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ARTICLE

Endophytic bacteria from *Jatropha curcas* suppress *Meloidogyne* spp. and promote eggplant growth under greenhouse conditions

Ahmed Ibrahim Alrashid Yousif[1,2,*], Yuda Purwana Roswanjaya[1], Elrasheed Siddig Libs Ibrahim[2], Abdul Munif[3], Ankardiansyah Pandu Pradana[4], Naseer Ahmed[5]

[1] Research Center for Applied Microbiology, Research Organization for Life Sciences and Environment, National Research and Innovation Agency (BRIN), Jl. Raya Jakarta-Bogor Km. 46, Bogor, Indonesia, 16911
[2] Department of Plant Protection, Omdurman Islamic University, Alfetehab, Omdurman, Sudan, 11111
[3] Crop Protection Department, Bogor Agricultural University, Dramaga, Bogor, Indonesia, 16680
[4] Department of Plant Protection, University of Jember, Jember, Indonesia, 68121
[5] Department of Chemistry, University of Haripur, Pakistan, 22620

ABSTRACT In recent years, pesticide use has increased, posing risks to humans, the environment, and other life forms. This study evaluated the potential of endophytic bacteria isolated from *Jatropha curcas* L. to promote growth and suppress *Meloidogyne* spp. in eggplant (*Solanum melongena* L.) under greenhouse conditions. Three isolates, FJS23 (*Pseudomonas* sp.), SJS54 (*Micrococcus* sp.), and RJS175 (*Pseudomonas* sp.), were selected based on biosafety and biochemical screening and identified using 16S rRNA gene sequencing. Before application, bacterial suspensions were adjusted to OD_{600} = 1.0 and applied as root dips followed by soil drenching, either singly or in two- and three-isolate combinations. Plant growth and nematode parameters were assessed 40 days after nematode inoculation. All treatments significantly enhanced plant growth compared with the control (DMRT, α = 0.05; n = 7). Isolate SJS54 (*Micrococcus* sp.) produced the tallest plants (60.10 cm), while the combination FJS23 (*Pseudomonas* sp.) + SJS54 (*Micrococcus* sp.) resulted in the highest shoot fresh weight (93.30 g), dry weight (17.91 g), and leaf number (20.5). Nematode infestation and root galling were markedly reduced by all treatments compared with the control (131.5 galls root^{-1} and 3.046 galls g^{-1} root). Notably, SJS54 (*Micrococcus* sp.) reduced gall formation to 1.25 galls root^{-1} and 0.015 galls g^{-1} root, representing a >99% reduction relative to the control (DMRT, α = 0.05; n = 7). These results demonstrate that *J. curcas*-derived endophytes, particularly SJS54 (*Micrococcus* sp.) and its combinations, can effectively promote plant growth and suppress root-knot nematodes, offering a sustainable alternative to chemical nematicides for eggplant production.

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***Corresponding author**
E-mail: aia.yousif@oiu.edu.sd

INTRODUCTION

The Solanaceae family, recognized as a vital vegetable family on a global scale, encompasses over 100 genera and 3000 species (Niño-Medina et al. 2017). Eggplant (*Solanum melongena* L.), also known as *brinjal* or *aubergine*, is among the top ten vegetable crops cultivated worldwide and ranks as the third most cultivated solanaceous species after potato and tomato, with global production exceeding 58.6 million tons in 2021, largely because of its adaptability to different seasons (Saha et al. 2023). The economic significance of eggplant is noteworthy, particularly in Asia, Africa, and the subtropics (e.g., Central America). Eggplants also thrive in warm temperate zones, including the Mediterranean and southern United States (Niño-Medina et al. 2017).

