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Biological Control of *Fusarium* Wilt in Chili Pepper (*Capsicum frutescens* L.) using Antagonistic Bacteria

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ABSTRACT

Background and Objective: *Fusarium* wilt is a major constraint in cayenne pepper (*Capsicum frutescens* L.) cultivation, causing significant yield losses. This study aimed to evaluate the effectiveness of antagonistic bacteria in controlling *Fusarium* wilt and to compare the efficacy of three bacterial species-*Acetobacter xylinum*, *Bacillus subtilis*, and *Pseudomonas fluorescens*-at different concentrations. **Materials and Methods:** The experiment was conducted under controlled greenhouse conditions. Plant growth and disease parameters, including plant height, leaf number, wilted and yellow leaves, fruit number, and root biomass, were recorded. Bacterial treatments were applied at concentrations of 10^6, 10^7, and 10^8 CFU/mL. Data were analyzed using Analysis of Variance (ANOVA) followed by Duncan's multiple range test at the 5% significance level. **Results:** Bacterial treatments significantly affected several growth and disease parameters. *Pseudomonas fluorescens* at 10^8 CFU/mL was the most effective, suppressing *Fusarium* wilt symptoms and enhancing leaf number and fruit yield compared to other treatments. **Conclusion:** Antagonistic bacteria, particularly *Pseudomonas fluorescens*, show strong potential as eco-friendly biological control agents for *Fusarium* wilt in cayenne pepper. These findings support their use in sustainable crop management strategies.

KEYWORDS

Antagonistic bacteria, *Fusarium oxysporum*, biological control, *Capsicum frutescens*, *Pseudomonas fluorescens*, plant growth

INTRODUCTION

Chili pepper (*Capsicum frutescens* L.) is one of the most important horticultural commodities with high economic value and global demand. Its extensive use as a spice, food ingredient, and medicinal raw material makes chili cultivation a promising agribusiness. In Indonesia, chili also experiences the highest price fluctuations among horticultural crops, with substantial profit potential for farmers[1]. However, production often faces serious challenges, particularly diseases that significantly reduce yield and fruit quality.

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Chili pepper production in Indonesia, has experienced a declining trend. Among the major factors limiting production is *Fusarium* wilt, a devastating disease that infects chili plants and causes significant yield losses[2]. The pathogen infects plants through root wounds, colonizes the epidermis, cortex, and endodermis, and eventually invades the xylem vessels. This blockage disrupts water transport, causing wilting, leaf chlorosis, and ultimately plant death[3].

Farmers commonly use chemical fungicides and insecticides to manage *Fusarium* wilt; however, these methods are often ineffective because the pathogen persists deep in the soil where chemical agents cannot reach. Moreover, chemical control poses environmental and health risks. Hence, biological control using antagonistic microorganisms, such as bacteria and fungi, has emerged as a sustainable and environmentally friendly alternative[4].

Antagonistic bacteria can suppress fungal pathogens through various mechanisms, including competition, antibiosis, and induction of plant defense responses. Several studies have demonstrated the inhibitory activity of different bacterial genera respectively such as *Bacillus* (73.1%), *Gliocladium* (70.33%), and *Trichoderma* (95%)[5-7]. In addition to pathogen suppression, these bacteria can promote plant growth by enhancing nutrient solubilization (e.g., phosphate), producing growth hormones and vitamins, improving root architecture, and increasing mineral uptake[8]. The use of antagonistic bacteria is cost-effective, safe for humans and animals, and leaves no harmful residues in the environment[9].

Bacillus and *Pseudomonas* spp. could serve as effective biological control agents in managing wilt disease in chili pepper[10]. Therefore, this study aimed to evaluate the effectiveness of different antagonistic bacteria in suppressing *Fusarium* wilt disease in chili pepper and to compare their ability to inhibit *F. oxysporum* while promoting plant growth under controlled conditions.

MATERIALS AND METHODS

Study area and duration: The study was conducted at the greenhouse of the Department of Biology, Faculty of Mathematics and Natural Sciences, Universitas Negeri Makassar, Makassar, Indonesia, from January to May 2025.

Materials: The materials used in this study included *Capsicum frutescens* L. (Dewata F1 variety) seeds, synthetic fungicide (benomyl), and local isolates of *Acetobacter xylinum*, *Bacillus subtilis*, *Pseudomonas fluorescens*, and *Fusarium oxysporum* obtained from the culture collection of Hasanuddin University.

