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Endophytic Bacteria from the Wild Plant Solanum sisymbriifolium with Biocontrol Potential Against Fusarium oxysporum f. sp. melongenae and Growth Promotion in Eggplant

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Abstract

Endophytic bacteria offer a sustainable alternative to conventional agricultural practices through their dual potential for plant growth promotion and pathogen biocontrol. This study isolated endophytic bacteria from the wild plant *Solanum sisymbriifolium* and evaluated their antagonistic activity against *Fusarium oxysporum* f. sp. *melongenae* (*Fom*MRL1) and growth promotion in eggplant. From surface-sterilized stems, 80 endophytic isolates were obtained, representing a high isolation frequency of 92%. Dual-culture assays revealed all isolates showed some level of inhibition against the pathogen, with 12 isolates exhibiting strong antagonistic activity (> 60% inhibition) at 12 days post-inoculation. MRL.B40 (78.6%), MRL.B17 (75.4%), and MRL.B59 (68.3%) were the most effective. Volatile organic compounds were not the primary mechanism of antagonism. Under pathogen stress, these isolates significantly protected seeds, achieving protection efficiencies of 67.9%, 53.6%, and 46.4%, respectively ($p < 0.001$–0.01). Select isolates produced indole-3-acetic acid, solubilized potassium and phosphorus, and secreted protease enzymes. In pot trials, MRL.B17 significantly increased plant height by 14.8% ($p < 0.01$) and MRL.B40 by 12.6% ($p < 0.05$) at 45 days after transplanting, with corresponding numerical yield increases of 13.5% and 12.2%. Molecular identification via 16S rRNA gene sequencing confirmed MRL.B17 as *Bacillus* sp., MRL.B22 as *Bacillus licheniformis*, MRL.B40 as *Acinetobacter* sp., MRL.B44 as *Klebsiella* sp., MRL.B50 as *Staphylococcus* sp., and MRL.B59 as *Staphylococcus epidermidis*. These findings demonstrate that wild relatives such as *S. sisymbriifolium* harbor diverse endophytic bacteria with strong biocontrol and growth-promoting potential, offering promising candidates for developing sustainable bio-inoculants to combat Fusarium wilt and enhance eggplant productivity.

1. Introduction

Eggplant (*Solanum melongena* L.), also known as brinjal or aubergine, is a widely cultivated and consumed vegetable of the Solanaceae family. It is affordable, accessible, and nutritionally valuable, making it an essential part of diets and agricultural systems globally (Chapman, 2019; Gürbüz et al., 2018). In Bangladesh, eggplant holds particular social, cultural, and economic importance as a staple vegetable cultivated extensively throughout both Rabi and Kharif seasons (Begum et al., 2013; Islam et al., 2018). In 2023-24, eggplant was 509,000 metric tons eggplant was produced in Bangladesh(Bangladesh Bureau of Statistics, 2024). Despite its significant economic and nutritional importance, eggplant yield often remains below its potential due to various constraints, particularly diseases.

Among the major challenges to eggplant cultivation, Fusarium wilt, caused by *Fusarium oxysporum* f. sp. *melongenae* (*Fom*), is one of the most devastating soil-borne diseases, leading to significant economic losses worldwide (Kumar et al., 2024; Sarnaik et al., 2025). The disease primarily targets eggplants during their growth phase, particularly young seedlings as they begin to develop vines and bear fruit. Early symptoms include stem base contraction, browning and wilting of leaves, drooping, and eventual leaf collapse. Infected plants exhibit stunted growth, yellowing of lower leaves, and increased susceptibility to wilting during the day. While some plants may recover partially during cooler hours,

others succumb within a few days. The severity of symptoms varies, influenced by the extent to which the fungus has infiltrated the plant's vascular system. This soil-borne pathogen not only reduces yields but also compromises produce quality, causing plant mortality rates ranging from 20–30% in affected fields worldwide (Kumar et al., 2024; Sarnaik et al., 2025). Fusarium wilt is particularly challenging to manage due to the ability of *Fusarium* to persist in soil for long periods through chlamydospores and its wide host range, which includes several hundred plant species from many families (Gordon, 2017; Nikitin et al., 2023; Smith, 2007).

Conventional management of Fusarium wilt relies on the use of resistant varieties, crop rotation, agronomic practices, and chemical control (Kaniyassery et al., 2023; Kumar et al., 2024). However, cultural practices and crop rotation often provide limited control due to the pathogen's long survival period in soil. The indiscriminate use of chemical pesticides creates harmful environmental and ecological effects, leading to eggplant products with residual effects that restrict export from countries like Bangladesh (Ahmed et al., 2021; Chowdhury et al., 2013; Nisha et al., 2021; Rifa, 2026). Additionally, the development of resistant varieties through conventional breeding has been slow due to the scarcity of resistant germplasm and the complex genetics of resistance (Bletsos et al., 1998; Collonnier et al., 2001; Kang and Kole, 2013). These limitations have necessitated the development of alternative and sustainable disease management strategies.

Biological control has emerged as a promising alternative to chemical control, offering an eco-friendly and sustainable approach to managing plant diseases. Among the various biological control agents, endophytic microorganisms have received significant attention for their potential in agriculture (Madlhophe et al., 2025; Mohapatra et al., 2026; Rakhalaru et al., 2025). Endophytes, which include bacteria, fungi, and viruses, reside within plant tissues without causing harm and form symbiotic or mutualistic relationships with their hosts (Dastogeer et al., 2020b; Rodriguez et al., 2009). These microorganisms contribute to plant health by enhancing nutrient uptake, producing growth-promoting hormones such as indole-3-acetic acid (IAA), solubilizing essential minerals like phosphorus and potassium, and protecting plants against pathogens through mechanisms such as induced systemic resistance (ISR), competition for nutrients and colonization sites, and the production of hydrolytic enzymes and antimicrobial compounds (Compant et al., 2019; Eid et al., 2021; Ercole et al., 2025).

Endophytic bacteria, in particular, not only improve plant health and productivity but also mitigate the adverse effects of chemical inputs on soil quality and the environment (Ercole et al., 2025; Harman and Uphoff, 2019; Kumar et al., 2025). Compared to traditional fungicides, endophytes offer long-term efficacy, biosafety, and compatibility with sustainable agricultural practices. The combination of biocontrol and plant growth-promoting activities in a single endophyte represents a valuable resource for sustainable agriculture, as it can reduce reliance on both chemical pesticides and synthetic fertilizers.

Wild plants are valuable sources of endophytic microorganisms with biocontrol and growth-promoting potential. These plants thrive in diverse environments and have co-evolved with endophytes that enhance their adaptability to various stresses, including pathogens. Wild relatives of crops frequently

share genetic and physiological similarities with cultivated species, making their associated endophytes highly compatible for agricultural applications. Endophytes from wild plants often exhibit unique traits such as enhanced production of secondary metabolites, enzymes, and antibiotics, which are crucial for disease suppression (Garcha, 2023; Kernaghan et al., 2017; Pérez-Jaramillo et al., 2018). Wild plants often survive in pathogen-rich soils, indicating that their associated microbiota may have evolved mechanisms to counteract soil-borne pathogen like Fusarium (Hung et al., 2007; Kernaghan et al., 2017; Llorens et al., 2019; Mousa et al., 2015). Wild plant such as *Solanum sisymbriifolium* (commonly known as katabegun in Bangladesh), in particular, is known for its resistance to various soil-borne pathogens, including *Fusarium* and *Verticillium* species, and has been used as a rootstock for eggplant to manage soil-borne diseases (Bletsos et al., 2003; Wu et al., 2023). Despite its valuable traits, the endophytic bacterial communities associated with *S. sisymbriifolium* have not been systematically characterized for their biocontrol and plant growth-promoting potential.

The global market for biological control agents (BCAs) and plant growth-promoting agents (PGPAs) has witnessed significant growth in recent years, driven by an increasing demand for sustainable and eco-friendly agricultural practices (Afonso et al., 2025; DunhamTrimmer, 2023). The global Biocontrol Agents market size is estimated at USD 4.29 billion in 2026 and is projected to reach USD 5.98 billion by 2031, reflecting a Compound Annual Growth Rate (CAGR) of 6.89% (Mordor Intelligence, 2026). This market expansion is primarily fueled by stringent regulatory restrictions on synthetic pesticide usage—particularly in the European Union and North America—alongside a rising consumer preference for organic, residue-free produce (Gensch et al., 2024; Handford et al., 2015). Furthermore, the increasing global awareness of the adverse environmental and health impacts of chemical pesticides has accelerated the adoption of microbial-based solutions in integrated pest management (IPM) programs (Fenibo et al., 2022; Zhou et al., 2025).