Despite its importance, eggplant cultivation faces substantial challenges owing to a broad spectrum of insect pests and associated diseases. Among these, root-knot nematodes (RKN; *Meloidogyne* spp.) are a significant threat that leads to plant stunting and pronounced yield reduction (Tapia-Vázquez et al. 2022; Sharma and Kaushik 2021; Ralmi et al. 2016). Several strategies exist for managing RKN infestation, but chemical nematicides remain the predominant approach. However, their use poses environmental and ecological risks, highlighting the need for safer, environmentally friendly alternatives (Tiwari 2024). The extensive host range of RKN also limits the availability of resistant cultivars and complicates

the development of immune or highly resistant crop varieties (Yadav et al. 2025; Kaur et al. 2018). Efforts to mitigate RKN infestation in eggplants include breeding approaches that utilize wild eggplant relatives, such as *Solanum torvum*, which exhibits notable resistance to *Meloidogyne* spp. (Sujatha et al. 2008).

To complement such strategies, attention has increasingly turned to biological resources such as beneficial endophytes. In this context, *Jatropha curcas* L. (family Euphorbiaceae), originally from Central America but now widely distributed, is a promising candidate. The rapid growth of *J. curcas* and its ability to thrive under stressful conditions, such as nutrient-deficient soils and varying rainfall patterns, make it a suitable crop for cultivation in human-influenced or unproductive areas (Debnath and Bisen 2008; Kumar et al. 2017). The diverse characteristics of *J. curcas* also make it a promising choice for both agricultural practices and bioenergy applications, in line with initiatives for sustainable development (Pandey et al. 2012). In addition, *J. curcas* is highly suitable for sourcing endophytic bacteria because of its unique ecological and physiological traits. This plant thrives in nutrient-poor soils, drought-prone conditions, and harsh environments, which likely drives the evolution of a resilient and adaptive endophytic microbiome (Massoukou Pamba et al. 2024; Mohanty et al. 2017).

Endophytic bacteria, as highlighted by Afzal et al. (2017), colonize internal plant tissues without inducing disease. Their association with plants serves various beneficial purposes, including facilitation of growth, nutrient absorption, enhanced resistance to abiotic stress, and improved disease resistance (Eid et al. 2021; Verma et al. 2021). Despite the importance of endophytes in crop-related contexts and their potential for disease control, comprehensive studies in this domain are still limited. Previous studies have demonstrated the efficacy of endophytic microorganisms in controlling plant pathogens, insects, and nematodes (Grabka et al. 2022; Ryan et al. 2008). The protective role of endophytic bacteria is mediated by several mechanisms, including the production of hydrolytic enzymes and other bioactive metabolites, as well as competition for nutrients and spatial niches, which together can induce systemic resistance in the host plant (Eid et al. 2021; Madhaiyan et al. 2015; Vandana et al. 2021).

In the context of nematode control, three essential modes of action attributed to bacterial endophytes are preemptive colonization, direct antagonism via toxic metabolites, and induced systemic resistance (ISR) (Sikora et al. 2007; Migunova and Sasanelli 2021). Moreover, previous research has shown that *J. curcas* harbors beneficial endophytic bacteria that can promote host development and exhibit nematicidal and antimicrobial activities (Rampadarath et al. 2016; Yousif et al. 2017a, b). These properties are particularly valuable for the biological control of *Meloidogyne* spp., which are major soil-borne pests affecting solanaceous crops such as eggplant. Therefore, selecting *J. curcas* as a host for endophyte isolation is strategic, as it increases the likelihood of identifying robust and multifunctional bacterial strains with potential applications in sustainable agriculture, especially in integrated pest management (IPM) systems targeting root-knot nematodes.

This study investigated the combined effects of endophytic bacteria derived from *J. curcas* and evaluated their potential as inducers of plant growth and as biocontrol agents against *Meloidogyne* spp. under greenhouse conditions.

Materials and Methods

The three endophytic bacteria used in this study were selected from 195 isolates obtained from *Jatropha curcas* L. The selection of the three isolates was based on biosafety and biochemical characterization assays. Biosafety assessment included hemolysis testing on blood agar and a hypersensitive reaction (HR) test, as described by Yousif et al. (2017), and each biosafety assay was conducted in three replicates. Plant samples were collected from Sukabumi at the National Center of Industrial Plants (BALITRI) in Indonesia. Isolation was performed using a surface sterilization method (Yousif et al. 2017).