Pure culture preparation: The isolates of *A. xylinum*, *B. subtilis*, *P. fluorescens*, and *F. oxysporum* were sub-cultured on nutrient agar (NA) for bacteria and potato dextrose agar (PDA) for fungi in Petri dishes and incubated at 25±2°C for 7 days.

Preparation of antagonistic bacteria and *Fusarium oxysporum* suspensions: Antagonistic bacterial suspensions were prepared by adding sterile 0.85% NaCl solution to actively growing cultures on NA plates. The surface of the colonies was gently scraped using a sterile swab to release bacterial cells. The suspension was transferred into sterile Erlenmeyer flasks and serially diluted to obtain concentrations of 10^6, 10^7, and 10^8 CFU/mL.

The fungal suspension of *F. oxysporum* was prepared from 7-day-old cultures grown on PDA. Spores were dislodged by adding 10 mL of sterile distilled water and gently scraping the colony surface with a sterile swab. The suspension was filtered through sterile gauze and adjusted to a concentration of 10^6 conidia/mL using a hemocytometer under a light microscope[11].

Planting procedure: Chili seedlings were first raised in seed trays and transplanted into small polybags. After two weeks, the seedlings were transferred to larger polybags containing sterilized soil and compost (2:1 v/v).

Inoculation and treatment application: *Fusarium oxysporum* inoculation was performed at 50 days after sowing (DAS) by injecting 20 mL of the 10 conidia/mL suspension around the root zone. Antagonistic bacterial treatments (*A. xylinum*, *B. subtilis*, and *P. fluorescens*) were applied at 70 DAS by injecting 25 mL of bacterial suspension (10^6-10^8 CFU/mL) into the root zone. The positive control received synthetic fungicide (benomyl), while the negative control received sterile water only.

Observation parameters: Observations were conducted at 55 days after *F. oxysporum* inoculation. The parameters measured included plant height (cm), number of leaves, number of wilted leaves, and number of yellow leaves.

Data analysis: All data were analyzed using Analysis of Variance (ANOVA) to determine treatment effects. When significant differences were detected ($p<0.05$), Duncan's Multiple Range Test (DMRT) was performed for mean comparison.

RESULTS

Mean plant height of cayenne pepper (*Capsicum frutescens* L.): Based on statistical analysis at a 5% significance level ($\alpha = 0.05$), the mean plant height of *C. frutescens* varied among treatments from 20 to 110 days after planting (DAP). The results are presented in Table 1.

According to the statistical analysis using ANOVA, the significance value obtained was 0.014 (<0.05), indicating that the treatments had a significant effect on plant height (Table 1). The Duncan's multiple range test revealed that treatment P1 (*Acetobacter xylinum* 10 CFU/mL) did not differ significantly from treatments P7 (*Pseudomonas fluorescens* 10^8 CFU/mL) and P2 (*Acetobacter xylinum* 10^7 CFU/mL), which produced mean plant heights of 109.40 cm and 105.80 cm, respectively. However, these treatments showed significant differences compared to the negative control.

These results suggest that the three treatments demonstrated strong potential to enhance plant growth under pathogen stress. At 110 days after planting (DAP), the highest mean plant height was recorded in the positive control treatment (fungicide+*Fusarium*) at 121.00 cm, while the lowest was observed in the negative control (untreated) at 90.00 cm. Treatment P1 (*A. xylinum* 10^6 CFU/mL) resulted in an average plant height of 113.20 cm, which was not significantly different from the positive control but significantly higher than the negative control. This indicates the effectiveness of *A. xylinum* in suppressing *Fusarium* infection while supporting plant growth. This result indicates that the application of bacteria such as *Acetobacter xylinum* and *Bacillus subtilis* can enhance plant growth, particularly in terms of plant height.

Average number of leaves of chili pepper (*Capsicum frutescens* L.): Based on statistical analysis at a significance level of $\alpha = 0.05$, the average number of chili pepper leaves for each treatment from 20 to 110 days after planting (DAP) is presented in Table 2.

Based on the results of the ANOVA test at 70 days after planting (DAP), a significance value of 0.032 ($p<0.05$) was obtained, indicating that there were significant differences among treatments in terms of the number of chili leaves. Therefore, a Duncan Multiple Range Test (DMRT) at the 5% significance level was conducted to determine which treatments showed significant differences.