Native strains of biocontrol agents hold particular promise in this expanding market due to their adaptation to local environmental conditions and specific plant-pathogen interactions. These strains are often more effective than non-native ones, as they are well-suited to the soil, climate, and microbiome of the target region. Moreover, the use of native strains reduces the risk of ecological disruption, as they are less likely to become invasive or negatively impact non-target species (Chen et al., 2024; De Clercq et al., 2011; Reddy et al., 2024). Developing biocontrol solutions using native strains can also enhance the accessibility and affordability of these technologies for farmers, particularly in regions like Bangladesh, where Fusarium wilt poses a significant threat to eggplant production.

This research focuses on isolating and characterizing culturable endophytic bacteria from *Solanum sisymbriifolium* to address the dual challenges of Fusarium wilt management and growth promotion in eggplant cultivation. The primary objectives were: (1) to isolate endophytic bacteria from *S. sisymbriifolium* and screen them for antagonistic activity against *Fusarium oxysporum* f. sp. *melongenae* using dual-culture assays; (2) to evaluate the ability of selected isolates to protect eggplant seeds from pathogen-induced germination failure; (3) to characterize the plant growth-promoting traits of selected isolates, including IAA production and nutrient solubilization; (4) to assess the plant growth-promoting

effects of promising isolates on eggplant seedlings under pot conditions; and (5) to identify promising isolates through 16S rRNA gene sequencing. The overall goal was to identify endophytic bacteria from *S. sisymbriifolium* with potential for development as bio-inoculants for integrated management of Fusarium wilt and sustainable production of eggplant.

2. Materials and Methods

2.1 Isolation and pathogenicity of wilt causing *Fusarium*

Wilted eggplant was collected from farmers field and stem tissues were plated on potato dextrose agar (PDA), yielding fungal colonies after 12 days of incubation. Based on colony on plate and morphological characteristics under light microscopy, the pathogen was identified as *Fusarium oxysporum* f. sp. *melongenae* and designated as *Fom*MRL1. On PDA, the fungus produced whitish mycelium that later developed into light gray colonies with sporulation. Microscopic examination revealed slightly curved macroconidia with two to three cells and single-celled microconidia (Fig. S1). The pathogenicity of *Fom*MRL1 was confirmed using the root dip inoculation method (Devi and Srinivas, 2012). Inoculated plants developed typical wilting symptoms within 14 days post-inoculation, including leaf drooping, stem base contraction, and vascular discoloration upon stem sectioning (Fig. S1). No symptoms were observed in control plants, and the pathogen was successfully re-isolated from symptomatic plants, fulfilling Koch's postulates.

2.2 Isolation and Preservation of Endophytic Bacteria

Healthy *Solanum sisymbriifolium* (locally known as ‘Katabegun’) plants were collected from the Agronomy Field Laboratory at Bangladesh Agricultural University (BAU). Endophytic bacteria were isolated using a modified standard protocol (Hallmann et al., 1997; Hardoim et al., 2015; Sinong et al., 2021). Briefly, stem tissues were surface sterilized by sequential immersion in 70% ethanol (1 min) and 1% sodium hypochlorite (1 min), followed by three rinses with sterile distilled water to ensure the removal of epiphytic microorganisms. To verify sterilization efficacy, the final rinse water was plated as a negative control (Anjum et al., 2019; Sahu et al., 2022). Surface-sterilized tissues were then placed on 0.25× nutrient agar (NA) plates and incubated at 28°C for 3 days. Morphologically distinct bacterial colonies were purified on fresh NA and preserved in 25% glycerol at − 80°C for long-term storage.

2.3 Screening of bacteria for Antagonistic Activity

The *in vitro* antagonistic activity of 60 selected bacterial isolates against *Fom*MRL1 was evaluated using the dual-culture screening. A 5-mm mycelial plug (7d old) of the pathogen was placed on one side of a PDA plate, and the bacterial isolate was streaked 3 cm away. Plates were incubated at 28°C for 12 days. Each isolate was tested in triplicate and fungal growth inhibition was calculated as (Vincent, 1947):

Inhibition (%) = [(Control growth − Treatment growth) / Control growth] × 100

2.4. Assay for Volatile Organic Compound (VOC)-mediated Fungal Suppression

The potential of bacterial endophytes to produce antifungal VOCs was evaluated using the inverted plate (sandwich) assay, as described by Giorgio et al. (2015). Briefly, selected bacterial isolates were streaked onto 0.5× NA plates, while a 5-mm mycelial plug of *Fom*MRL1 was placed at the center of a 0.5× PDA plate. The lids were removed, and the bacterial plate was inverted over the fungal plate. The two bases were hermetically sealed with a double layer of Parafilm to ensure the containment of volatile metabolites. Controls consisted of *Fom*MRL1 plates paired with non-inoculated 0.5× NA plates. After incubation at 28°C for 12 days, the growth of the pathogen was measured, and the percentage of volatile-mediated inhibition was calculated.

2.6. Characterization of Plant Growth-Promoting (PGP) and Enzymatic Traits

Bacterial isolates were screened for multiple plant growth-promoting (PGP) traits using standard qualitative microbiological assays. Indole-3-acetic acid (IAA) production was assessed using the Salkowski colorimetric method following established protocols (Bric et al., 1991; Gordon and Weber, 1951). Briefly, bacterial cultures were grown in Winogradsky broth supplemented with 2 g L^{-1} L-tryptophan for 48 h at 30°C. Following centrifugation (10,000 × g for 10 min), the supernatant was mixed with Salkowski reagent (50 mL 35% $HClO_4$ and 1 mL 0.5 M $FeCl_3$). The development of a pink-to-red color after 30 min of incubation in the dark was visually scored as weak (+), moderate (++), or strong (+++).

Mineral solubilization was evaluated using selective agar media. Phosphate solubilization was assessed on Pikovskaya (PVK) agar following Pikovskaya (1948), while potassium solubilization was evaluated on Aleksandrov agar as described for potassium-solubilizing bacteria (Parmar and Sindhu, 2019). Plates were inoculated with bacterial isolates and incubated at 28°C for 4 days. The formation of a clear halo (zone of solubilization) around colonies was considered indicative of positive activity.

Protease activity was determined using skim milk agar as described by Cappuccino and Sherman (2014). Bacterial isolates were spot-inoculated and incubated at 30°C for 72 h. The appearance of clear zones around the colonies, indicating casein hydrolysis, was recorded as positive protease activity.

2.7 Effect of Endophytic Bacteria on Eggplant Seed Germination under Normal and Pathogen-Stressed Conditions

Bacterial cultures were grown in nutrient broth (NB) at 28°C with constant shaking at 180 rpm for 24–48 h. Cultures were centrifuged at 10,000 × g for 10 min, and bacterial pellets were resuspended in sterile distilled water to prepare standardized suspensions. Eggplant seeds were surface-sterilized and for the germination assay, 25 seeds per treatment were placed on sterile blotter paper in Petri dishes and

inoculated by spraying with 750 µL of bacterial suspension. Control seeds received an equal volume of sterile distilled water. Plates were incubated at 30°C for 72 h. Germination percentage was calculated as:

Germination (%) = (Number of germinated seeds / Total number of seeds) × 100

Each treatment was performed in triplicate, following established screening protocols for plant growth-promoting bacteria.

For the germination assay under pathogen-challenge, seeds were first treated with 750 µL of *Fom*MRL1 suspension (1 × 10^6 spores/mL) prepared from a 7-day-old culture, followed by 750 µL of the respective bacterial suspension. Pathogen controls received fungal suspension and sterile distilled water only. Germination was recorded after 72 h to evaluate the protective efficacy of the endophytes against fungal-induced inhibition. Protection efficiency (PE) was calculated as:

PE (%) = (G_treatment – G_pathogen) / (G_control – G_pathogen) × 100

where:

- G_treatment = germination percentage of seeds treated with bacteria + pathogen
- G_pathogen = germination percentage of seeds treated with pathogen alone
- G_control = germination percentage of untreated, non-inoculated control seeds

This formula quantifies the proportion of pathogen-induced germination inhibition that is restored by bacterial treatment, relative to the full inhibition observed in the pathogen-only control.

2.8. Pot Experiment: Evaluation of Endophytic Bacteria on Eggplant Growth and Yield

The pot experiment was conducted to evaluate the biocontrol and growth-promoting potential of the selected endophytic isolates under greenhouse conditions. The growth medium consisted of soil, vermicompost, and sand mixed in a 2:2:1 ratio. The mixture was sterilized with a 5% formaldehyde solution and air-dried for 48 h to ensure the complete dissipation of residual gases. Pots (six replicates per treatment) were filled with the sterilized soil mixture to ensure adequate statistical power for detecting treatment effects. Basal fertilizers, including Urea, Di-ammonium Phosphate (DAP), Muriate of Potash (MoP), Gypsum, Boron, and Zinc Sulfate, were applied according to the recommended doses for eggplant (*Solanum melongena*) in Bangladesh (BARI, 2019). The hybrid F1 eggplant variety 'Purple King' was used as the host plant. For the pathogen treatment, a standardized spore suspension of *Fom*MRL1 (1 × 10^6 spores/mL) was prepared from 7-day-old PDA cultures. Each pot was infested with 10 mL of the fungal suspension two days prior to seedling transplantation. Bacterial inoculants were prepared as described in Section 2.7. Four-week-old healthy seedlings were inoculated using the root-dip method, where roots were immersed in the bacterial suspension for overnight before transplanting. Control seedlings were immersed in sterile distilled water.

