si (25 mL at 3 mM concentration, the leaf spray method) + *M. javanica*.
8. N + B: Plants treated with *P. fluorescens* CHA0 (25 mL at 10^9 CFU, the soil drenching method) + *M. javanica*.
9. B + SiO_2 (LS): Plants treated with *P. fluorescens* CHA0 (25 mL at 10^9 CFU, the soil drenching method) + Si (25 mL at 3 mM concentration, the leaf spray method).
10. B + SiO_2 (SD): Plants treated with *P. fluorescens* CHA0 (25 mL at 10^9 CFU, the soil drenching method) + Si (25 mL at 3 mM concentration, the soil drenching method).
11. N + B + SiO_2 (SD): Plants treated with *P. fluorescens* CHA0 (25 mL with 10^9 CFU, the soil drenching method) + Si (25 mL at 3 mM concentration, the soil drenching method) + *M. javanica*.
12. N + B + SiO_2 (LS): Plants treated with *P. fluorescens* CHA0 (25 mL at 10^9 CFU, the soil drenching method) + Si (25 mL at 3 mM concentration, the leaf spray method) + *M. javanica*.

The treated pots were located in the greenhouse, and the experiment lasted 45 days after the inoculation of the nematode *M. javanica*. At the end of

this period, the samples were collected, washed, and analysed.

Determination of enzymatic activity

In the present study, the enzymatic activities of peroxidase (POX) and phenylalanine ammonia-lyase (PAL) were assessed in the root tissues of the plants. The tomato plants were cultivated as previously described, and the inoculation was carried out with *M. javanica*, *P. fluorescens* CHA0 and Si. The samples were taken on the first, third, fifth, and seventh days after infection with the nematode.

The enzymatic activity of PAL was estimated based on the rate of cinnamic acid production, following a procedure described elsewhere (Wang *et al.* 2006). Additionally, the enzymatic activity of POX was assessed by measuring the appearance of a pink/brown colour resulting from guaiacol oxidation in the presence of hydrogen peroxide, according to the method previously outlined by Gholamnezhad *et al.* (2016).

Statistical analyses

This experiment was conducted following a completely randomised design with four replications. All statistical analyses were performed using SPSS 23 software, followed by Duncan's multiple range test (at the 5% significance level) to compare the treatment means.

RESULTS AND DISCUSSION

Growth rate of P. fluorescens CHA0

As shown in Figure 1, the growth rate of *P. fluorescens* CHA0 in the silicon-treated groups significantly decreased compared to the control group ($P < 0.05$). Bacterial growth in all treatments, including 1, 2, 3, 4, 5, 6, and 7 mM silicon, was reduced by 3.86%, 12.11%, 14.94%, 45.11%, 51.54%, 61.85%, and 67.52%, respectively. Consequently, the reduction rates at 1, 2 and 3 mM were lower than those at 4, 5, 6, and 7 mM. This observation indicated that the growth rate of *P. fluorescens* CHA0 decreased with increasing silicon concentration, with the lowest growth rate occurring at the 7 mM concentration.

Quantity of galls per plant

The results of measuring the number of galls per plant indicated a significant difference between all treatments and the nitrogen (N) treatment group ($P < 0.05$) (Figure 2). Compared to the control plants, all combined treatments resulted in a reduction in the number of galls per plant. Similarly, compared with the N-treated group, the percentage of galls per plant in the N + B, N + SiO_2 (SD), N + B + SiO_2 (SD), and N + B + SiO_2 (LS) treatment groups decreased by 60.04%, 43.17%, 47.69%, 63.07%, and 61.53%, respectively, in response to all other treatments. The N and N + B + SiO_2 (SD) treatments produced the highest and lowest number of galls per plant, respectively. These findings suggested that the N + B + SiO_2 (SD) treatment had the greatest effect in reducing the number of galls per plant. Additionally, there was no significant difference between the application of silicon through leaf spray or soil drenching ($P < 0.05$).

