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PGPM Tablets: A Sustainable Solution for Managing Foot Rot Disease in Black Pepper

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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ABSTRACT

Black pepper holds significant importance as a spice crop in Kerala, a state often referred to as the "Land of Spices" for its substantial contribution to India's economy through exports. *Phytophthora* foot rot poses a significant challenge in nurseries across the black pepper-growing regions of

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Kerala, leading to substantial economic losses for farmers. A study was undertaken to develop and evaluate a tablet formulation of Plant Growth Promoting Microbes (PGPM) and other biocontrol agents for promoting growth and managing foot rot disease in black pepper (*Piper nigrum* L.). The findings revealed that the PGPM tablet formulation, along with the liquid formulation of *Trichoderma* (KAU), emerged as the most effective treatments for suppressing foot rot. Biometric analysis showed that plants treated with the PGPM tablet (*Bacillus cereus*., *Trichoderma* spp.) formulation recorded the greatest plant height, number of nodes, and leaves, performing on par with the talc-based PGPM formulation. Soil microbial analysis, conducted before and after treatment using serial dilution and plating techniques, indicated that the PGPM tablet consistently supported the highest counts of viable fungi, bacteria, and actinomycetes in the soil. Thus, the tablet formulation of PGPM emerged as the most effective treatment for promoting growth and managing *Phytophthora* disease in black pepper, showcasing its potential as a promising solution for sustainable crop health and productivity.

Keywords: Tablet; PGPM; Trichoderma; foot rot.

1. INTRODUCTION

The cultivation of black pepper (*Piper nigrum* L.) holds a pivotal role in the agricultural economies of many tropical regions, contributing significantly to the global spice market.). India holds a prominent position in the global spice market, contributing substantially to the production, consumption, and export of black pepper. The cultivation of black pepper in India is highly significant, with the crop being cultivated over an extensive area of approximately 278,050 hectares, yielding an annual production of 64,000 tonnes (Spices Board, 2024). However, black pepper cultivation faces substantial challenges due to diseases such as foot rot, primarily caused by *Phytophthora capsici*. This soil-borne pathogen leads to severe yield losses and compromises the quality of the produce (Sarma, 2003; Nair and Gupta, 2003; Krishnamoorthy and Parthasarathy, 2011). Traditional management practices largely rely on chemical fungicides, which, despite their effectiveness, present environmental and health concerns. To prevent foot rot, the use of fungicides such as metalaxyl, phosphonates, and copper-based compounds is recommended (KAU, 2011; Anandaraj, 2000). Moreover, repeated application of systemic fungicide like metalaxyl has resulted in evolution of insensitivity to metalaxyl which has been widely observed in *P. capsici* (Parra et al., 2001; Silvar et al., 2006; Wang et al., 2021). Therefore, there is an increasing need for sustainable and eco-friendly alternatives. Plant Growth-Promoting Microorganisms (PGPM) have emerged as a promising solution, offering benefits that extend beyond disease control. These beneficial microbes enhance plant growth by improving nutrient uptake, inducing resistance to pathogens, and promoting root development. Recent advancements have focused on developing various formulations of PGPM to enhance their application and effectiveness.

This research paper aims to evaluate the efficacy of a tablet formulation of PGPM for growth promotion and the management of foot rot in black pepper. Specifically, the study investigates the impact of this formulation on the percent disease incidence (PDI) and biometric parameters of black pepper plants. The objective is to provide a sustainable and effective alternative to chemical fungicides, aligning with the global push towards greener agricultural practices.

2. MATERIALS AND METHODS

A pot culture experiment was laid out to test the biocontrol efficacy of tablet formulation of PGPM which includes *Bacillus cereus* and *Trichoderma* spp. (Fig. 1.) against *Phytophthora capsici* causing foot rot of black pepper during July – August 2024 at College of Agriculture, Vellanikkara. The study was laid out in a Completely Randomized Design (CRD) using the black pepper variety *Panniyur-1*. A total of nine treatments were tested, each replicated three times, with 25 cuttings per replication. Treatments were applied to black pepper cuttings as foliar spray and soil drench in polybags at 120 Days after Planting (120 DAP). Thereafter, the polybags were challenge inoculated with the pathogen, *Phytophthora capsici* 15 days after treatment (135 DAP) application. On symptom appearance (Fig. 2), treatments were applied thrice as soil and foliar application at 10 days interval.