Plants were maintained under natural photoperiod conditions with regular watering and manual weeding. Plant height was recorded at 15, 30, and 45 days after transplanting (DAT). Fruit harvesting commenced at 60 DAT and continued at 7-day intervals for a total of eight harvests. While plants began exhibiting signs of pot-bound stress after approximately 65 DAT—characterized by reduced vigor, leaf chlorosis, and restricted root growth—harvesting continued until symptoms became severely limiting to yield (see Discussion).

2.9. Molecular Identification of Promising Bacterial Isolates

Six promising isolates (MRL.B17, MRL.B22, MRL.B40, MRL.B44, MRL.B50, and MRL.B59) were selected for molecular identification based on their superior antagonistic and plant growth-promoting traits. Genomic DNA was extracted using the Wizard® Genomic DNA Purification Kit (Promega, USA) following the manufacturer's instructions. The 16S rRNA gene was amplified using universal bacterial primers 27F (5'-AGAGTTTGATCCTGGCTCAG-3') and 1492R (5'-CGGTTACCTTGTTACGACTT-3') (Lane, 1991; Weisburg et al., 1991). PCR reactions (25 µL) contained 12.5 µL GoTaq® G2 Hot Start Master Mix (Promega, USA), 1 µL template DNA, 1 µL of each primer (10–20 pM), and 9.5 µL nuclease-free water. Thermal cycling was performed with an initial denaturation at 95°C for 3 min, followed by 35 cycles of 95°C for 30 s, annealing at 49°C for 30 s, and extension at 72°C for 90 s, with a final extension at 72°C for 5 min. PCR products were visualized on a 1% (w/v) agarose gel to confirm amplification of ~ 1500 bp fragments (SF.2). Amplicons were purified using the Wizard® SV Gel and PCR Clean-Up System (Promega, USA) and sequenced commercially (Apical Scientific, Malaysia).

Sequence chromatograms were inspected and ambiguous bases corrected manually using FinchTV v1.4.0 (Geospiza, Inc.). Chimeras were checked using UCHIME2 implemented in vsearch v2.22.1 (Edgar, 2016; Rognes et al., 2016). Taxonomic assignment was performed by comparing sequences against the NCBI nucleotide database using BLASTn (Altschul et al., 1990). Due to poor forward read quality for most isolates, identification was based on reverse sequences alone, except for MRL.B17 and MRL.B40, where high-quality forward and reverse reads were available and assembled into consensus sequences using the EMBOSS consensus tool (Rice et al., 2000) after generating the reverse complement of reverse reads. Following established guidelines, isolates exhibiting ≥ 98.7% sequence similarity were assigned to the species level, while those with 95–98.6% similarity were assigned to the genus level (Kim et al., 2014; Yarza et al., 2014). The 16S rRNA gene sequences obtained in this study have been deposited in GenBank under accession numbers [PZ196236–PZ196241].

2.10 Statistical Analysis

All statistical analyses were performed using RStudio (version 2022.2.3.492; (RStudio Team, 2022) with R software (version 4.2.2; (R Core Team, 2022). Results are presented as mean ± standard error (SE), and statistical significance was set at $p < 0.05$ for all analyses. Normality was assessed using Shapiro-Wilk test (Shapiro and Wilk, 1965) from base R, and homogeneity of variances was evaluated using Levene's test from the *car* package (Fox and Weisberg, 2019) where applicable. For the Dual-culture assay, data

were analyzed separately for each time point (5, 8, and 12 dpi) using one-way analysis of variance (ANOVA) with the *aov* function from base R, followed by Dunnett's test for comparisons against the control using the *glht* function from the *multcomp* package (Dunnett, 1955; Hothorn et al., 2008). For isolates with constant growth values where ANOVA assumptions were violated, pairwise t-tests with Bonferroni correction. Seed germination data were analyzed using a binomial generalized linear model (GLM) with *logit* link using the *glm* function from base R (McCullagh and Nelder, 1989). Dunnett's test was applied to compare each treatment against the control separately for pathogen-challenged and non-challenged conditions. Plant height and total yield data were analyzed using one-way ANOVA with the *aov* function followed by Dunnett's test. Cumulative yield was analyzed using a linear mixed-effects model with plant as random intercept and week as fixed effect, using restricted maximum likelihood (REML) estimation with the *lmer* function from the *lme4* package (Bates et al., 2015). Model significance was assessed using the *anova* function with Satterthwaite's approximation for denominator degrees of freedom from the lmerTest package (Kuznetsova et al., 2017). Pearson's correlation coefficient was calculated to assess the relationship between plant height at 45 days and total fruit yield per plant (Pearson, 1895).

3. Results

3.1 Isolation of Endophytic Bacteria from Wild *S. sisymbriifolium* and Their Antagonistic Activity Against *FomMRL1*

Endophytic bacteria were isolated from surface-sterilized root tissues of healthy *S. sisymbriifolium* plants, yielding a total of 80 bacterial morphotypes selected based on diverse colony characteristics, including shape (round to irregular), color (off-white, white, or yellowish), edge (regular to wavy), and texture. The isolation frequency was high at 92%, representing 80 isolates from 100 plated tissue pieces. To evaluate their biocontrol potential, 60 of these isolates were screened for antagonistic activity against *FomMRL1* using a dual-culture assay. Based on the inhibition of mycelial growth, isolates were categorized into low (15–29%), moderate (30–59%), or high (≥ 60%) antagonistic levels (Fig. 1). At 5 days post-inoculation (dpi), the majority of isolates (63.3%) exhibited low inhibition, while 36.7% showed moderate inhibition, with isolate MRL.B22 demonstrating the strongest suppression (56%) at this early stage (Fig. 2). By 8 dpi, the distribution shifted as the proportion of low-inhibition isolates decreased to 53.3%, while 15.0% of the isolates achieved high inhibition. Notably, MRL.B40 recorded the highest inhibition (67.9%) at this interval, restricting pathogen growth to 2.07 cm compared to 6.13 cm in the control group. By 12 dpi, all 60 isolates demonstrated statistically significant inhibition ($p < 0.05$), with 12 isolates reaching the high-inhibition threshold (≥ 60%). MRL.B17 emerged as the most effective antagonist with 75.4% inhibition, followed closely by MRL.B18, MRL.B50, MRL.B54, and MRL.B55 (74.6% each), as well as MRL.B22 and MRL.B40 (74.2% each) (Figs. 2 & 3)

3.2 Effect of Volatile Organic Compounds (VOCs) on Suppression of *Fom*MRL1 Growth

The 10 bacterial isolates that exhibited the highest antagonistic activity against FomMRL1 in the dual-culture assay were selected to evaluate the potential role of volatile organic compounds (VOCs) in fungal growth suppression using the inverted plate (sandwich) assay. After 13 days of incubation, one-way ANOVA revealed significant variation among treatments ($p = 0.0004$). Pairwise comparisons with Bonferroni correction showed that MRL.B17 and MRL.B18 exhibited modest but significant reductions in fungal growth area (-14.2% and − 12.7%, respectively; $p < 0.05$) (Fig. 4). However, all plates were completely covered with fungal mycelium, and the reductions were minimal compared to the control (51.98 cm^2). No other isolates showed significant differences ($p > 0.05$ for all). These results indicate that volatile organic compounds are not the primary mechanism of antifungal activity for these isolates under the tested conditions.

3.3 Effect of Endophytic Bacteria on Eggplant Seed Germination

The impact of the ten top-performing bacterial isolates—selected based on their superior fungal growth inhibition—on eggplant seed germination was evaluated under both non-challenged and *Fom*MRL1-challenged conditions (Fig. 5). In the absence of the pathogen, the control group exhibited a germination rate of 57.3%. Among the isolates, MRL.B17 significantly enhanced germination to 82.7% ($p = 0.0013$) and MRL.B22 to 78.7% ($p = 0.0129$). Other isolates did not result in significant differences compared to the non-challenged control (Fig. 4). Conversely, under *Fom*MRL1 challenge, control germination was severely suppressed to 6.7%. With the exception of MRL.B50 and MRL.B55, all isolates provided significant protection to the seeds. MRL.B40 emerged as the most effective treatment, achieving 41.3% germination ($p < 0.001$) with a protection efficiency (PE) of 68.4%. This was followed by MRL.B17 (33.3%, $p = 0.0013$, PE = 52.6%), MRL.B18 (29.3%, $p = 0.0053$, PE = 44.7%), and MRL.B59 (29.3%, $p = 0.0051$, PE = 44.7%). Significant protection was also observed for isolates MRL.B22, MRL.B44, MRL.B45, and MRL.B54 (all $p < 0.05$), with protection efficiencies ranging from 31.6% to 39.5% (Fig. 5, Table 2).