Quantity of eggs per plant

After the application of the *P. fluorescens* CHA0 and Si treatments, the quantity of egg masses per plant was markedly lower than in plants affected by only *M. javanica* ($P < 0.05$) (Figure 3). Similarly, compared with those in plants treated with *M. javanica*, the quantity of egg masses per plant in the N + B, N + SiO_2 (SD), N + SiO_2 (SD), and N + B + SiO_2 (LS) treatments decreased by 50.27%, 20.47%, 34.18%, 38.75%, and 44.24%, respectively. Compared with the other treatments, simultaneous treatment with *M. javanica* and *P. fluorescens* CHA0 (the N + B treatment) resulted in the greatest decrease in egg mass. However, the lowest decrease in egg mass was found in the N+SiO_2 (SD) treatment (*M. javanica* + silicon [soil drenching]).

Quantity of eggs per egg mass

All treatments significantly reduced the number of eggs per egg mass compared to the group solely infected with *Meloidogyne javanica* (N) ($P < 0.05$) (Figure 4). Specifically, the number of egg masses per plant in the N + B, N + SiO_2 (SD), N + SiO_2 (LS), and N + B + SiO_2 (LS) treatments decreased by 35.59%, 11.08%, 31.63%, 44.17%, and 48.46%, respectively, in comparison to the N treatment. Notably, the N + B + SiO_2 (LS) treatment, involving plants incubated with *M. javanica*, *P. fluorescens* CHA0, or silicon as a leaf spray, exhibited a more

substantial reduction in egg numbers than either the control or the other treatment groups. Furthermore, a statistically significant difference was identified between the N group and the remaining treatment groups.

Phenylalanine ammonia-lyase (PAL) activity

Analysis of PAL enzyme activity in the root tissues revealed no significant difference between the plants treated with *M. javanica* and the control group (Figure 5). The highest enzymatic activity of PAL was observed in plants treated with the combination of *M. javanica* and *P. fluorescens* CHA0, as well as in those treated with *M. javanica* and silicon applied via the leaf spray method (N + B + SiO_2 (LS)). In all treatments investigated, PAL activity

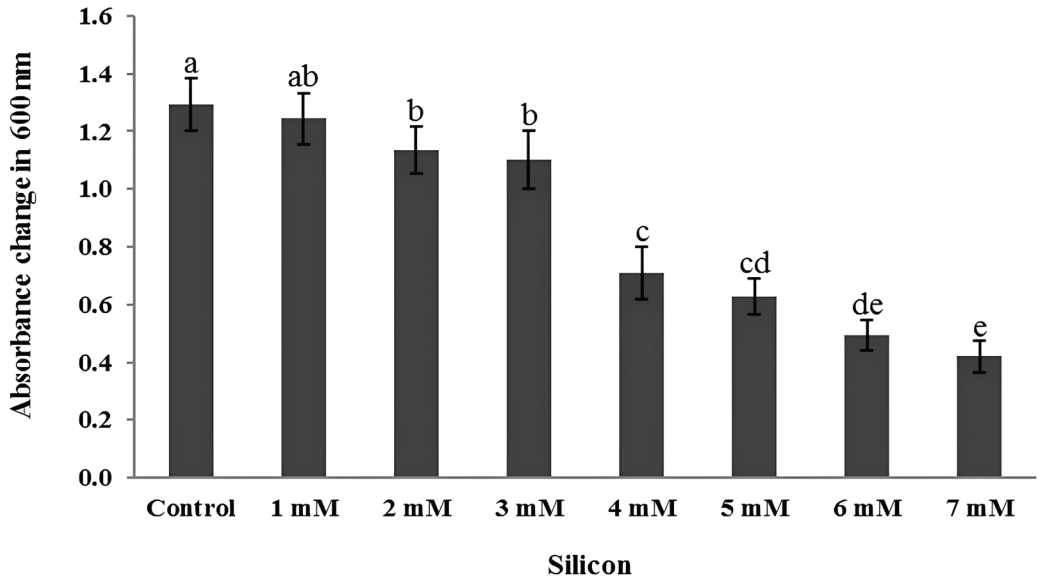

Figure 1. Effect of different silicon concentrations on the growth rate of *P. fluorescens* CHA0. The values represent the means of four replicates ± SDs. The various lowercase letters on the error bars indicate significant differences at the 5% error level according to Duncan's multiple range test.