According to the Duncan test results, the P3 treatment (*Acetobacter xylinum* 10^8) produced the highest number of leaves (310.40), which was significantly different from the negative control, yielding the lowest number of leaves (193.20). The Duncan test results indicated significant differences among treatments, as represented by different letters in the column of leaf number at 70 DAP. Treatments followed by the same letter were not significantly different, whereas treatments followed by different letters showed significant differences.

Table 1: Observation results of the height of cayenne pepper plants in each treatment

	Plant height (cm)			
Treatment	20 DAP	50 DAP	70 DAP	110 DAP
Control (-)	54.20	60.40^{a}	72.00^{a}	90.00^{a}
Control (+)	64.20	78.00^{c}	90.00^{b}	121.00^{c}
P1 (10^6)	57.40	71.00^{abc}	83.80^{ab}	113.20^{bc}
P2 (10^7)	55.80	66.40^{abc}	80.20^{ab}	106.00^{abc}
P3 (10^8)	60.00	69.20^{abc}	78.00^{ab}	96.80^{ab}
P4 (10^6)	57.00	68.60^{abc}	80.80^{ab}	99.20^{ab}
P5 (10^7)	63.20	74.80^{bc}	82.00^{ab}	105.20^{abc}
P6 (10^8)	57.60	68.00^{abc}	79.20^{ab}	105.80^{bc}
P7 (10^6)	59.40	69.60^{abc}	82.40^{ab}	109.40^{bc}
P8 (10^7)	56.20	63.60^{ab}	74.00^{a}	101.40^{ab}
P9 (10^8)	56.40	69.60^{abc}	81.20^{ab}	102.20^{ab}

Average value followed by the same letter indicates that there is no significant difference, while different letters indicate a significant difference in the Duncan test at the 5% level

Table 2: Observation results of the number of chili leaves in each treatment

	Number of leaves (Sheets)			
Treatment	20 DAP	50 DAP	70 DAP	110 DAP
Control (-)	124.60	156.20^{a}	193.20^{a}	291.20
Control (+)	149.00	219.00^{ab}	286.80^{b}	367.60
P1 (10^6)	137.40	241.20^{ab}	270.40^{b}	375.00
P2 (10^7)	115.60	229.20^{ab}	280.20^{b}	364.20
P3 (10^8)	144.60	236.00^{ab}	310.40^{b}	374.40
P4 (10^6)	154.00	234.00^{a}	273.40^{b}	349.40
P5 (10^7)	151.80	243.60^{b}	302.00^{b}	365.00
P6 (10^8)	139.40	237.40^{ab}	297.60^{b}	359.00
P7 (10^6)	110.80	213.40^{ab}	288.40^{b}	369.20
P8 (10^7)	145.80	220.60^{ab}	280.00^{b}	358.60
P9 (10^8)	159.60	267.00^{b}	300.00^{b}	376.00

Mean values followed by the same letter (a, ab, b) show no significant difference based on Duncan's test at 5% level. Treatments followed by different letters show significant differences

Table 3: Observation results of wilted leaves of chili pepper plants in each treatment

	Wilted leaves (Shells)	
Treatment	50 DAP	70 DAP
Control (-)	0.00^{a}	0.00
Control (+)	11.00^{b}	0.80
P1 (10^6)	18.40^{b}	1.40
P2 (10^7)	10.40^{ab}	0.60
P3 (10^8)	9.60^{ab}	0.40
P4 (10^6)	7.80^{ab}	0.60
P5 (10^7)	9.80^{ab}	0.00
P6 (10^8)	8.20^{ab}	0.00
P7 (10^6)	14.20^{b}	0.00
P8 (10^7)	17.80^{b}	0.00
P9 (10^8)	13.80^{b}	0.40

Numbers followed by different letters indicate significant differences at the 5% Duncan test level. The same letters (such as ab) indicate no significant difference between treatments

Based on Table 3, the results of the ANOVA at 50 days after planting (DAP) showed a significance value of 0.022 ($p<0.05$), indicating a significant difference among treatments in the number of wilted leaves of chili plants. Therefore, a Duncan Multiple Range Test (DMRT) at a 5% significance level was conducted to determine which treatments differed significantly. The Duncan test revealed that the P1 treatment (*Acetobacter xylinum* 10^6) produced the highest number of wilted leaves (18.40), followed by P8 and P7. In contrast, the negative control (K^-) showed the lowest number of wilted leaves (0.00), indicating the absence of wilt symptoms in the treatment without *Fusarium* inoculation. At 20, 70, and 110 DAP, no significant differences were observed among treatments.