Table 2
Protection efficiency of endophytic bacterial isolates against *Fusarium oxysporum* f. sp. *melongenae* (*FomMRL1*) during eggplant seed germination*

Endophyte	Protection Efficiency (%)	*p*-value
MRL.B40	68.4	< 0.001
MRL.B17	52.6	0.0013
MRL.B18	44.7	0.0053
MRL.B59	44.7	0.0051
MRL.B22	39.5	0.0129
MRL.B44	34.2	0.0298
MRL.B45	31.6	0.0445
MRL.B54	31.6	0.0446
MRL.B50	21.1	0.2041
MRL.B55	7.9	0.8859

** Protection efficiency = [(Treatment germination − Control germination) / (Control no-pathogen germination − Control with-pathogen germination)] × 100, p-values are from Dunnett's test following binomial GLM comparing each treatment to Control under pathogen stress.*

3.4 Plant Growth-Promoting Traits of Endophytic Bacterial Isolates

The ten selected endophytic bacterial isolates were evaluated for key plant growth-promoting (PGP) traits, including indole-3-acetic acid (IAA) production and the solubilization of potassium (K) and phosphorus (P) (Table 3). Among the isolates, MRL.B44 and MRL.B59 exhibited highly intensive IAA production, while MRL.B17 and MRL.B45 showed moderate production. Slight IAA production was observed in MRL.B50 and MRL.B55, whereas isolates MRL.B18, MRL.B22, MRL.B40, and MRL.B54 showed no detectable production. Regarding nutrient solubilization, only four isolates (MRL.B17, MRL.B18, MRL.B22, and MRL.B40) demonstrated K-solubilization capacity. P-solubilization was broader, observed in MRL.B17, MRL.B18, MRL.B22, MRL.B40, and MRL.B44. Notably, MRL.B17 was the only isolate to test positive for all three PGP traits (IAA, K, and P solubilization), while MRL.B44 was distinguished by both high IAA production and P-solubilization capacity (Table 3).

Table 3
Plant growth-promoting traits of endophytic bacterial isolates from *Solanum sisymbriifolium**.

Endophyte	IAA Production	K-solubilization	P-solubilization
Control	–	–	–
MRL.B17	++	+	+
MRL.B18	–	+	+
MRL.B22	–	+	+
MRL.B40	–	+	+
MRL.B44	+++	–	+
MRL.B45	++	–	–
MRL.B50	+	–	–
MRL.B54	–	–	–
MRL.B55	+	–	–
MRL.B59	+++	–	–

** IAA production intensity: (+++) highly intensive, (++) moderately intensive, (+) slightly intensive. K-solubilization and P-solubilization: (+) positive, (–) negative.*

3.5 Effect of Endophytic Bacteria on Eggplant Plant Height

The influence of endophytic isolates on eggplant growth was evaluated at 15, 30, and 45 days post-inoculation (dpi). Throughout the experimental period under pot-culture conditions, no visible *Fusarium* wilt symptoms were observed in either the control or treated groups. At 15 dpi, control plants reached an average height of 7.0 cm. While no statistically significant differences were observed among treatments at this early stage, MRL.B17 (7.5 cm, + 6.5%) and MRL.B59 (7.4 cm, + 5.3%) exhibited numerically higher growth (Fig. 6). By 30 dpi, control plants reached a mean height of 9.9 cm; at this interval, MRL.B17 demonstrated the strongest growth-promoting effect with a mean height of 11.9 cm (20.5% increase, $p < 0.05$). MRL.B40 also showed significant promotion at 30 dpi, reaching 11.6 cm (+ 17.7%, $p < 0.05$). At the final assessment (45 dpi), the control plants averaged 15.9 cm. MRL.B17 maintained the highest growth promotion, reaching 18.2 cm (14.8% increase, $p < 0.01$), with MRL.B40 also showing sustained significant growth (17.9 cm, + 12.6%, $p < 0.05$). Although MRL.B18 (17.5 cm, + 10.4%) and MRL.B22 (17.3 cm, + 8.9%) showed numerical increases, the remaining isolates performed comparably to the control group (Fig. 6).

3.6 Effect of Endophytic Bacteria on Eggplant Fruit Yield

Analysis of total fruit yield per plant revealed no significant differences between the endophyte treatments and the untreated control ($F_{8,37}$ = 1.52, p = 0.177). Despite the lack of statistical significance, distinct numerical trends were observed among the bacterial strains (Table 4). MRL.B17 and MRL.B22 emerged as the top-performing strains, producing mean yields of 514.1 ± 22.4 g and 508.3 ± 19.8 g per plant, respectively, representing numerical increases of 13.5% and 12.2% over the untreated control (452.9 ± 24.3 g). Intermediate yield increases were observed for MRL.B40 (485.4 ± 25.1 g, + 7.2%), MRL.B44 (473.1 ± 18.2 g, + 4.5%), and MRL.B59 (469.3 ± 21.6 g, + 3.6%), while MRL.B55 (445.5 ± 23.5 g, -1.6%) and MRL.B50 (431.5 ± 19.4 g, -4.7%) exhibited slight inhibitory trends (Table 4). MRL.B44

Table 4
Performance of endophytic bacterial isolates on total fruit yield per plant*

Treatment	Mean Total Yield (g)	% Change vs. Control	p-value
MRL.B17	514.1 ± 22.4	13.5	0.455
MRL.B22	508.3 ± 19.8	12.2	0.512
MRL.B40	485.4 ± 25.1	7.2	0.88
MRL.B44	473.1 ± 18.2	4.5	0.954
MRL.B59	469.3 ± 21.6	3.6	0.978
MRL.B45	451.0 ± 20.1	-0.4	0.999
MRL.B55	445.5 ± 23.5	-1.6	0.995
MRL.B50	431.5 ± 19.4	-4.7	0.982
Control	452.9 ± 24.3	—	—

**Values represent mean ± standard error (n = 6). p-values are from Dunnett's test comparing each treatment to Control. No significant differences were detected (p > 0.05 for all comparisons).*

Cumulative yield progression was monitored over the harvest period to evaluate the consistency of the endophytic effect (Fig. 7A). A linear mixed-effects model indicated a marginal temporal effect on yield (Week: $F_{1,37}$ = 3.26, p = 0.072), reflecting the natural increase in yield over the growing season. However, the lack of a significant interaction between endophyte treatment and time ($F_{8,37}$ = 0.16, p = 0.996) indicates that the isolates did not alter the phenological timing of peak fruit production.

A strong positive correlation was observed between plant height at 45 days and total fruit yield (r = 0.799, 95% CI [0.287, 0.956], p = 0.010), suggesting that plants with greater vegetative growth during tended to produce higher yields (Fig. 7B). This correlation supports the interpretation that growth-promoting effects during vegetative development are directly linked to yield potential. Notably, the tallest plants (MRL.B17 and MRL.B22) also displayed the highest numerical yields, suggesting their full potential was likely constrained by the physical limitations of the containers. All experimental units began to exhibit symptoms of pot-bound stress during the later stages of the trial; after approximately 70 days, visible

root restriction and reduced plant vigor were observed across all treatments. This physical constraint likely imposed a "yield ceiling," particularly on the most vigorous treatments such as MRL.B17 and MRL.B22, which displayed the highest height (Section 3.5) and the most pronounced signs of root confinement.

3.7 Molecular Identification of Promising Endophytic Isolates

Six endophytic bacterial isolates (MRL.B17, MRL.B22, MRL.B40, MRL.B44, MRL.B50, and MRL.B59) demonstrating significant plant growth-promoting and antagonistic activities were selected for molecular identification using 16S rRNA gene sequencing. PCR amplification of the 16S rRNA gene produced fragments of approximately 1500 bp for all isolates, consistent with the expected size for bacterial identification (Fig. S3). Isolate MRL.B17 showed 98.18% identity with *Bacillus amyloliquefaciens* (KY780586.1) at 99% query cover, placing it within the genus *Bacillus*. Isolate MRL.B22 exhibited 99.66% identity with *Bacillus licheniformis* (JX027378.1), confirming its identity as *Bacillus licheniformis*. Isolate MRL.B40 was identified as an *Acinetobacter* sp., showing 97.03% identity with *Acinetobacter pittii* (OQ654031.1) at 99% query cover. Isolate MRL.B44 showed 96.05% identity with *Klebsiella pneumoniae* (KC683726.1) at 100% query cover, belonging to the genus *Klebsiella*. Isolates MRL.B50 and MRL.B59 were identified as belonging to the genus *Staphylococcus*; MRL.B59 showed high confidence (99.52% identity) as *Staphylococcus epidermidis* (OR755045.1), while MRL.B50 showed 95.64% identity with *Staphylococcus epidermidis* (PP962756.1) (Table 5).