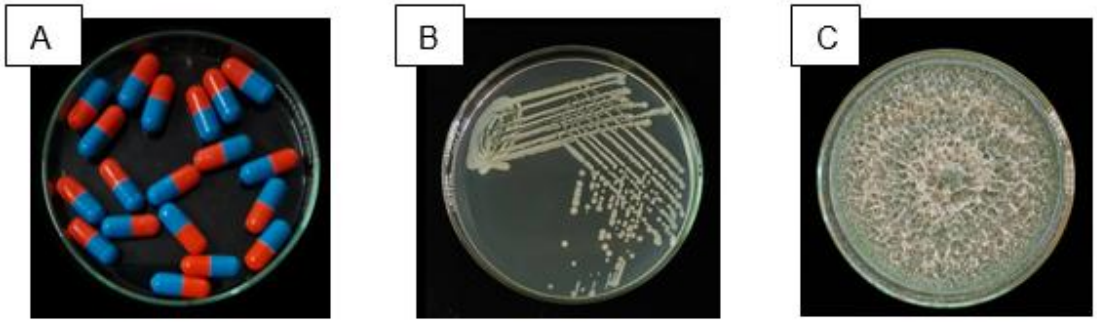

Fig. 1. Tablet formulation of PGPM (A), *Bacillus cereus* (B), *Trichoderma* spp. (C)

Table 1. Score chart for severity of *Phytophthora* foot rot in black pepper

Score	Description
0	Healthy plants (0 per cent infection)
1	Plants with 1-10 per cent infection
2	Plants with11-25per cent infection
3	Plants with 25-50per cent infection
4	Plants with 50-75per cent infection
5	Plants with more than75per cent infection

Treatment details: T_1: Tablet of PGPM ($x10^6$ cfu g-1), T_2: Talc formulation of PGPM (2%) (KAU strain), T_3: Talc formulation of *Trichoderma* (2%) (KAU strain), T_4: Talc formulation of *Pseudomonas* (2%) (KAU strain), T_5: Liquid formulation of *Trichoderma* (0.5%) (KAU strain), T_6: Liquid formulation of *Pseudomonas* (0.5%) (KAU strain), T_7: Copper oxychloride (0.25%), T_8: Control, T_9: Absolute control

Phytophthora isolated from black pepper was mass multiplied in soil. For this the soil was sterilized by autoclaving at 121°C and 15 psi pressure for 2 h. The sterilized soil then mixed with black pepper leaves in a tray surface sterilized with alcohol and 10 mm mycelial discs of *Phytophthora* was inoculated into the mixture and incubated for 10 days before challenge inoculation. Thereafter the plants were challenge inoculated with mass multiplied *Phytophthora* @ 5 g per bag.

The biometric observations on the plant such as number of leaves, plant height, number of nodes at 120, 135,145,155 and 165 DAP were recorded to check whether the treatments have any impact on plant growth.

Incidence of *Phytophthora* foot rot in the pot culture experiment was recorded frequently after one week of challenge inoculation and the per cent disease incidence was calculated by adopting the formula given by Wheeler (1969). Each plant was checked for the foot rot disease severity at seven days after challenge inoculation with *Phytophthora capsici* based on a score chart from 0-5 (Jibat et al., 2023) as shown in Table 1. Per cent disease severity was calculated using the formula suggested by James (1971). Observations were taken before treatment applications.

$$\text{Per cent disease severity} = \frac{\text{Sum of all numerical ratings x 100}}{\text{No. of leaves assessed x Maximum disease score}}$$

Microbial population in soil l in every treatment was estimated at 120,135,145 and 155 Days After Planting (DAP). The soil was serially diluted and plating was done by pour plate method to estimate the population of fungi, actinomycetes and bacteria.

Data obtained from *in vivo* studies were undergone analysis of variance (ANOVA) by using Wasp 2 and GRAPES software after appropriate transformations wherever needed. Critical difference (CD) values were calculated for each observation in significant treatments using t' values at 5 per cent level of significance and the significance of the treatments was compared with CD values (Gomez and Gomez, 1984).

Fig. 2. Symptoms of foot rot in black pepper

3. RESULTS AND DISCUSSION

3.1 Per cent Disease Incidence and Per cent Disease Severity

The study evaluated the percent disease incidence (PDI) of foot rot in black pepper under different treatments at 145, 155, and 165 days after planting (DAP). The results (Table 2) revealed that the tablet formulation of PGPM (T_1) and the liquid formulation of *Trichoderma* (T_5) were the most effective treatments, as there was no incidence throughout the study period. These treatments completely controlled foot rot, highlighting their superior efficacy. In contrast, the untreated control (T_8) was noticed with high disease progression, with PDI increasing significantly from 41.33 per cent at 145 DAP to 72.00 per cent at 165 DAP, emphasizing the importance of effective interventions.