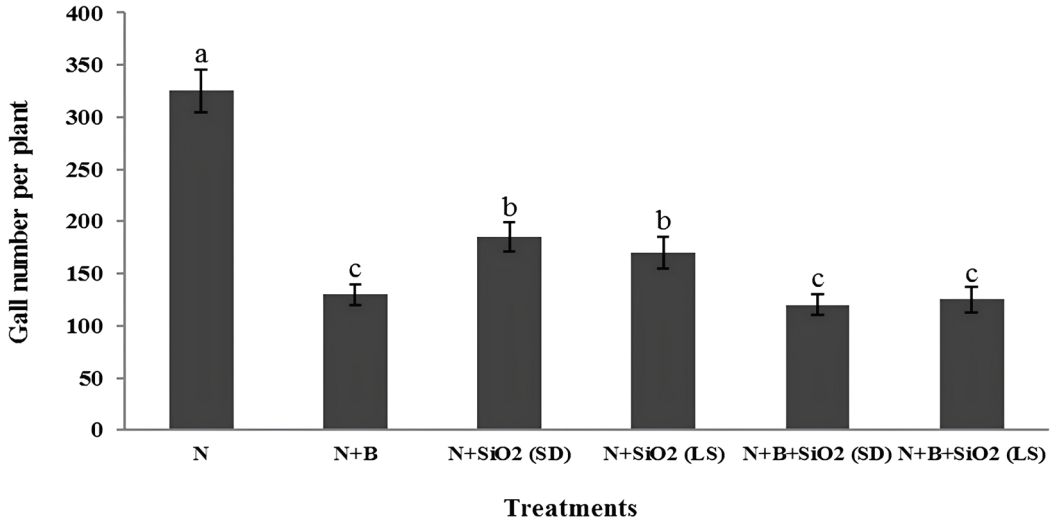

Figure 2. Effects of silicon and *P. fluorescens* CHA0 on the number of galls on tomato plants infected with *M. javanica*. The values represent the means of four replicates ± SDs. The various lowercase letters on the error bars indicate significant differences at the 5% error level according to Duncan's multiple range test. N – nematode; N + B – nematode + bacterial agent; N + SiO_2 (SD) – nematode + silicon (soil drenching); N + SiO_2 (LS) – nematode + silicon (leaf spray); N + B + SiO_2 (SD) – nematode + bacterial agent + silicon (soil drenching); N + B + SiO_2 (LS) – nematode + bacterial agent + silicon (leaf spray).

increased until the fifth day, after which it declined by the seventh day.

Peroxidase (POX) activity

The application of *M. javanica, P. fluorescens* CHA0, and silicon, both individually and in combination, resulted in significant changes in the enzymatic activity of POX in the root tissues of tomato plants ($P<0.05$) (Figure 6). The highest enzyme activity was observed in plants treated with the combination of *M. javanica, P. fluorescens* CHA0 and silicon (N + B + SiO_2 (LS) group). Additionally, significant differences were noted across the treatment days. In all groups examined, the lowest and highest POX activities were recorded on the first and fifth days, respectively. Enzymatic activity of POX