Table 5
Molecular identification of endophytic bacterial isolates from *Solanum sisymbriifolium* based on 16S rRNA gene sequence analysis. Values represent percent identity and query cover from BLASTn searches against the NCBI nucleotide database. Taxonomic assignment followed established thresholds (≥ 98.7% identity for species level; 95–98.6% for genus level). Accession numbers in parentheses refer to the top BLAST hit for each isolate.

Isolate	Top BLAST Hit (Accession No.)	Identity (%)	Query Cover (%)	Proposed Identification
MRL.B17	*Bacillus amyloliquefaciens* (KY780586.1)	98.18	99	*Bacillus sp.*
MRL.B22	*Bacillus licheniformis* (JX027378.1)	99.66%	100	*Bacillus licheniformis*
MRL.B40	*Acinetobacter pittii* (OQ654031.1)	97.03	99	*Acinetobacter* sp.
MRL.B44	*Klebsiella pneumoniae* (KC683726.1)	96.05	100	*Klebsiella* sp.
MRL.B50	*Staphylococcus epidermidis* (PP962756.1)	95.64	100	*Staphylococcus* sp.
MRL.B59	*Staphylococcus epidermidis* (OR755045.1)	99.52	92	*Staphylococcus epidermidis*

4. Discussion

4.1. Wild S. sisymbriifolium: A Reservoir of Diverse and Adaptive Stem Endophytes

The successful isolation of 80 bacterial morphotypes with a high isolation frequency (92%) from the stems of *S. sisymbriifolium* reinforces the growing understanding that wild relatives of crop plants serve as important reservoirs of microbial diversity. *S. sisymbriifolium* is a robust, relatively underutilized species that thrives in disturbed environments such as roadsides, waste areas, dykes and crop aisles without human intervention (Biswas et al., 2023; Karaer and Kutbay, 2007; Perpétuo et al., 2021). The absence of visible wilt symptoms in natural populations suggests an inherent resilience, which may be partially mediated by its associated microbiome(Hardoim et al., 2015).

This high colonization frequency is consistent with findings in other wild Solanaceae, including *Solanum lycocarpum* (Lisboa et al., 2021) and *Solanum hindsianum* (Corral-Federico et al., 2024), where native plants harbor abundant communities of plant growth-promoting bacteria and other plants (Campisano et al., 2015). In contrast, domesticated crops often experience reductions in microbial diversity due to genetic bottlenecks and intensive agricultural practices (Lobato et al., 2024; Sun et al., 2020). Consequently, wild genotypes such as *S. sisymbriifolium* are likely to retain complex plant–microbe associations shaped by long-term co-evolution in pathogen-rich environments (Hardoim et al., 2015).

Notably, while most previous studies have focused on root-associated microbiomes, this study specifically targeted stem tissues. This represents an important methodological distinction, as stem-associated endophytes may be particularly relevant for systemic colonization and above-ground disease suppression (Dastogeer et al., 2020a; Martínez-Arias et al., 2021; Mili, 2023; Moudjeber, 2022). Such compartments remain comparatively underexplored, and their investigation may reveal functionally distinct microbial communities with unique ecological roles.

4.2. Antagonistic Potential and the “Wild Advantage”

A key finding of this study was the consistent antagonistic activity observed across all tested isolates, with each demonstrating statistically significant inhibition of *Fusarium oxysporum* f. sp. *melongenae*. While 12 isolates achieved high inhibition levels (≥ 60%), the widespread antagonism suggests that the native microbiome of *S. sisymbriifolium* is inherently enriched in microorganisms capable of suppressing soil-borne pathogens. This observation is consistent with the concept that wild plant-associated microbiomes contribute to host defense and ecological fitness (Berg et al., 2005; Hardoim et al., 2015).

These findings align with previous studies on wild Solanaceae, where endophytes have demonstrated strong biocontrol potential against *Fusarium* wilt (Aydi-Ben-Abdallah et al., 2020). The inhibition levels observed in this study (up to 78.6%) are comparable to, and in some cases exceed, those reported for endophytes isolated from cultivated systems. This supports the notion of a “wild advantage,” whereby

those plants retain beneficial microbial functions that may be reduced in cultivated plants during domestication (Barnes et al., 2025; Garcha, 2023; Ramirez-Villacis et al., 2025; Sun et al., 2020).

4.3. Seed Gemination, Growth Promotion and Mechanisms

Despite the promising in vitro antagonism observed in Dual-culture assays, testing for volatile organic compound (VOC) production revealed that most isolates did not produce VOCs capable of significantly inhibiting the pathogen. Only MRL.B17 and MRL.B18 exhibited modest reductions in fungal growth area (-14.2% and − 12.7%, respectively; $p < 0.05$), indicating that VOCs are not the primary mechanism of antagonism. This contrasts with other studies that identified volatile compounds as a key mechanism of antagonism (Razo-Belman and Ozuna, 2023). For instance, a study by Raza et al. (2016) demonstrated that certain endophytic bacteria, such as *Bacillus* spp., produce volatile compounds like ammonia and hydrogen cyanide, which inhibit the growth of *F. oxysporum*. The absence of volatile-mediated inhibition among the top-performing isolates suggests that antagonism is primarily mediated by diffusible antifungal metabolites and/or extracellular enzymatic activity. This is consistent with the metabolic capabilities of the many bacterial agents, which produces bioactive lipopeptides such as surfactin and fengycin that disrupt fungal cell membranes (Brader et al., 2014; Fan et al., 2018; Köhl et al., 2019; Rabbee et al., 2019). The strong inhibition observed in Dual-culture assays (up to 78.6% for MRL.B40) further supports diffusible compounds as the primary mode of action. The modest VOC-mediated reductions in MRL.B17 and MRL.B18, suggests that any volatile compounds produced by these isolates play a minor role, if any, in the overall antagonistic mechanism. Future studies should focus on characterizing the diffusible antifungal compounds produced by the most effective isolates, including MRL.B40, MRL.B17, and MRL.B18, to elucidate the molecular basis of their strong biocontrol activity.

In addition to pathogen suppression, several isolates significantly enhanced seed germination (up to 26.9%) and plant height (up to 20.5%), indicating strong plant growth-promoting potential. These effects are likely associated with multiple mechanisms, including phytohormone production (e.g., indole-3-acetic acid), nutrient solubilization, and improved root development (Santoyo et al., 2016; Spaepen and Vanderleyden, 2011). The strong positive correlation between plant height and yield ($r = 0.799$, $p = 0.010$) further indicates that early vegetative vigor contributes meaningfully to reproductive performance, even though yield differences were not statistically significant potentially due to experimental constrains discussed in section below.

4.4. Yield Response and Experimental Constraints

Although numerical yield increases of up to 13.5% were observed, these differences were not statistically significant ($F_{8,37} = 1.52$, $p = 0.177$). This outcome is best interpreted in the context of experimental constraints rather than an absence of biological effect. Restricted root volume in pot-based systems can impose a physiological limitation or “yield ceiling,” constraining water and nutrient uptake during critical growth stages (Passioura, 2006). In this study, plants treated with growth-promoting isolates exhibited greater vegetative vigor and may therefore have reached these spatial limitations earlier than control plants, potentially masking their full yield potential. Additionally, the absence of

pathogen pressure in the experimental setup likely underestimated the contribution of biocontrol mechanisms, which would be expected to have a more pronounced effect under field conditions with natural *Fusarium* incidence. Our findings are consistent with others discussed on modest or non-significant yield responses under controlled conditions, where environmental constraints limit the expression of plant–microbe interactions (Backer et al., 2018; Fadiji et al., 2025; Santoyo et al., 2016). Field-based evaluations under realistic agronomic conditions are therefore essential to fully assess the agronomic value of these endophytes.

4.5. Taxonomic Identity and Biosafety Considerations

Molecular identification confirmed that the most effective isolates belong to genera commonly associated with plant growth promotion, including *Bacillus* and *Acinetobacter*, which are frequently reported as components of the core microbiome of Solanaceae (Corral-Federico et al., 2024). The predominance of *Bacillus* spp. among high-performing isolates is consistent with their well-established role in biological control, mediated through the production of antimicrobial lipopeptides, extracellular enzymes, and induction of systemic resistance (Anckaert et al., 2021; Borriss, 2011; Villarreal-Delgado et al., 2018). Notably, MRL.B22 was identified as *Bacillus licheniformis* (99.66% identity), a species known for its diverse plant growth-promoting traits, including IAA production, siderophore synthesis, and phosphate solubilization (García et al., 2004; Muras et al., 2021; Nigris et al., 2018; Tariq et al., 2025).