Moderate control of the disease was observed with the talc formulation of PGPM (T_2) and *Trichoderma* (T_3), which reduced PDI from 5.33 per cent at 145 DAP to 1.33 per cent at 165 DAP. The talc formulation of *Pseudomonas* (T_4) maintained a consistent PDI of 1.33 per cent across all intervals, showing limited but stable disease suppression. The liquid formulation of *Pseudomonas* (T_6) exhibited partial control, with disease incidence decreasing from 8.00 per cent at 145 DAP to 2.67 per cent at 165 DAP. The chemical treatment copper oxychloride (T_7) initially showed 4.00 per cent disease incidence at 145 DAP and thereafter no incidence of foot rot was observed at 165 DAP, indicating effectiveness over time.

The data highlights that T_1 (tablet formulation of PGPM) and T_5 (liquid formulation of *Trichoderma*) were the most effective treatments, significantly reducing disease incidence compared to all other formulations. The moderate efficacy of T_2 (talc formulation of PGPM), T_3 (talc formulation of *Trichoderma*), and T_4 (talc formulation of *Pseudomonas*) suggests their potential but underscores the superiority of the tablet and liquid formulations of PGPM and *Trichoderma*. Overall, the study demonstrates the potential of bioformulations, particularly PGPM tablets and liquid formulation of *Trichoderma*, as effective and sustainable options for managing foot rot in black pepper.

The study (Table 3) assessed the effectiveness of various treatments in reducing the per cent disease severity (PDS) of foot rot in black pepper at 145, 155, and 165 days after planting (DAP). Among the treatments, T_1 (tablet of PGPM) and T_5 (liquid formulation of *Trichoderma*) showed remarkable efficacy indicating their strong potential for disease suppression. T_2 (talc formulation of PGPM) and T_4 (talc formulation of *Pseudomonas*) displayed moderate effectiveness, with PDS decreasing over time to 2.50 per cent and 1.48 per cent, respectively, at 165 DAP. Similarly, T_3 (talc formulation of *Trichoderma*) showed a gradual reduction in PDS from 6.25% at 145 DAP to 3.91% at 165 DAP, although it was less effective compared to T_1 and T_2.

T_6 (liquid formulation of *Pseudomonas*) showed limited disease suppression, with PDS remaining relatively high across all intervals (7.26%, 7.26%, and 6.82%). The chemical treatment, T_7 (copper oxychloride), was effective in controlling disease by 165 DAP, where the PDS reached 0.00%, but its performance at earlier stages was less satisfactory. The untreated control (T_8) recorded the highest PDS values, progressively increasing from 24.91% at 145 DAP to 37.08% at 165 DAP, highlighting the severity of the disease in the absence of any treatment.

Rajan et al. (2002) documented a substantial decline in foot rot disease incidence in black

pepper during a three-year field trial. Out of the five *Trichoderma* isolates evaluated, *Trichoderma virens*-12 and *Trichoderma harzianum*-26 emerged as the most effective in disease control. Notably, *Trichoderma harzianum*-26 demonstrated exceptional adaptability to the black pepper rhizosphere, establishing itself as a highly suitable option for sustainable management of the disease. The findings of Rini and Remya (2020) highlight the effectiveness of a talc-based formulation of a PGPM mix in managing *Phytophthora* foot rot in black pepper. When applied both to the rhizosphere soil and as a foliar spray, the PGPM mix offered superior protection against the pathogen compared to conventional chemical fungicides.

In a related study, Amalraj et al. (2010) highlighted the potential of *Trichoderma* species in thriving under extreme environmental conditions, attributing their effectiveness to robust rhizosphere competence and competitive saprophytic ability. These traits enable *Trichoderma* to shield plants from abiotic stresses effectively. Similarly, Jisha et al. (2002) demonstrated that *Trichoderma harzianum* and *Pseudomonas fluorescens* (IISR-6) not only enhanced the growth and vigor of black pepper plants but also suppressed soil-borne fungal pathogens in field conditions. These findings align closely with the results of the present study, further reinforcing the role of such bioagents in sustainable crop management.