Table 4: Observation results of yellow leaves of cayenne pepper plants in each treatment

	Yellow leaves (Shells)	
Treatments	50 DAP	70 DAP
Control (-)	0.00[a]	0.00
Control (+)	4.20[b]	1.00
P1 (10^6)	5.80[b]	1.40
P2 (10^7)	4.60[b]	0.80
P3 (10^8)	4.40[b]	1.00
P4 (10^6)	3.00[ab]	1.20
P5 (10^7)	3.40[ab]	0.80
P6 (10^8)	3.60[ab]	0.60
P7 (10^6)	4.80[b]	1.00
P8 (10^7)	4.40[b]	0.40
P9 (10^8)	4.40[b]	0.60

Values followed by different letters indicate a significant difference among treatments in the number of yellow leaves of chili plants

Average number of yellow leaves in chili plants (*Capsicum frutescens* L.): Based on statistical analysis at a significance level of α = 0.05, the average number of yellow leaves in chili plants at 50 and 70 DAP is presented in Table 4.

Based on Table 4, the results of the statistical analysis using ANOVA at 50 days after planting (DAP) showed a significance value of 0.151 ($p<0.05$), indicating that there was a significant difference among treatments in the number of yellow leaves. Therefore, a follow-up test using the Duncan Multiple Range Test (DMRT) at a 5% significance level was conducted to determine which treatments showed significant differences. The Duncan test results revealed that at 50 DAP, the highest number of yellow leaves was observed in the *Acetobacter xylinum* 10^6 (P1) treatment, with an average of 5.80 leaves, whereas the negative control (K^-) and several other treatments showed the lowest number of yellow leaves (0.00 leaves).

Based on the average number of yellow leaves of chili plants at 50 days after planting (DAP), the treatment P1 (*Acetobacter xylinum* 10^6) showed the highest number of yellow leaves, while the negative control (K^-) exhibited the lowest. Several antagonistic bacterial treatments, such as P3 (*Acetobacter xylinum* 10^8) and P5 (*Bacillus subtilis* 10^7), showed relatively low numbers of yellow leaves and were not significantly different from the negative control, indicating their ability to suppress early disease symptoms. Although the differences were not statistically significant, the graphical data suggest that the application of antagonistic bacteria at higher concentrations tends to be more effective in reducing yellow leaf symptoms caused by *Fusarium oxysporum* infection.

Average number of fruits of chili plants (*Capsicum frutescens* L.): Based on the results of the ANOVA test at 70 days after planting (DAP), the significance value (Sig.) = 0.498, which is greater than 0.05, indicating that there was no significant difference among treatments in the number of fruits at 70 DAP. Similarly, at 110 DAP, the significance value (Sig.) = 0.829>0.05, suggesting that no significant difference was observed among treatments at this stage either. The highest average number of fruits at 110 DAP was recorded in treatment P9 (*Pseudomonas fluorescens* 10^8) with 65.40 fruits, followed by P1 (*Acetobacter xylinum* 10^6) with 64.60 fruits and P8 (*Pseudomonas fluorescens* 10^7) with 61.60 fruits. In contrast, the negative control (P0) produced the lowest number of fruits, with only 47.40 fruits, among all treatments in Table 5.

Average root weight of chili plants (*Capsicum frutescens* L.): Based on statistical analysis at a significance level of α = 0.05, the ANOVA results at 110 DAP showed a significance value of 0.829 ($p>0.05$), indicating no significant difference among treatments in root weight. However, descriptively, the highest root weight was observed in P5 (*Bacillus subtilis* 10^7 CFU/mL) with 94.20 g, while the lowest was recorded in the negative control (K^-) with 28.20 g in Table 6.