The identification of *Acinetobacter* sp. (MRL.B40) as a strong antagonist is particularly noteworthy. Although members of this genus have been increasingly recognized for plant growth-promoting and biocontrol traits, including siderophore production and nutrient mobilization (Rokhbakhsh-Zamin et al., 2011; Xue et al., 2009), reports of their effectiveness against *Fusarium* wilt in Solanaceae remain limited. This study provides evidence of its potential as a novel biocontrol agent.

In contrast, the detection of *Klebsiella* (MRL.B44) and *Staphylococcus* spp. (MRL.B50, MRL.B59) among antagonistic isolates warrants careful consideration. Although plant-associated strains of these genera have been reported to exhibit beneficial traits (Kumar et al., 2021; Sachdev et al., 2009; Triplett et al., 2008), they also include opportunistic human pathogens (Rodríguez-Medina et al., 2019; Sigudu et al., 2023). Notably, MRL.B59 was identified as *Staphylococcus epidermidis* (99.52% identity), a species commonly found on human skin but also reported from plant environments (Burke et al., 2023). Consequently, any future application of such isolates in agriculture requires comprehensive biosafety evaluation, including assessment of pathogenicity, antibiotic resistance profiles, and potential for horizontal gene transfer (Eilenberg and Hokkanen, 2006; Etesami, 2025; Tariq et al., 2022).

4.6. Limitations and Future Directions

This study was constrained by the inability to perform molecular identification of all isolates due to resource limitations, a common challenge in endophyte research. Furthermore, identification based on 16S rRNA gene sequencing may not fully resolve species-level taxonomy within closely related groups. In addition, the functional characterization of isolates was limited to antagonistic activity and selected plant growth-promoting traits. Other potentially valuable attributes—such as tolerance to abiotic stresses

(e.g., drought and salinity) and the production of bioactive secondary metabolites—remain unexplored (Corral-Federico et al., 2024; Mili, 2023). Future research should therefore prioritize: (i) field trials under natural disease pressure; (ii) whole-genome sequencing to enable precise taxonomic resolution and identification of biosynthetic gene clusters; (iii) expanded functional screening; and (iv) the development of stable formulations for practical agricultural application.

5. Conclusions

This study demonstrates that the wild species *S. sisymbriifolium* represents a promising and underexplored reservoir of endophytic bacteria with biocontrol and plant growth-promoting potential. The recovery of isolates exhibiting consistent antagonistic activity and measurable growth enhancement —particularly *Bacillus* sp. MRL.B17 and *Acinetobacter* sp. MRL.B40—highlights their potential for development as bio-inoculants for the management of *Fusarium* wilt in eggplant. By leveraging microbial functions preserved in wild plant systems, it may be possible to reintroduce beneficial traits into domesticated crops and enhance their resilience to biotic stress.

Declarations

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Conflict of Interest Statement

The authors declare no conflict of interest.

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Figures

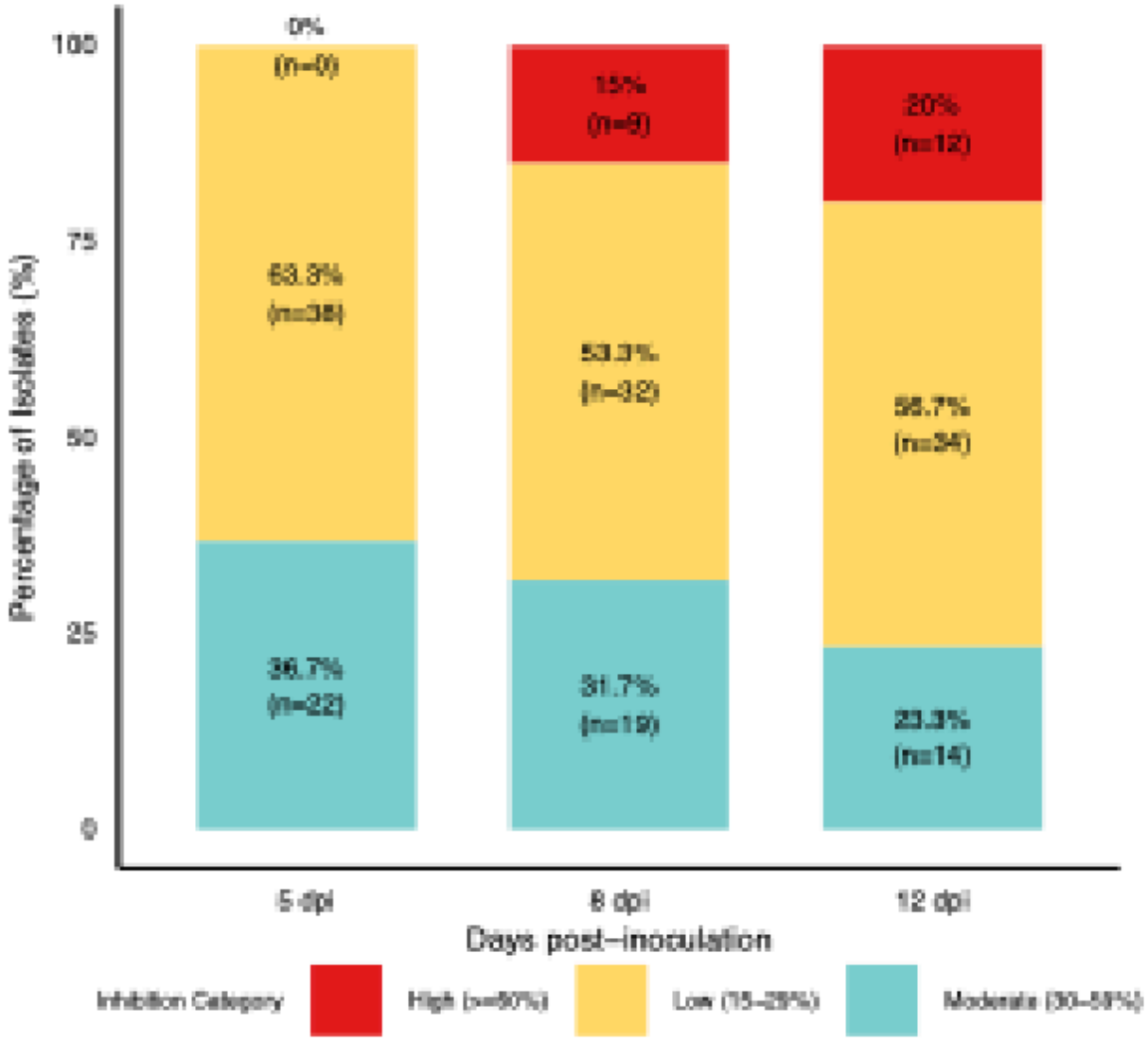


Figure 1

Distribution of antagonistic activity levels of 60 endophytic bacterial isolates from *Solanum sisymbriifolium* against *Fusarium oxysporum* f. sp. *Melongenae* (*Fom*MRL1) at 5, 8, and 12 days post-inoculation (dpi). Stacked bars show the percentage of isolates in each inhibition category (low: 15–29%, moderate: 30–59%, high: ≥60%). Numbers inside bars indicate percentage and count of isolates.