Table 2. Effect of different treatments on PDI

Treatments	PDI		
	145 DAP	155 DAP	165 DAP
T_1: Tablet of PGPM (×10⁶ cfu g⁻¹)	0.00^{c}	0.00^{b}	0.00^{b}
T_2: Talc formulation of PGPM (2%) (KAU)	5.33^{bc}	2.67^{b}	1.33^{b}
T_3: Talc formulation of *Trichoderma* (2%) (KAU)	5.33^{bc}	4.00^{b}	1.33^{b}
T_4: Talc formulation of *Pseudomonas* (2%) (KAU)	1.33^{bc}	1.33^{b}	1.33^{b}
T_5: Liquid formulation of *Trichoderma* (0.5%) (KAU)	0.00^{c}	0.00^{b}	0.00^{b}
T_6: Liquid formulation of *Pseudomonas* (0.5%) (KAU)	8.00^{b}	2.67^{b}	2.67^{b}
T_7: Copper oxychloride (0.25%)	4.00^{bc}	1.33^{b}	0.00^{b}
T_8: Control	41.33^{a}	54.67^{a}	72.00^{a}
T_9: Absolute control	0.00^{c}	0.00^{b}	0.00^{b}
CD (0.05)	7.70	5.44	5.27

DAP – Days after planting

** Mean of three replications. In each column figure followed by same superscript do not significantly differ according to DMRT*

Table 3. Effect of different treatments on PDS

Treatments	PDS		
	145 DAP	155 DAP	165 DAP
T_1: Tablet of PGPM (x10⁶ cfu g⁻¹)	0.00^{b}	0.00^{c}	0.00^{c}
T_2: Talc formulation of PGPM (2%) (KAU)	4.17^{b}	2.86^{bc}	2.50^{bc}
T_3: Talc formulation of *Trichoderma* (2%) (KAU)	6.25^{b}	4.62^{b}	3.91^{bc}
T_4: Talc formulation of *Pseudomonas* (2%) (KAU)	2.67^{b}	2.00^{b}	1.48^{bc}
T_5: Liquid formulation of *Trichoderma* (0.5%) (KAU)	0.00^{b}	0.00^{b}	0.00^{c}
T_6: Liquid formulation of *Pseudomonas* (0.5%) (KAU)	7.26^{b}	7.26^{b}	6.82^{b}
T_7: Copper oxychloride (0.25%)	1.33^{b}	1.33^{b}	0.00^{c}
T_8: Control	24.91^{a}	34.38^{a}	37.08^{a}
T_9: Absolute control	0.00^{b}	0.00^{b}	0.00^{c}
CD (0.05)	8.14	6.68	6.09

DAP – Days after planting

** Mean of three replications. In each column figure followed by same superscript do not significantly differ according to DMRT*

Table 4. Effect of different treatments on plant height of black pepper cuttings

Treatments	Plant height (cm)				
	120 DAP	135 DAP	145 DAP	155 DAP	165 DAP
T_1	35.9^{a}	57.33^{a}	74.66^{a}	98.57^{a}	126.9^{a}
T_2	35.4^{a}	53.25^{b}	69.3^{b}	90.70^{b}	118.26^{b}
T_3	34.47^{ab}	50.28^{b}	60.74^{d}	79.88^{c}	96.90^{d}
T_4	32.67^{b}	48.44^{d}	55.05^{e}	70.7^{d}	83.89^{e}
T_5	35.49^{a}	52.33^{b}	63.89^{c}	81.62^{d}	105.52^{c}
T_6	32.2^{b}	44.90^{e}	51.87^{fg}	70.03^{d}	78.27^{f}
T_7	35.32^{a}	42.29^{f}	52.40^{f}	56.75^{e}	67.66^{g}
T_8	35.33^{a}	41.83^{f}	50.09^{gh}	49.67^{f}	65.57^{gh}
T_9	32.33^{b}	40.93^{f}	48.6^{h}	46.97^{f}	62.27^{h}
CD (0.05)	2.31	1.54	2.12	2.96	3.65

DAP :Days after planting

T_1- Tablet of PGPM (x10^6 cfu g $^{-1}$); T_2- Talc formulation of PGPM (2%) (KAU); T_3- Talc formulation of Trichoderma (2%) (KAU); T_4- Talc formulation of Pseudomonas (2%) (KAU); T_5- Liquid formulation of Trichoderma (0.5%) (KAU); T_6- Liquid formulation of Pseudomonas (0.5%) (KAU); T_7- Copper oxychloride (0.25%); T_8- (control) ; T_9- Absolute control

**Mean of three replications. In each column figure followed by same superscript do not differ significantly according to DMRT*

Table 5. Effect of different treatments on number of leaves of black pepper cuttings