Table 5: Observation results of the number of chili pepper fruit in each treatment

	Number of fruits	
Treatments	70 DAP	110 DAP
Control (-)	25.00	47.40
Control (+)	26.80	57.60
P1 (10^6)	38.60	64.60
P2 (10^7)	24.00	49.20
P3 (10^8)	35.80	61.00
P4 (10^6)	24.20	59.40
P5 (10^7)	22.20	53.80
P6 (10^8)	22.00	53.20
P7 (10^6)	21.00	53.40
P8 (10^7)	32.20	61.60
P9 (10^8)	30.60	65.40

K-: No Treatment, K+: Fungicide+*Fusarium* 10^6, P1: *Acetobacter* 10^6+*Fusarium* 10^6, P2: *Acetobacter* 10^7+*Fusarium* 10^6, P3: *Acetobacter* 10^8+*Fusarium* 10^6, P4: *Bacilus* 10^6+*Fusarium* 10^6, P5: *Bacilus* 10^7+*Fusarium* 10^6, P6: *Bacilus* 10^8+*Fusarium* 10^6, P7: *Pseudomonas* 10^6+*Fusarium* 10^6, P8: *Pseudomonas* 10^7+*Fusarium* 10^7 and P9: *Pseudomonas* 10^8+*Fusarium* 10^6

Table 6: Results of root weight observations on chili pepper plants in each treatment

Treatment	Root weight (grams) 110 DAP
Control (-)	28.60
Control (+)	73.00
P1 (10^6)	67.40
P2 (10^7)	87.00
P3 (10^8)	73.80
P4 (10^6)	70.40
P5 (10^7)	94.20
P6 (10^8)	89.80
P7 (10^6)	90.40
P8 (10^7)	87.40
P9 (10^8)	83.40

K-: No treatment, K+: Fungisida+*Fusarium* 10^6, P1: *Acetobacter* 10^6+*Fusarium* 10^6, P2: *Acetobacter* 10^7+*Fusarium* 10^6, P3: *Acetobacter* 10^8+*Fusarium* 10^6, P4: *Bacilus* 10^6+*Fusarium* 10^6, P5: *Bacilus* 10^7+*Fusarium* 10^6, P6: *Bacilus* 10^8+*Fusarium* 10^6, P7: *Pseudomonas* 10^6+*Fusarium* 10^6, P8: *Pseudomonas* 10^7+*Fusarium* 10^7 and P9: *Pseudomonas* 10^8+*Fusarium* 10^6

Table 7: Results of observations of the length of roots of cayenne pepper plants in each treatment

Treatment	Root length (cm) 110 DAP
Control (-)	34.20
Control (+)	39.40
P1 (10^6)	35.40
P2 (10^7)	42.60
P3 (10^8)	40.80
P4 (10^6)	43.20
P5 (10^7)	42.60
P6 (10^8)	42.40
P7 (10^6)	40.20
P8 (10^7)	38.40
P9 (10^8)	35.00

K-: No treatment K+: Fungisida+*Fusarium* 10^6, P1: *Acetobacter* 10^6+*Fusarium* 10^6, P2: *Acetobacter* 10^7+*Fusarium* 10^6, P3: *Acetobacter* 10^8+*Fusarium* 10^6, P4: *Bacilus* 10^6+*Fusarium* 10^6, P5: *Bacilus* 10^7+*Fusarium* 10^6, P6 : *Bacilus* 10^8+*Fusarium* 10^6, P7: *Pseudomonas* 10^6+*Fusarium* 10^6, P8: *Pseudomonas* 10^7+*Fusarium* 10^7 and P9: *Pseudomonas* 10^8+*Fusarium* 10^6

Average root length of chili plants (*Capsicum frutescens* L.): Based on the ANOVA results at 110 DAP, the significance value was 0.531 ($p>0.05$), indicating no significant difference among treatments in root length. Descriptively, the longest root was recorded in P4 (*Bacillus subtilis* 10^6 CFU/mL) with 43.20 cm, followed by P5 (*Bacillus subtilis* 10 CFU/mL) with 42.60 cm, and P6 (*Bacillus subtilis* 10^8 CFU/mL) with 42.40 cm. The shortest root was found in the negative control (K^-) at 34.20 cm.

As illustrated in Table 7, *Bacillus subtilis* at various concentrations tended to promote longer root growth compared to the control, although statistically insignificant. This indicates that antagonistic bacteria may contribute to improved root elongation through indirect stimulation of root physiology and nutrient uptake.

DISCUSSION

The present study demonstrated that the application of antagonistic bacteria significantly influenced several vegetative growth parameters of *Capsicum frutescens* under *Fusarium oxysporum* stress. Treatments involving *Acetobacter xylinum*, *Bacillus subtilis*, and *Pseudomonas fluorescens* generally resulted in greater plant height and increased leaf number compared to the negative control, indicating the beneficial role of Plant Growth-Promoting Rhizobacteria (PGPR) in supporting plant growth under pathogen pressure. Similar findings were reported by Iqbal et al., who showed that PGPR application enhanced vegetative growth and reduced disease symptoms in chili plants infected by *Fusarium*[12].