Moreover, these bacteria were tested using several assays to assess physiological attributes associated with biocontrol and plant growth promotion, including phosphate solubilization, hydrolytic enzyme activities, nitrogen fixation, and production of hydrogen cyanide (HCN). These three isolates were then selected and identified by 16S rRNA gene sequencing for prokaryotic identification.

Surface sterilization and isolation of endophytic bacteria

To isolate endophytic bacteria, healthy tissues of *J. curcas* (roots, stems, and leaves) were collected and thoroughly washed under running tap water to remove any surface debris. The samples were then subjected to surface sterilization following the method described by Yousif et al. (2017). Plant tissues were immersed sequentially in 70% ethanol for 1 min, followed by 2% sodium hypochlorite (NaOCl) for 3 min, and then rinsed three times with sterile distilled water to remove any remaining disinfectant.

To confirm the effectiveness of surface sterilization, the final rinse water was plated onto Tryptic Soy Agar (TSA) and incubated at 28 ± 2 °C for 48 h. The absence of bacterial growth indicated successful sterilization. After

sterilization, plant tissues were aseptically cut into small segments (approximately 1 cm²) and placed on TSA plates. The plates were incubated at 28 ± 2 °C for 48–72 h, and emerging bacterial colonies from the internal tissues were subcultured on fresh TSA plates to obtain pure isolates.

Soil mix and sterilization methods

A greenhouse-based experiment was performed to determine the effectiveness of endophytic bacteria on eggplant growth and the extent of nematode damage to plants. A 2:1 mixture of potting soil and compost was used as the substrate in each polybag. Before the experiment, the soil mixture was autoclaved to eradicate potential pathogens and ensure that the plants were pathogen-free.

Seedling preparation

Eggplant seeds were surface sterilized, soaked in sterile water for 24 h, and then sown in sterile peat moss under aseptic conditions. Ten-day-old eggplant seedlings were transferred to sterilized soil to minimize contamination and were subsequently used in the experimental trial. Seedlings were watered daily, with volumes adjusted according to environmental conditions such as temperature and humidity.

Biochemical assays

Phosphate-solubilising activity

Using a plate measurement approach, phosphate-solubilising microorganisms were evaluated on Pikovskaya (PVK) agar medium containing 1.5% Bacto agar. Colonies and halo zones were measured after four days of incubation at 28 °C (Gupta et al. 2018).

Nitrogen fixation

Isolates (1 mL cultures) were evaluated for nitrogen fixation by growing them in a nitrogen-fixing bacterial (NFB) semi-solid medium. The incubation period was 4–7 days, and nitrogen-fixing ability was indicated by a colour change from green to bluish green, with a ring or film of organisms appearing in the medium (Grobelak et al. 2015).

Chitinolytic activity

Chitinolytic activity was evaluated by streaking bacterial cells on a semi-minimal medium (three parts SM to one part nutrient broth) supplemented with 0.2% colloidal chitin and 1.5% agar. After incubation at 30 °C for 72–96 h, clear zones of chitin clearance around the colonies were observed (Aggarwal et al. 2015).

Proteolysis activity test

Proteolytic phenotypes were evaluated on skim milk agar (SMA) and TSA media supplemented with 2% skim milk. The isolates were spread on skim milk agar and incubated at 37 °C for 24 h. The proteolysis index was determined as the transparent zone width divided by the diameter of the bacterial colonies (Gusman et al. 2022).

Production of hydrogen cyanide (HCN)

Endophytic bacteria were screened for hydrogen cyanide production using the method described by Millar and Higgins (1970). TSA plates containing glycine were incubated at 28 °C for one week before assessing growth. The reaction was recorded by the change in colour of the filter paper in the lid of the Petri dish as no change (yellow to light brown), slight (brown), or strong (reddish-brown) (Nejad and Johnson 2000).