Treatments	Number of leaves				
	120 DAP	135 DAP	145 DAP	155 DAP	165 DAP
T_1	4.22	8.56^{a}	12.00^{a}	13.56^{a}	17.67^{a}
T_2	4.45	7.33^{ab}	11.56^{a}	13.67^{a}	16.33^{b}
T_3	4.11	6.22^{bcd}	9.00^{cd}	11.11^{b}	15.22^{bc}
T_4	4.11	5.89^{cd}	8.67^{de}	9.89^{c}	12.44^{d}
T_5	3.56	6.45^{bc}	10.1^{b}	11.33^{b}	15.33^{bc}
T_6	3.78	6.22^{bcd}	9.78^{bc}	10.33^{c}	15.00^{c}
T_7	4.22	5.1^{cde}	7.22^{f}	7.89^{de}	12.55^{d}
T_8	4.00	4.89^{de}	7.89^{f}	8.22^{d}	11.55^{d}
T_9	3.33	4.22^{e}	7.11^{f}	7.44^{e}	9.33^{e}
CD (0.05)	NS	1.34	0.97	0.71	1.31

DAP:Days after planting

T_1- Tablet of PGPM (x10^6 cfu g $^{-1}$); T_2- Talc formulation of PGPM (2%) (KAU); T_3- Talc formulation of Trichoderma (2%) (KAU); T_4- Talc formulation of Pseudomonas (2%) (KAU); T_5- Liquid formulation of Trichoderma (0.5%) (KAU); T_6- Liquid formulation of Pseudomonas (0.5%) (KAU); T_7- Copper oxychloride (0.25%); T_8- (control); T_9- Absolute control

**Mean of three replications. In each column figure followed by same superscript do not differ significantly according to DMRT*

3.2 Biometric Characters of Black Pepper under Different Treatment Conditions

The plant height (Table 4) of black pepper was recorded at five intervals *viz*., 120, 135, 145, 155, and 165 days after planting (DAP) so as to evaluate the effects of different treatments. Among all treatments, T_1 (tablet of PGPM) consistently showed the highest plant height across all intervals, with values of 35.9 cm at 120 DAP, increasing to 126.9 cm at 165 DAP. This indicates its superior efficacy in promoting plant growth. T_2 (talc formulation of PGPM) ranked second, demonstrating a steady increase in plant height from 35.4 cm at 120 DAP to 118.26 cm at 165 DAP. T_5 (liquid formulation of *Trichoderma*) also exhibited significant growth enhancement, with plant height reaching 105.52 cm at 165 DAP, although it was slightly less effective than T_1 and T_2. In comparison, T_3 (talc formulation of *Trichoderma*) resulted in moderate growth, with plant height progressing to 96.90 cm by 165 DAP. Similarly, T_4 (talc formulation of *Pseudomonas*) and T_6 (liquid formulation of *Pseudomonas*) were less effective, recording plant heights of 83.89 cm and 78.27 cm, respectively, at 165 DAP. The chemical treatment, T_7 (copper oxychloride), resulted in

limited plant growth, with plant height increasing modestly from 35.32 cm at 120 DAP to 67.66 cm at 165 DAP. The untreated controls, T_8 (control) and T_9 (absolute control), showed the least plant height at all intervals, with T_9 recording the lowest height of 62.27 cm at 165 DAP.

The number of leaves (Table 5) in black pepper plants was recorded at five intervals (120, 135, 145, 155, and 165 DAP) under various treatments. At 120 DAP, there was no significant difference in the number of leaves across treatments. However, from 135 DAP onwards, the differences became apparent. T_1 (tablet of PGPM) consistently showed the highest leaf count across all intervals, reaching 17.67 leaves at 165 DAP, followed closely by T_2 (talc formulation of PGPM), which recorded 16.33 leaves at the same time. These results highlight the superior efficacy of these PGPM-based formulations in promoting leaf production. Among the other treatments, T_3 (talc formulation of *Trichoderma*) and T_5 (liquid formulation of *Trichoderma*) performed moderately well, with leaf counts of 15.22 and 15.33, respectively, at 165 DAP. T_4 (talc formulation of *Pseudomonas*) and T_6 (liquid formulation of *Pseudomonas*) were less effective, recording 12.44 and 15.00 leaves, respectively, by 165 DAP. Chemical treatment with T_7 (copper oxychloride) resulted in limited leaf production, with 12.55 leaves at 165 DAP. The untreated controls, T_8 (control) and T_9 (absolute control), recorded the lowest leaf counts, with T_9 being the least productive, having only 9.33 leaves at 165 DAP.