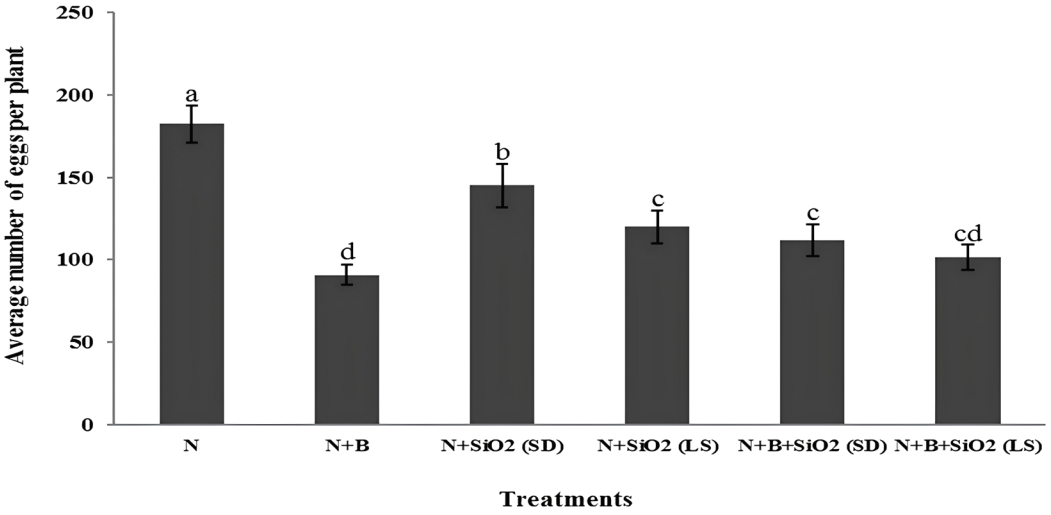

Figure 3. Effects of silicon and *P. fluorescens* CHA0 on the average number of eggs per plant on tomato plants infected with *M. javanica*. The values represent the means of four replicates ± SDs. The various lowercase letters on the error bars indicate significant differences at the 5% error level according to Duncan's multiple range test. N – nematode; N + B – nematode + bacterial agent; N + SiO_2 (SD) – nematode + silicon (soil drenching); N + SiO_2 (LS) – nematode + silicon (leaf spray); N + B + SiO_2 (SD) – nematode + bacterial agent + silicon (soil drenching); N + B + SiO_2 (LS) – nematode + bacterial agent + silicon (leaf spray).

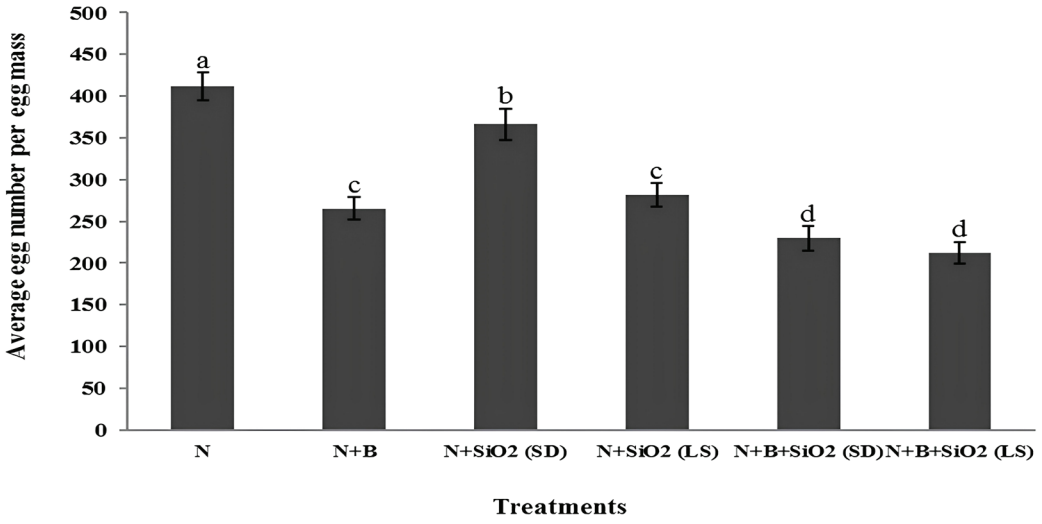

Figure 4. Effects of silicon and *P. fluorescens* CHA0 on the average number of eggs per egg mass in tomato plants infected with *M. javanica*. The values represent the means of four replicates ± SDs. The various lowercase letters on the error bars indicate significant differences at the 5% error level according to Duncan's multiple range test. N – Nematode; N + B – Nematode + Bacterial agent; N + SiO_2 (SD) – nematode + silicon (soil drenching); N + SiO_2 (LS) – nematode + silicon (leaf spray); N + B + SiO_2 (SD) – nematode + bacterial agent + silicon (soil drenching); N + B + SiO_2 (LS) – nematode + bacterial agent + silicon (leaf spray).

increased from the first to the fifth day and subsequently decreased from the fifth to the seventh day.