Amplification and sequencing of endophytic bacterial 16S rRNA gene

Genomic DNA of pure endophytic bacterial cultures was isolated using the Geneaid Bacterial Genomic DNA Extraction Kit (Presto™ Mini gDNA Bacteria Kit, Geneaid, Taipei, Taiwan) according to the manufacturer's instructions (Chen et al. 2015). The subsequent PCR stage used 3 µL of genomic DNA as a template (Park et al. 2014). KOD Fx Neo polymerase was used for the PCR amplification of the bacterial 16S rRNA gene.

Amplification was performed using a pair of universal primers (Chain Biotech): 16SA1 (5'-AGAGTTTGATCMTGGCTCAG-3') and 16SB1 (5'-TACGGYTACCTTGTTACGACTT-3') (Itoh et al. 2014). The PCR program consisted of an initial denaturation at 94 °C for 2 min, followed by 20 cycles of 10 s at 98 °C, 30 s at 55 °C, and 90 s at 68 °C. The resulting ~1.5 kb PCR products were purified and sequenced using the universal primer 357F. Purified PCR products were sequenced using the AutoSeq 96 System (GE Healthcare) with bidirectional sequencing (Szenthe and Bánáti 2016).

Effects of endophytic bacteria on plant growth and nematode suppression in greenhouse

The three selected endophytic isolates were tested under greenhouse conditions, individually and in combination. Bacteria were grown on TSA and incubated at 28 ± 2 °C for 48 h. After incubation, 100 mL of sterile distilled water was added to the plates to suspend the bacterial colonies. The bacterial population density was then adjusted spectrophotometrically at a wavelength of 600 nm (OD_{600} = 1.0), corresponding to approximately 1×10^8–1×10^9 CFU mL^{-1} for each isolate, as determined from serial dilution and plate count calibration curves. For the combined treatments, equal concentrations of each isolate were mixed, and the total CFU per pot was kept equivalent to that used for the single-strain treatments.

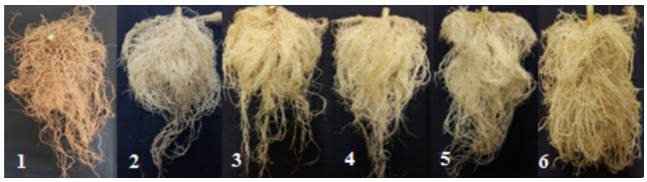

Figure 2 Effect of endophytic bacteria on root growth and reduction in the number of galls in the root system. 1. Control. 2. SJS 54+RJS 175+FJS 23. 3. SJS 54. 4. FJS 23+SJS 54. 5. RJS 175. 6. FJS 23.

Eggplant seedlings (three weeks old) were inoculated by immersing the roots in the bacterial suspension for 5 min and then transplanting the seedlings into polybags (first dose) (Munif et al. 2013). One week after the first dose, 30 mL of the bacterial suspension was applied to the soil mixture (sterile compost and sterile natural soil at a 1:2 kg ratio) (Munif et al. 2013). Sterile water was used as a control.

Then, 5 mL of nematode suspension containing 1000 second-stage juveniles (J2) of *Meloidogyne* spp. was inoculated into a 1 cm deep hole near the root zone of each plant. Nematode species were identified based on morphological characteristics, particularly the perineal pattern of adult females, using standard taxonomic keys. Inoculum was obtained from a pure culture maintained on tomato (*Solanum lycopersicum* L.) roots under controlled greenhouse conditions.

Experimental design (CRD)

The experiment followed a completely randomized design (CRD). Seven replicates (n = 7) were used for each treatment. Plants were grown under greenhouse conditions. The average temperature was 25 ± 2 °C, relative humidity ranged from 60 to 70%, and a 16 h light/8 h dark photoperiod was maintained. Treatments were randomly assigned to the experimental units using random number generation to ensure unbiased allocation.