The number of nodes (Table 6) in black pepper plants was recorded at 120, 135, 145, 155, and 165 days after planting (DAP) across various treatments. T_1 (tablet of PGPM) consistently recorded the highest number of nodes across all intervals, reaching 18.33 nodes at 165 DAP. T_2 (talc formulation of PGPM) closely followed, recording 17.56 nodes at 165 DAP, demonstrating the superior ability of PGPM-based formulations to enhance node production. Among the biological formulations, T_3 (talc formulation of *Trichoderma*) and T_5 (liquid formulation of *Trichoderma*) exhibited moderate effectiveness, producing 15.56 and 15.78 nodes, respectively, by 165 DAP. In contrast, T_4 (talc formulation of *Pseudomonas*) and T_6 (liquid formulation of *Pseudomonas*) were comparatively less effective, with 12.78 and 15.22 nodes, respectively, at the same interval. T_7 (copper oxychloride), a chemical treatment, resulted in significantly lower node counts, with only 11.78 nodes at 165 DAP. The untreated controls, T_8 (control) and T_9 (absolute control), recorded the lowest node numbers, with T_9 producing the least, at just 9.89 nodes by 165 DAP.

Sidorenko et al. (1996) demonstrated that the combined inoculation of *Azotobacter*, *Bacillus*, and *Pseudomonas* significantly enhanced plant height, biomass, and tuber yield in potatoes. Burelle et al. (2002) reported that field trials with various PGPR formulations, including LS213 (*Bacillus subtilis* strain GBO3 + *B. amyloliquefaciens* strain IN937a), LS254 (*B. subtilis* strain GBO3 + *B. pumilus* strain SE34), LS255 (*B. subtilis* strain GBO3 + *B. subtilis* strain IN937b), LS256 (*B. subtilis* strain GBO3 + *B. pumilus* strain INR7), and LS261 (*B. subtilis* strain GBO3 + *B. cereus* strain C4), significantly enhanced the growth and yield of tomatoes and peppers. Similarly, Karunakaran et al. (2003) observed that under glasshouse conditions, the combinations of *Pseudomonas fluorescens* + *Bacillus subtilis* and *P. fluorescens* + *Trichoderma viride* were the most effective treatments. At 90 days after planting (DAP), Vithya et al. (2018) reported significant variations in growth parameters of black pepper plants under different treatments. The application of PGPR Mix-II (T_8, KAU reference culture) resulted in the tallest plants, with a maximum height of 25.5 cm. This was closely followed by treatments with fluorescent pseudomonads T_4 (PAP isolate) and T_6 (*Pseudomonas fluorescens*, KAU reference culture) which recorded plant heights of 22.6 cm and 21.5 cm, respectively, both statistically comparable to T_8. In terms of foliage development, T_8 also achieved the highest number of leaves at 90 DAP, with T_4 ranking second. Similarly, the number of nodes per plant followed the same trend, with T_8 recording the highest node count (4.2), followed by T_4 (3.6). These findings highlight the effectiveness of PGPR Mix-II in promoting vegetative growth in black pepper, surpassing other treatments in terms of plant height, leaf production, and node development, aligning well with the present study's results.

Table 6. Effect of different treatments on number of nodes of black pepper cuttings

Treatments	Number of nodes				
	120 DAP	135 DAP	145 DAP	155 DAP	165 DAP
T_1	4.45^{a}	8.78^{a}	12.22^{a}	15.00^{a}	18.33^{a}
T_2	4.67^{a}	7.89^{a}	12.56^{a}	13.78^{b}	17.56^{b}
T_3	4.22^{a}	6.11^{bc}	9.11^{cd}	11.67^{c}	15.56^{c}
T_4	4.44^{a}	6.56^{b}	9.33^{c}	10.78^{d}	12.78^{e}
T_5	3.78^{a}	6.45^{b}	10.55^{b}	11.56^{cd}	15.78^{c}
T_6	3.89^{a}	6.22^{bc}	10.00^{bc}	10.33^{e}	15.22^{d}
T_7	4.33^{a}	5.33^{bcd}	7.44^{e}	8.22^{g}	11.78^{g}
T_8	4.22^{a}	5.11^{cd}	8.22^{de}	8.78^{f}	12.22^{f}
T_9	2.11^{b}	4.44^{d}	7.44^{e}	7.78^{g}	9.89^{h}
CD (0.05)	1.41	1.30	0.98	0.31	0.31