The increase in plant height observed in treatments P1, P7, and P2 is consistent with previous studies reporting that PGPR promote plant growth through phytohormone production, improved nutrient uptake, and enhanced root activity[13,14]. In particular, *Bacillus subtilis* and *Pseudomonas fluorescens* have been widely documented to produce indole-3-acetic acid (IAA), solubilize phosphate, and suppress soil-borne pathogens, thereby improving plant vigor and growth performance[15,16]. The comparable plant height between certain bacterial treatments and the positive control in this study suggests that biological control agents may serve as effective alternatives to chemical fungicides under controlled conditions.

Leaf development, which is a critical indicator of photosynthetic capacity, was also positively influenced by antagonistic bacterial treatments. The higher number of leaves observed in treatments P3, P5, and P9 supports earlier reports that PGPR enhance vegetative growth by stimulating nutrient assimilation and improving plant physiological status[14,17]. Conversely, the negative control exhibited the lowest leaf number, indicating that *Fusarium* infection without biological or chemical intervention significantly suppressed plant growth. These results are in agreement that untreated chili plants showed reduced leaf formation due to pathogen-induced stress[13].

Although wilted and yellow leaf symptoms varied among treatments, several bacterial applications tended to reduce disease severity compared to the positive control, suggesting partial suppression of *Fusarium* wilt. Similar trends were reported in previous studies, where PGPR reduced disease expression through induced systemic resistance and antagonistic interactions in the rhizosphere. However, variability in symptom suppression among treatments may be attributed to differences in bacterial concentration, colonization efficiency, and interactions with the host plant[14].

Yield-related parameters, including fruit number, root weight, and root length, did not show statistically significant differences among treatments, although descriptive data indicated higher values in several bacterial treatments compared to the negative control. Such inconsistencies have also been observed in other PGPR studies, where growth promotion effects were more pronounced in vegetative stages than in reproductive parameters[15-19]. Environmental conditions, experimental duration, and plant genotype may influence the extent to which PGPR affect yield components, potentially explaining the lack of significant differences observed in this study. In addition to bacterial antagonists, recent studies have also demonstrated that fungal antagonists such as *Trichoderma harzianum*, *Metarhizium anisopliae*, and *Beauveria bassiana* can significantly reduce *Fusarium* wilt intensity and enhance growth in *Capsicum frutescens*, with *T. harzianum* showing the highest effectiveness among them[20].

Microorganisms isolated from the rhizosphere, including fungi and bacteria, have been widely reported as potential biological control agents against plant pests and diseases[21]. Despite the generally positive trends, this study has several limitations. First, the experiment was conducted under greenhouse conditions, which may not fully represent field environments where biotic and abiotic stresses are more promotion and disease suppression was inferred from phenotypic observations without molecular or biochemical validation. Third, yield responses were variable and not statistically significant, suggesting that longer experimental periods or larger sample sizes may be required.

Future research should focus on field-scale evaluations to assess the consistency of PGPR performance under natural conditions and investigate the molecular mechanisms involved in plant-microbe-pathogen interactions. In addition, combining compatible bacterial strains and optimizing inoculum concentrations may further enhance the effectiveness of biological control strategies against *Fusarium* wilt in chili cultivation.

CONCLUSION

The application of antagonistic bacteria significantly influenced several growth parameters of chili plants, particularly plant height and leaf number at 70 and 110 days after planting. Among all treatments, *Pseudomonas fluorescens* at 10^8 CFU/mL (P9) and *Acetobacter xylinum* at 10^6 CFU/mL (P1) produced the best results in enhancing plant height, leaf number, and fruit yield compared to the control. These findings suggest that the use of antagonistic bacteria can effectively promote chili plant growth and serve as a potential biological agent for managing *Fusarium* wilt disease.

SIGNIFICANCE STATEMENT

This study highlights the potential of antagonistic bacteria, specifically *Pseudomonas fluorescens* and *Acetobacter xylinum*, as effective biocontrol agents against *Fusarium* wilt in chili pepper. By significantly improving plant height and leaf development, these eco-friendly alternatives to chemical fungicides support sustainable agriculture, offering a viable strategy to enhance crop resilience and productivity while reducing environmental impact.

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