Forty days after nematode inoculation, agronomic parameters such as plant height, root length, and biomass were evaluated. Pathological parameters, such as the number of galls in the plant roots, were also recorded (Harni and Khaerati 2013).

Data analysis

Data from the greenhouse experiment were analyzed using analysis of variance (ANOVA) at a significance level of $\alpha = 0.05$. When treatment effects were significant, means were separated using Duncan's Multiple Range Test at the 5% error level. Statistical analyses were performed using SAS version 9.1.

Results

Biochemical assays

According to the physiological characterization, isolate RJS175 (*Pseudomonas* sp.) was able to solubilise phosphate, produce protease enzymes, and synthesize HCN. Isolate SJS54 (*Micrococcus* sp.) was a nitrogen-fixing bacterium that also produced protease enzymes. Isolate FJS23 (*Pseudomonas* sp.) was able to solubilise phosphate but did not show nitrogen-fixing, proteolytic, or HCN-producing activity (Table 1).

Molecular identification of endophytic bacterial strains associated with J. curcas and their plant growth-promoting characteristics

PCR products were sequenced, and the obtained nucleotide sequences were compared with known bacterial sequences from the National Center for Biotechnology Information (NCBI). Sequence lengths were 1417, 1363, and 1363 bp for isolates FJS23 (*Pseudomonas* sp.), SJS54 (*Micrococcus* sp.), and RJS175 (*Pseudomonas* sp.), respectively (Fig. 1). Alignment results using the Basic Local Alignment Search Tool (BLAST) at NCBI showed that FJS23 and RJS175 belonged to the genus *Pseudomonas*, whereas SJS54 belonged to the genus *Micrococcus*. All isolates were deposited in GenBank with the accession numbers PX472921, PX472930, and PX472932, respectively.

Table 1. Three selected endophytic bacterial isolates and their physiological criteria.

Isolates ID	*Pseudomonas* sp. RJS175	*Micrococcus* sp. SJS54	*Pseudomonas* sp. FJS23
Gram test	-	+	-
Nitrogen fixation	-	+++	-
Phosphate solubilization	+++	-	+
Chitinase	-	-	-
Protease	+++	+++	-
HCN	+++	-	-

+) positive result; ++) moderately positive result; +++) strongly positive result; -) negative result.

Table 2. The effect of single and combination of endophytic bacteria on plant growth and control for *Meloidogyne* spp. in greenhouse.

Treatment	Plant height (cm)	Leaves number	Fresh weight (g)	Dry weight (g)	Galls /root	Gall /g root
FJS23	56.25 ± 4.22a	15.00 ± 2.16c	75.75 ± 7.53ab	14.08 ± 1.39b	7.25 ± 1.37b	0.096 ± 0.013b
SJS54	60.10 ± 4.20a	17.50 ± 2.51ab	83.75 ± 7.03ab	15.03 ± 1.13ab	1.25 ± 0.31b	0.015 ± 0.003b
RJS175	54.75 ± 3.97a	16.00 ± 1.72bc	70.75 ± 5.25bc	13.66 ± 1.00b	4.75 ± 1.02b	0.067 ± 0.007b
FJS23+SJS54	56.05 ± 4.16a	20.50 ± 1.72a	93.30 ± 5.84a	17.91 ± 0.95a	3.75 ± 0.74b	0.040 ± 0.004b
FJS23+RJS175	56.50 ± 3.64a	16.50 ± 1.72bc	83.15 ± 5.59ab	14.39 ± 0.78ab	7.00 ± 0.99b	0.084 ± 0.007b
SJS54+RJS175	54.78 ± 3.57a	18.50 ± 1.72ab	74.18 ± 4.83ab	13.87 ± 0.76b	3.25 ± 0.58b	0.044 ± 0.005b
SJS54+RJS175+FJS23	55.95 ± 3.36a	17.25 ± 1.51bc	85.70 ± 4.99ab	14.84 ± 0.91ab	1.50 ± 0.27b	0.018 ± 0.002b
Control	38.75 ± 3.35b	9.50 ± 0.98d	43.18 ± 4.99d	6.43 ± 0.65d	131.50 ± 7.04a	3.046 ± 0.15a