DAP:Days after planting

T_1- Tablet of PGPM (x10^6 cfu g $^{-1}$); T_2- Talc formulation of PGPM (2%) (KAU); T_3- Talc formulation of Trichoderma (2%) (KAU); T_4- Talc formulation of Pseudomonas (2%) (KAU); T_5- Liquid formulation of Trichoderma (0.5%) (KAU); T_6- Liquid formulation of Pseudomonas (0.5%) (KAU); T_7- Copper oxychloride (0.25%); T_8- (control) ; T_9- Absolute control

**Mean of three replications. In each column figure followed by same superscript do not differ significantly according to DMRT*

3.3 Effect of Different Treatments on Soil Microbial Count

The microbial population dynamics (Table 7) at 120, 135, 145, and 155 DAP varied significantly across the treatments. At 120 DAP, T_9 (Absolute control) recorded the highest fungal population (12.50 × 10^3 cfu ml^{-1}), whereas T_3 (Talc formulation of *Trichoderma*) showed the highest bacterial count (14.00 × 10^8 cfu ml^{-1}). Actinomycetes were most abundant in T_4 (Talc formulation of *Pseudomonas*) with 12.50 × 10^5 cfu ml^{-1}. By 135 DAP, fungal populations peaked in T_1 (Tablet of PGPM) at 31.00 × 10^3 cfu ml^{-1}, followed closely by T_2 (Talc formulation of PGPM) at 29.00 × 10^3 cfu ml^{-1}. T_1 also exhibited the highest bacterial count (29.50 × 10^8 cfu ml^{-1}), with T_4 retaining the lead in actinomycete populations (8.00 × 10^5 cfu ml^{-1}). At 145 DAP, T_1 maintained the highest fungal population (57.00 × 10^3 cfu ml^{-1}) and bacterial count (44.00 × 10^8 cfu ml^{-1}), while actinomycetes were most abundant in T_3 (11.00 × 10^5 cfu ml^{-1}). T_2 also performed well with fungal and bacterial populations of 54.50 × 10^3 cfu ml^{-1} and 41.50 × 10^8 cfu ml^{-1}, respectively. By 155 DAP, T_1 recorded the highest microbial populations across fungi, bacteria, and actinomycetes, with values of 62.50 × 10^3 cfu ml^{-1}, 88.50 × 10^8 cfu ml^{-1}, and 3.00 × 10^5 cfu ml^{-1}, respectively. T_2 followed closely in fungal and bacterial counts (54.50 × 10^3 cfu ml^{-1} and 51.50 × 10^8 cfu ml^{-1}), while treatments like T_6, T_7, and T_8 showed limited microbial activity. T_9 consistently exhibited minimal or no microbial populations throughout the study period. Overall, the PGPM formulations, particularly T_1 and T_2, demonstrated a sustained capacity to support robust microbial populations across all time points.

These findings are in alignment with the study by Haritha (2013), which evaluated bio-inoculant consortia for the organic cultivation of ginger. Haritha's research highlighted the efficacy of T_8, a consortia treatment comprising KAU-AZO, KAU-PSB, KAU-KSB, and KAU-TV, which achieved the highest microbial population of 28.3 × 10^6 cfu/g. This demonstrates the significant potential of bio-inoculant consortia in enhancing soil microbial activity and nutrient availability.

Additionally, the study by Li et al. (2023) reinforces the importance of microbial inoculants. Their findings revealed that high dosages of bio-fertilizers significantly improved soil microbial biomass carbon, bacterial biodiversity, and soil health index compared to organic and chemical fertilizers. These results underline the ability of bio-fertilizers to promote the proliferation of beneficial microorganisms, which play a critical role in nutrient cycling, organic matter decomposition, and maintaining a balanced soil ecosystem.

Together, the current study, Haritha (2013), and Li et al. (2023) emphasize the efficacy of microbial inoculants in enhancing microbial