In this study, we investigated the efficacy of *P. fluorescens* CHA0 as a biological control agent, alongside silicon (Si) as a chemical control agent, as well as the effects of their combination against the root-knot nematode (*M. javanica*) in tomato plants. We also assessed the impact of varying Si concentrations on the growth rate of the antagonistic bacterium *P. fluorescens* strain CHA0. The results demonstrated that different concentrations of Si influenced the growth rate of *P. fluorescens* CHA0 in distinct ways. At low concentrations, Si had a negligible effect on growth, whereas at higher concentrations, it exhibited inhibitory and lethal effects. In *M. javanica*-infected plants treated with *P. fluo-*

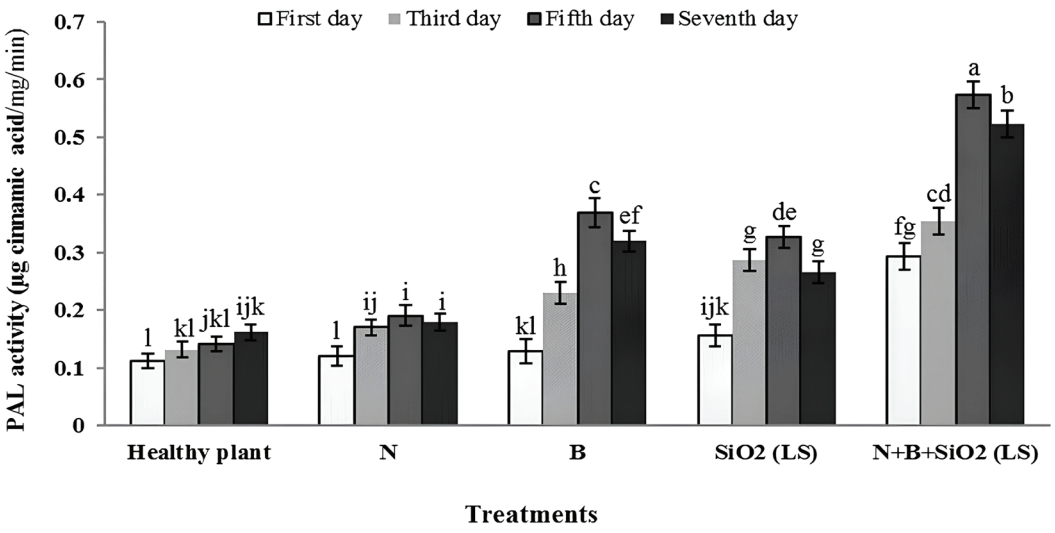

Figure 5. Activity of the PAL enzyme in tomato roots incubated with *P. fluorescens* CHA0, *M. javanica* and silicon. The values represent the means of four replicates ± SDs. The various lowercase letters on the error bars indicate significant differences at the 5% error level according to Duncan's multiple range test. N – nematodes; B – bacterial agent; SiO_2 (LS) – silicon (leaf spray); N + B + SiO_2 (LS) – nematode + bacterial agent + silicon (leaf spray).