Values are means ± standard deviation (n = 7). Means in the same column followed by the same letter are not significantly different according to Duncan's Multiple Range Test (DMRT) at α = 0.05. Digits followed by the same letter are not significantly different. Data were analyzed by SAS software using Duncan's multiple range test (DMRT) α=5%. The gall/g root was calculated using the total number of galls divided by the total fresh weight of the entire root system measured at harvesting time.

Effects of endophytic bacteria on plant growth and nematode suppression in greenhouse

Greenhouse experiments showed that the endophytic bacteria significantly affected plant growth and suppressed nematode infection (Fig. 2). Among the single-isolate treatments, SJS54 (*Micrococcus* sp.) resulted in the greatest plant height compared with the other isolates and the control. All treatments with FJS23 (*Pseudomonas* sp.), SJS54 (*Micrococcus* sp.), RJS175 (*Pseudomonas* sp.), and their combinations generally showed higher plant height and greater shoot fresh and dry weight than the control group.

The control plants had significantly higher gall counts and gall-to-root weight ratios, indicating greater susceptibility to *Meloidogyne* spp. infection. The combination of isolates FJS23 (*Pseudomonas* sp.) and SJS54 (*Micrococcus* sp.) resulted in marked increases in leaf number and shoot fresh and dry weight (Table 2). Combinations such as FJS23 (*Pseudomonas* sp.) + SJS54 (*Micrococcus* sp.) and SJS54 (*Micrococcus* sp.) + RJS175 (*Pseudomonas* sp.) + FJS23 (*Pseudomonas* sp.) had particularly positive effects on plant growth and nematode suppression, as reflected by their improved agronomic parameters and reduced galling compared with the control.

Discussion

The use of agrochemicals in agriculture, such as mineral fertilisers and pesticides, can be detrimental to human health and the environment (Lacava et al. 2022). Excessive and indiscriminate application also impairs soil ecology and disrupts plant- and soil-associated microbiomes. To address these problems, agricultural biotechnology has increasingly adopted microbial inoculants to enhance plant growth and reduce reliance on agrochemicals. Endophytic microorganisms, which live inside plants without causing disease, are of particular interest because of their ability to stimulate plant growth (Lacava et al. 2022). They promote growth by synthesising phytohormones and other bioactive compounds, improving nutrient uptake, and contributing to disease suppression. Furthermore, they