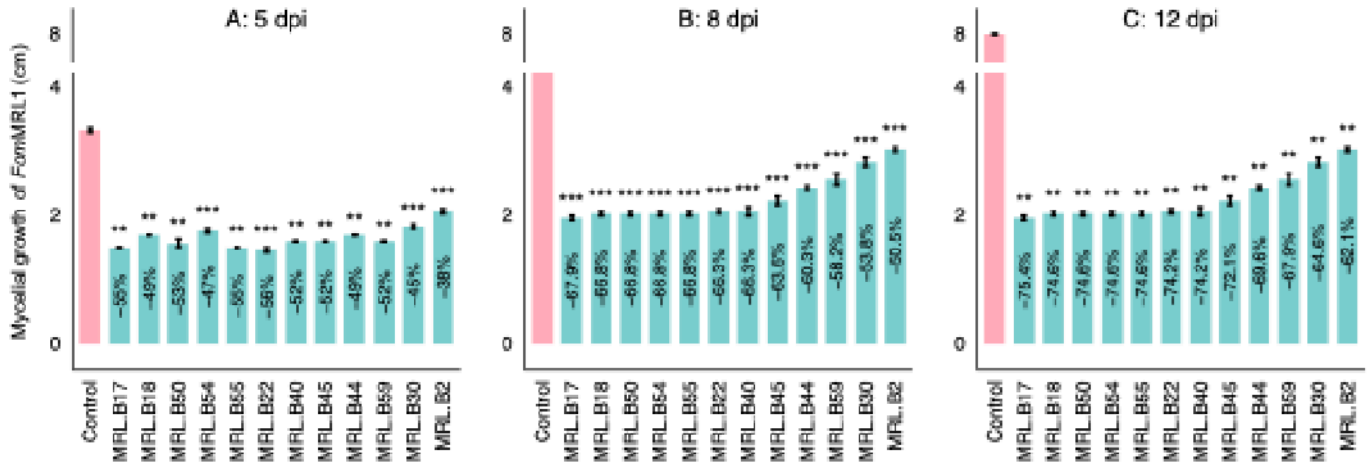


Figure 2

Antagonistic activity of top-performing endophytic bacteria (>60% inhibition) from *S. sisymbriifolium* against *F. oxysporum* f. sp. *Melongenae* (*Fom*MRL1) in dual-culture assay. Bar graphs show mean diameter growth (cm) of *Fom*MRL1 at (A) 5 dpi, (B) 8 dpi, and (C) 12 dpi. Bars represent mean ± SE (n = 3). Significance markers above bars indicate comparisons to control based on t-test with Bonferroni correction: *** $p < 0.001$, ** $p < 0.01$, * $p < 0.05$. Control bars in pink, endophyte treatments in light blue. Complete results for all 60 isolates are provided in Supplementary Table S1.

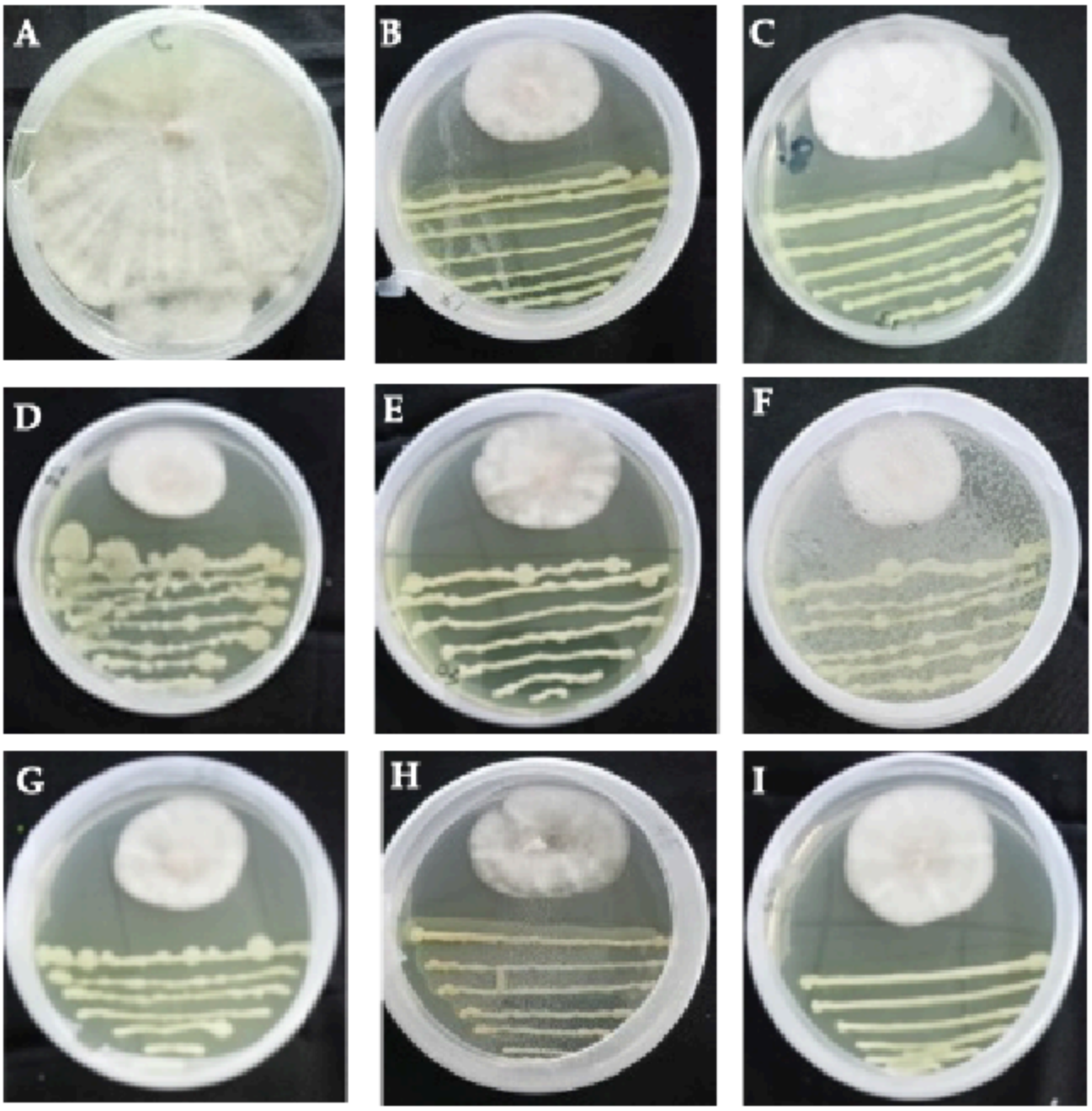


Figure 3

Dual-culture assay of endophytic bacterial isolates against *Fusarium oxysporum* f. sp. *melongenae* (*Fom*MRL1) at 12 days post-inoculation. **(A)** Control (pathogen alone); **(B–I)** Co-culture with isolates MRL.B17, MRL.B18, MRL.B22, MRL.B40, MRL.B44, MRL.B45, MRL.B50, and MRL.B59, respectively. Reduced fungal growth is evident in all co-culture plates.

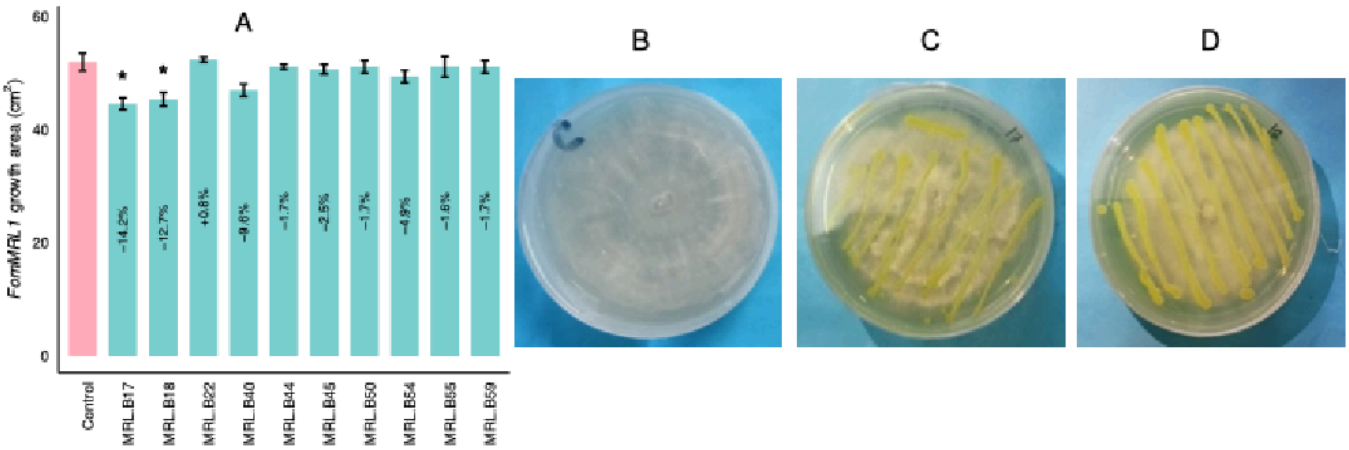


Figure 4

Effect of volatile organic compounds (VOCs) produced by endophytic bacterial isolates on *Fusarium oxysporum* f. sp. *melongenae* (*Fom*MRL1) growth. **(A)** Fungal growth area (cm²) in inverted plate (sandwich) assay at 13 days post-inoculation. Bars represent mean ± SE (n = 3). Values inside bars indicate percent change relative to control. Significance markers above bars indicate comparisons to control based on t-test with Bonferroni correction: * $p < 0.05$. Control bars in pink, endophyte treatments in light blue. **(B–D)** Representative plates showing fungal growth in the presence of VOCs from: **(B)** Control (no bacteria), **(C)** MRL.B17, and **(D)** MRL.B18.