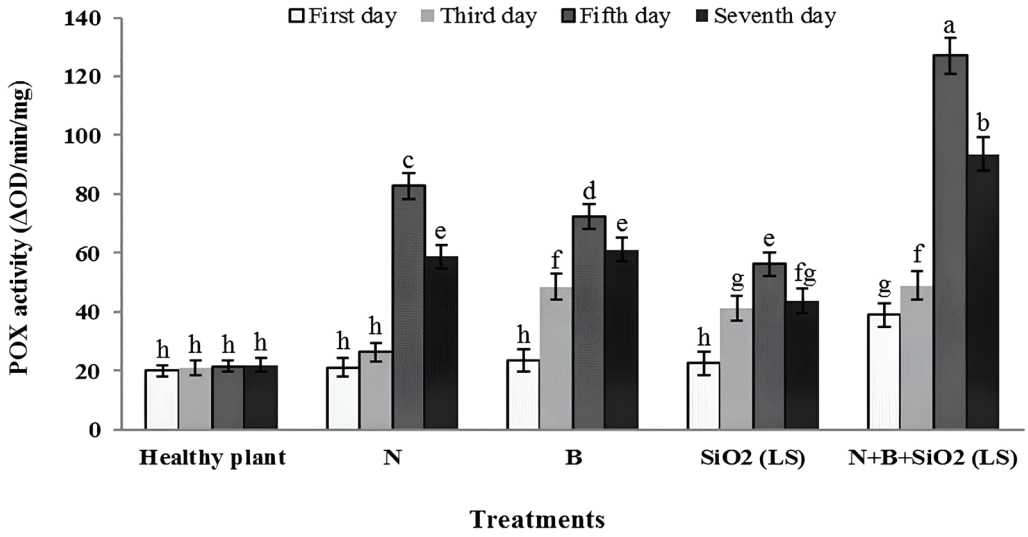

Figure 6. Activity of the POX enzyme in tomato roots incubated with *P. fluorescens* CHA0, *M. javanica* and silicon. The values represent the means of four replicates ± SDs. The various lowercase letters on the error bars indicate significant differences at the 5% error level according to Duncan's multiple range test. N – nematodes; B – bacterial agent; SiO_2 (LS) – silicon (leaf spray); N + B + SiO_2 (LS) – nematode + bacterial agent + silicon (leaf spray).

rescens CHA0 and Si, there was a notable reduction in disease indicators, including the number of galls, egg masses and eggs per egg mass. Previous studies have identified *P. fluorescens* as a biological control agent.

Previous studies have identified *P. fluorescens* as a biological control agent against root-knot nematodes due to its ability to enhance plant growth while simultaneously reducing nematode growth and reproduction. The application of silicon (Si), whether in combination with *P. fluorescens* CHA0 or independently via the leaf spray method, proved to be more effective in reducing disease incidence compared to application through soil drenching. Furthermore, prior research has demonstrated that *P. fluorescens* alleviates stress caused by *Meloidogyne* species in various plants, including *M. javanica* in tomatoes (Siddiqui *et al.* 2003; Siddiqui *et al.* 2006; Dehghanian *et al.* 2020; Moazezikho *et al.* 2020), *M. javanica* in chillies (Azam *et al.* 2018), *M. javanica* in eggplants (Sharma *et al.* 2021), *M. incognita* in tomatoes (Noureldeen *et al.* 2021), and *M. incognita* in vitro (Mahgoob *et al.* 2023).

It has been suggested that silicon (Si) influences various parameters and processes in plants. For instance, Si may affect crop growth and productivity (Meena *et al.* 2014), nutrient uptake (Mali & Aery 2008), production of secondary metabolites (Schaller *et al.* 2012), the antioxidant defence system (Pei *et al.* 2010), gene expression (Seal *et al.* 2018), disease suppression (Wang *et al.* 2013), insect attack and pest incidence (Chanchal Malhotra *et al.* 2016), as well as pathogen infestation (Rémus-Borel *et al.* 2009). Despite its beneficial effects on plant resistance to both biotic and abiotic challenges, Si does not exert significant negative impacts on the environment or agriculture. Consequently, this element is regarded as a critical factor in the control of plant diseases and pests (Sakr 2016). Zhan *et al.* (2018) demonstrated that root-applied Si had a priming effect on enhancing rice resistance to the root-knot nematode *M. graminicola*. In a study on coffee roots, it was found that Si could influence the penetration and reproduction of *M. exigua* (Silva *et al.* 2015). Dugui-Es *et al.* (2010) indicated that the application of 200 ppm Si, in the form of sodium metasilicate, to the shoots and roots of cucumber plants could reduce the number of galls associated with *M. incognita*, thus promoting plant growth. Silva *et al.* (2010) reported that the use of Si (calcium silicate) in the soil decreased the number of galls by 16.8% and the quantity of eggs by 28.1% in *M. exigua*, while also reducing the reproductive capacity of the nematode on coffee plants. Resende *et al.* (2009) discovered that Si enhanced the resistance of the susceptible sorghum line BR009 to anthracnose diseases caused by *Colletotrichum sublineolum*. Zuccarini (2008) proposed that Si, through its effects on photosynthesis, nutrient uptake, and water relations, improved the growth rate of *Phaseolus vulgaris* plants under NaCl stress. Bélanger *et al.* (2003) affirmed that Si application could enhance the resistance of wheat plants to powdery mildew disease caused by the fungus *Blumeria graminis*. In addition to Si, Si nanoparticles can also aid plants in defending against *M. javanica* in tomatoes (Charehgani *et al.* 2021), *M. incognita* in carrots (Ahamad *et al.* 2021), *M. javanica* in cowpeas (Gomes Sampaio *et al.* 2022), *M. incognita* in eggplants (El-Ashry *et al.* 2022), and *Meloidogyne* spp. in tomatoes (Tavallali & Karimi 2023).