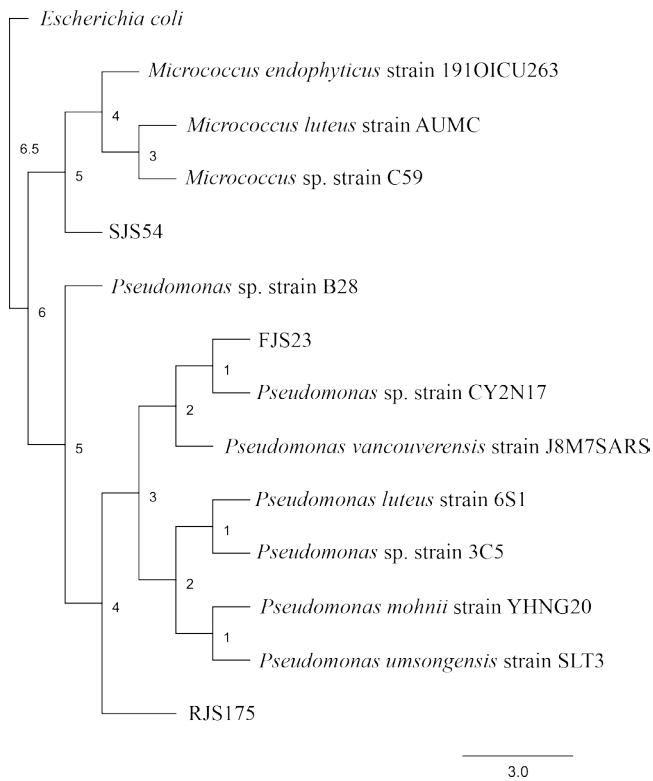

Figure 1. Phylogenetic tree showing the genetic relationship of isolates FJS23, SJS54, and RJS175 with closely related bacterial strains from NCBI GenBank based on 16S rRNA gene sequences. Phylogenetic tree was constructed with neighbor-joining method with 1000 replicates in the bootstrap test of the associated taxa and conducted using Mega11.

improve nutrient assimilation by solubilising phosphorus and making it more available to plants (Sande et al. 2024).

In our study, three endophytic bacterial isolates, FJS23 (*Pseudomonas* sp.), SJS54 (*Micrococcus* sp.), and RJS175 (*Pseudomonas* sp.), were isolated from *J. curcas* L. and identified using 16S rRNA gene sequencing. According to Mohanty et al. (2017), common endophytic bacterial genera isolated from *J. curcas* include *Paenibacillus*, *Bacillus*, *Brevibacillus*, *Sphingomonas*, *Staphylococcus* and *Terribacillus*. Bacteria belonging to both *Pseudomonas* spp. and *Micrococcus* spp. are known for their antimicrobial and antifungal properties (Mehmood et al. 2023; Nafis et al. 2020). By contrast, Machado et al. (2020) identified diverse endophytic bacterial strains from genera such as *Arthrobacter*, *Bacillus*, *Citrobacter*, *Curtobacterium*, *Enterococcus*, *Klebsiella*, *Leucobacter*, *Lysinibacillus*, *Microbacterium*, *Rhodococcus* and *Serratia* associated with *J. curcas*. The variation in bacterial genera isolated from *Jatropha* across different studies suggests that ecogeographical factors and the surrounding environment of the plant strongly influence the composition of endophytic bacterial communities (Ji et al. 2024).

In terms of growth improvement, all treatments significantly enhanced vegetative growth parameters of eggplant (*S. melongena* L.) under greenhouse conditions compared with the control. Notably, SJS54 (*Micrococcus* sp.) produced the tallest plants (60.10 cm), whereas the combination FJS23 (*Pseudomonas* sp.) + SJS54 (*Micrococcus* sp.) yielded the highest shoot fresh weight (93.30 g), dry weight (17.91 g) and leaf number (20.5). Endophytic bacteria are known to play a pivotal role in the enhancement of root and shoot growth. Mohanty et al. (2017) observed a marked increase in maize seedling growth following inoculation with endophytic bacteria, with increased root and shoot length indicating a positive effect of the endophytes on maize development. Key contributors to growth stimulation include the production of indole-3-acetic acid (IAA), phosphatases and 1-aminocyclopropane-1-carboxylate (ACC) deaminase activity (Kumar et al. 2025; Mohanty et al. 2017).

In this study, isolate SJS54 (*Micrococcus* sp.) significantly reduced the number of galls and improved plant growth, and its application resulted in marked nematode suppression in the root system of eggplants 40 d after inoculation (Table 2; Fig. 2). This result is consistent with the findings of Sharma et al. (2025), who reported that *Micrococcus* spp. suppressed *Meloidogyne incognita* in tomato through induced systemic resistance. Endophytic bacteria suppress root-knot nematodes (*Meloidogyne* spp.) through a combination of direct antagonism and plant-mediated resistance, thereby offering an environmentally sustainable alternative to chemical nematicides. These bacteria colonise root tissues and form physical and biochemical barriers that limit nematode invasion (Bakr et al. 2025; Hallmann et al. 2001). They produce a range of nematicidal compounds, including hydrogen cyanide, lytic enzymes (e.g. chitinases and proteases) and secondary metabolites such as antibiotics and phenolics, which directly damage nematode eggs, larvae and juveniles (Chitwood 2002; Medison et al. 2021; Mhatre et al. 2024).