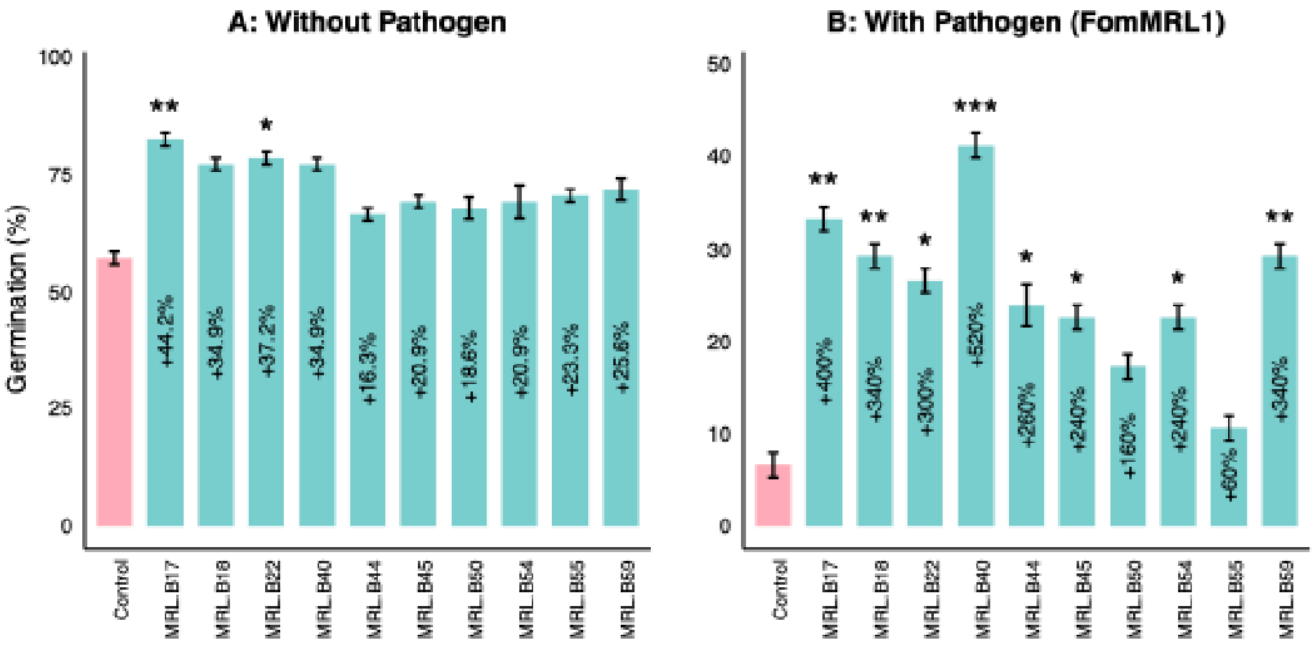


Figure 5

Effect of endophytic bacterial isolates from *S. sisymbriifolium* on eggplant seed germination. (A) Without pathogen. (B) Under *Fom*MRL1 pathogen challenge. Bars represent mean germination (%) ± SE (n = 3). Vertical values inside bars indicate percent change relative to control. Significance based on Dunnett's test following binomial GLM: *** p < 0.001, ** p < 0.01, * p < 0.05 (exact p-values are provided in Table 2). Control bars in pink, endophyte treatments in light blue.

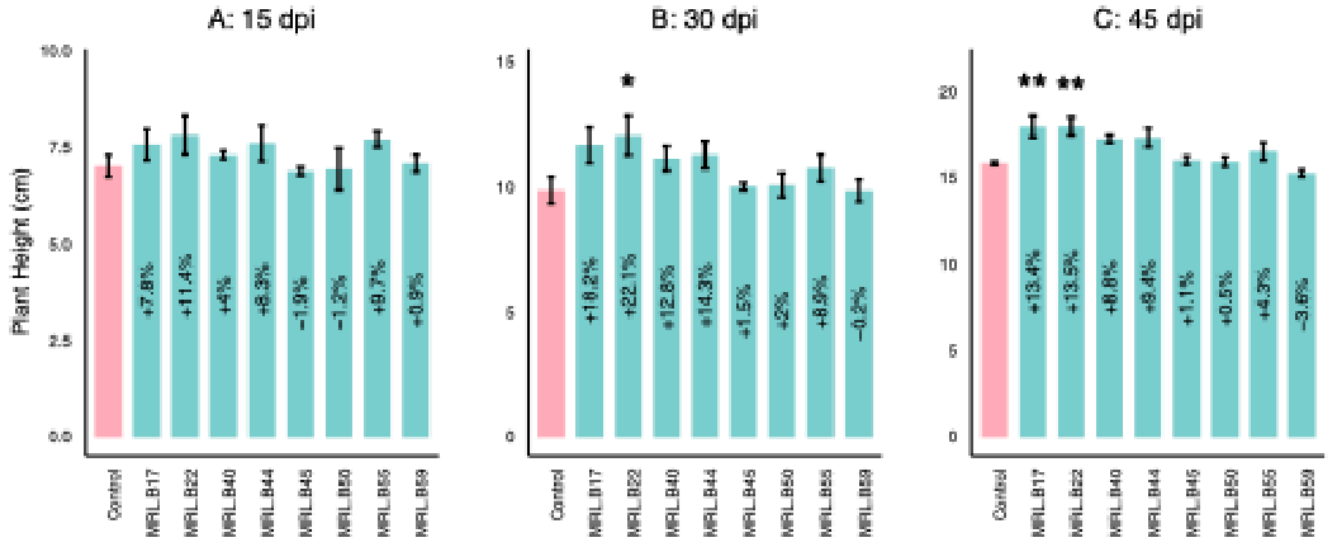


Figure 6

Effect of endophytic bacterial isolates from *S. sisymbriifolium* on eggplant (*S.melongena*) plant height at (A) 15 days, (B) 30 days, and (C) 45 days after sowing. Bars represent mean plant height (cm) ± SE. Control (n = 6), endophyte treatments (n = 5). Vertical values inside bars indicate percent change relative to control. Significance markers: ** p < 0.01, * p < 0.05 (Dunnett's test vs. control). Control bars in pink, endophyte treatments in light blue.

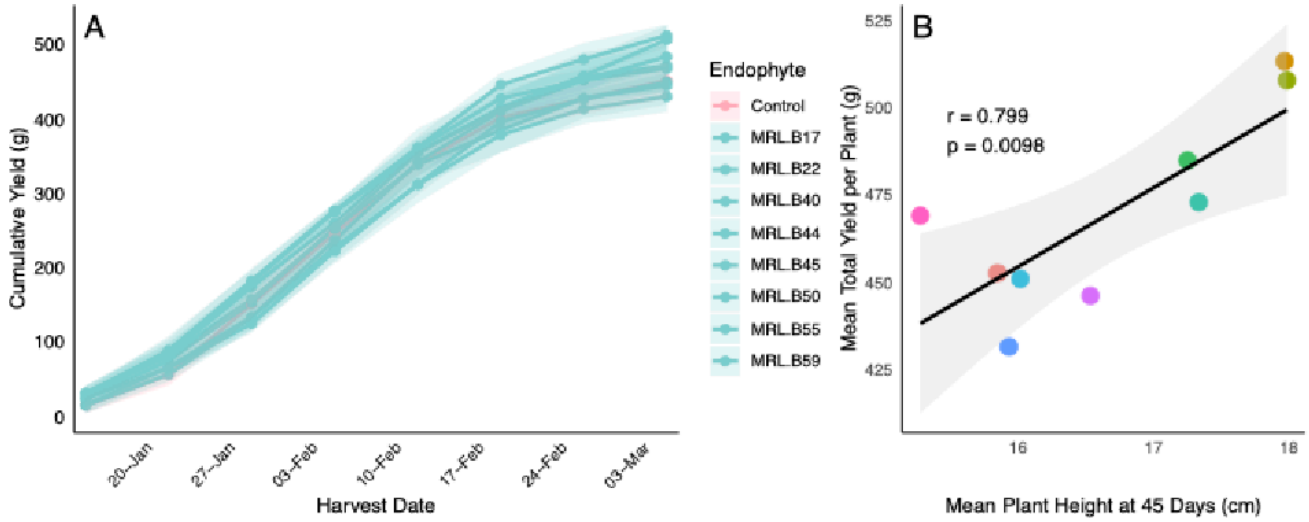


Figure 7

Eggplant yield performance under endophyte treatments. **(A)** Cumulative yield progression over harvest dates. Lines represent mean cumulative yield (g) per plant with shaded areas indicating ± SE (n = 6). **(B)** Correlation between plant height at 45 days and total yield per plant. Each point represents a treatment mean. A significant positive correlation was observed (r = 0.799, p = 0.010). Control bars in pink, endophyte treatments in light blue.

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- SupplementaryTableS1.docx