The enzymatic activities of PAL and POX increased until the fifth day and subsequently decreased over time. Silva *et al.* (2010) reported that silicon (Si) in the form of calcium silicate enhanced PAL and POX enzymatic activity in the roots of coffee plants inoculated with *M. exigua*. Zhu *et al.* (2004) suggested that Si could elevate the activity of antioxidant enzymes such as POX in the leaves of cucumber plants subjected to salt stress. Kalaiarasan (2009) demonstrated that increased PAL and POX enzymatic activities bolstered the resistance of tomato plants to the root-knot nematode *M. incognita.* It has been shown that lignin plays a crucial role in supporting tomato defence against *M. incognita* (Veronico *et al.* 2018). Therefore, enhancing the enzymatic activities of PAL and POX, which are involved in lignin biosynthesis, may improve plant resistance to root-knot nematodes. Mohammadi and Kazemi (2002) suggested that the POX enzyme could facilitate the oxidation of phenolic metabolites into antimicrobial quinones in plant tissues infected by phytopathogens, thereby enhancing disease resistance under stressful conditions. Furthermore, biochemical evidence indicates that Si accelerates the activation of enzymes in the

phenylpropanoid pathway, such as PAL, POX and polyphenol oxidases (PPOs), which are essential for the synthesis and deposition of phenolic compounds in plant cell walls during colonisation by *Alternaria alternata* in sorghum (Bathoova *et al.* 2021). The study by Qi *et al.* (2023) showed that applying Tetraethyl orthosilicate (TEOS) as a spray reduced the survival and population growth of *Sitobion avenae*, while simultaneously enhancing the defence mechanisms of wheat against aphids. This was achieved by boosting the activity of PAL and PPO in wheat and elevating the levels of total phenolics and jasmonic acid (Qi *et al.* 2023).

CONCLUSIONS

The results from the greenhouse experiments indicated that the application of silicon (Si) was more effective when delivered via the leaf spray method compared to soil drenching. Consequently, the leaf spray method was selected for further analyses. The findings revealed that the combined treatment of N+B+SiO_2 (LS) – which involved *M. javanica*, *P. fluorescens* CHA0, and Si applied through leaf spraying – was the most effective for enhancing the enzymatic activities of PAL and POX. This study supports the hypothesis that Si can enhance the effectiveness of biological agents in controlling *M. javanica*. It appears that Si influences the interactions among plants, *P. fluorescens* strain CHA0 and *M. javanica* through various mechanisms. However, further research is required to elucidate these mechanisms and their effects in greater detail. A deeper understanding of the plant-nematode interaction mechanisms of *M. javanica*, mediated by Si and *P. fluorescens*, will facilitate improvements in tomato yield and enhance plant resistance to this nematode. Collectively, these findings suggest that Si and *P. fluorescens* could serve as sustainable solutions for mitigating the impacts of potentially harmful elements and plant stress within agroecosystems, ultimately contributing to food security.

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