Additionally, endophytes enhance host defence through induced systemic resistance (ISR) and systemic acquired resistance (SAR), leading to cell wall reinforcement, activation of defence-related genes and increased production of protective enzymes (Qtu et al. 1997; Kumari et al. 2024). They also promote plant growth by synthesising IAA, fixing nitrogen, solubilising phosphate and lowering ethylene levels via ACC deaminase activity, thus improving plant vigour and tolerance to nematode stress (Gamalero and Glick 2020; Habteweld et al. 2024; Khanna et al. 2019). Moreover, some bacterial metabolites interfere with nematode chemosensory signalling, reducing their ability to detect and infect host roots (Dou et al. 2025; Zheng et al. 2025).

Our study indicates that certain combinations of bacterial isolates, especially FJS23 (*Pseudomonas* sp.) + SJS54 (*Micrococcus* sp.), exhibited stronger plant growth promotion than individual treatments, suggesting a beneficial combined effect among endophytes. Most biological control strategies traditionally rely on single-strain antagonists against a single plant pathogen. Our results align with those of Raupach and Kloepper (2000), who showed that mixtures of PGPR strains of *Bacillus pumilus*, *Bacillus subtilis* and *Curtobacterium flaccumfaciens* enhanced cucumber growth and protected against disease, thereby improving the consistency of biological control against single and multiple cucumber pathogens. Similarly, Asyiah et al. (2020) demonstrated that a consortium comprising *Bacillus* and *Pseudomonas* bacteria effectively suppressed the growth of *Pratylenchus coffeae* in Robusta coffee. When applied in a cost-effective molasses-based medium, the consortium was more effective in reducing nematode populations than individual applications. Furthermore, the bacterial consortium improved plant growth parameters such as height, leaf number and leaf area, suggesting a positive correlation between nematode suppression and plant development (Asyiah et al. 2020; Duong et al. 2022). Inoculating tomato roots with *Piriformospora indica*, *Bacillus pumilus* and *Pseudomonas fluorescens* has also been shown to effectively suppress *M. incognita*, with *P. indica* contributing significantly to plant immunity and improving the growth of infected plants (Varkey et al. 2018).

Our results support the potential use of *J. curcas*-derived endophytic bacteria, particularly SJS54 (*Micrococcus* sp.), as eco-friendly biocontrol agents and plant growth promoters in sustainable agriculture, offering viable alter-

natives to synthetic nematicides for managing root-knot nematodes. The developmental role of endophytic bacteria in root growth is significant, and their integrated use offers a promising approach for enhancing plant performance while mitigating environmental impacts. Continuous research in this domain is revealing the diverse capabilities of endophytes and is likely to pave the way for more effective and sustainable agricultural practices.

Conclusion

Single and combined treatments of endophytic bacteria from *J. curcas* significantly reduced *Meloidogyne* spp. galling and increased eggplant biomass compared with the untreated control. Among the isolates, SJS54 (*Micrococcus* sp.) alone provided the strongest nematode suppression, whereas the combination FJS23 (*Pseudomonas* sp.) + SJS54 (*Micrococcus* sp.) produced the greatest shoot fresh and dry weight and leaf number. The three strains showed complementary plant growth-promoting and biocontrol traits, including phosphate solubilisation (FJS23, RJS175), nitrogen fixation and protease production (SJS54), and HCN and protease production (RJS175). These results suggest that SJS54 alone, as well as consortia of *J. curcas*-derived endophytes, represent promising tools for the biological control of root-knot nematodes and the improvement of eggplant growth under greenhouse conditions.

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