Table 7. Effect of different treatments on soil microbial count

Treatments	Population of microbes (cfu ml^{-1})											
	120 DAP			135 DAP			145 DAP			155 DAP		
	Fungi (x10^3)	Bacteria (x10^8)	Actinomycetes (x10^5)	Fungi (x10^3)	Bacteria (x10^8)	Actinomycetes (x10^5)	Fungi (x10^3)	Bacteria (x10^8)	Actinomycetes (x10^5)	Fungi (x10^3)	Bacteria (x10^8)	Actinomycetes (x10^5)
T_1	6.50^{d} (0.874)	7.00^{e} (0.900)	8.50^{bc} (0.977)	31.00^{a} (1.763)	29.50^{a} (1.484)	8.50^{a} (0.977)	57.00^{a} (1.505)	44.00^{a} (1.653)	10.50^{a} (1.060)	62.50^{a} (1.802)	88.50^{a} (1.952)	3.00^{a} (0.588)
T_2	11.00^{abc} (1.078)	11.50^{bc} (1.097)	11.00^{ab} (1.078)	29.00^{ab} (1.744)	25.50^{b} (1.423)	7.50^{ab} (0.929)	54.50^{a} (1.477)	41.50^{a} (1.628)	7.50^{bc} (0.929)	54.50^{b} (1.744)	51.50^{b} (1.720)	0.00^{a} (0.000)
T_3	12.00^{ab} (1.113)	14.00^{a} (1.176)	9.50^{abc} (1.017)	27.00^{b} (1.518)	16.50^{d} (1.241)	6.50^{bc} (0.874)	45.00^{b} (1.446)	17.50^{c} (1.266)	11.00^{a} (1.078)	33.50^{c} (1.536)	14.00^{e} (1.175)	0.00^{b} (0.000)
T_4	10.00^{bc} (1.040)	12.50^{ab} (1.130)	12.50^{a} (1.130)	22.50^{c} (1.663)	21.00^{c} (1.342)	8.00^{ab} (0.952)	32.00^{d} (1.370)	25.00^{b} (1.415)	8.00^{b} (0.952)	29.00^{cd} (1.477)	35.00^{c} (1.556)	0.00^{b} (0.000)
T_5	9.50^{c} (1.021)	10.50^{cd} (1.060)	11.00^{ab} (1.078)	16.50^{d} (1.398)	13.00^{e} (1.146)	5.50^{c} (0.812)	40.50^{c} (1.241)	6.00^{d} (0.841)	7.00^{bcd} (0.900)	26.00^{d} (1.431)	7.50^{f} (0.929)	1.00^{b} (0.301)
T_6	11.00^{abc} (1.078)	5.50^{e} (0.812)	3.00^{d} (0.588)	14.00^{d} (1.618)	25.00^{b} (1.415)	3.50^{d} (0.651)	24.00^{e} (1.175)	26.00^{b} (1.431)	5.50^{cde} (0.812)	4.50^{f} (0.739)	27.00^{d} (1.446)	0.00^{b} (0.000)
T_7	13.00^{a} (1.146)	9.00^{d} (0.988)	7.00^{c} (0.900)	9.50^{e} (1.000)	4.50^{f} (0.739)	5.50^{c} (0.812)	9.00^{f} (1.021)	4.00^{d} (0.699)	5.00^{de} (0.778)	8.50^{e} (0.972)	2.00^{g} (0.452)	0.00^{b} (0.000)
T_8	12.50^{a} (1.130)	6.50^{e} (0.874)	6.75^{c} (0.870)	7.00^{e} (1.078)	4.00^{f} (0.699)	6.50^{bc} (0.874)	11.00^{f} (0.900)	3.00^{de} (0.540)	4.00^{e} (0.699)	4.50^{ef} (0.739)	1.00^{g} (0.301)	3.00^{a} (0.602)
T_9	0.00^{e} (0.000)	0.00^{f} (0.000)	0.00^{d} (0.000)	0.00^{f} (0.000)	0.00^{g} (0.000)	0.00^{e} (0.000)	0.00^{g} (0.000)	0.00^{e} (0.000)	0.00^{f} (0.000)	0.00^{f} (0.000)	0.00^{g} (0.000)	0.00^{b} (0.000)
CD (0.05)	2.32	1.92	3.66	3.81	3.20	1.77	3.06	3.67	2.06	5.17	4.23	1.06

DAP – Days after planting

T_1- Tablet of PGPM (x10^6 cfu g^{-1}); T_2- Talc formulation of PGPM (2%) (KAU); T_3- Talc formulation of Trichoderma (2%) (KAU); T_4- Talc formulation of Pseudomonas (2%) (KAU); T_5- Liquid formulation of Trichoderma (0.5%) (KAU); T_6- Liquid formulation of Pseudomonas (0.5%) (KAU); T_7- Copper oxychloride (0.25%); T_8- (control) ; T_9- Absolute control

**Mean of three replications.Log transformed values are given in the replication. In each column figure followed by same superscript do not differ significantly according to DMRT*

populations and soil health. They also highlight the potential of bio-fertilizers and microbial consortia as environmentally sustainable alternatives to traditional chemical fertilizers for improving soil fertility and crop productivity. These findings advocate for the integration of such biologically based strategies in sustainable agricultural practices (Anonymous, 2024).

4. CONCLUSION

Based on the results of the pot culture experiments, the tablet formulation of Plant Growth-Promoting Microorganisms (PGPM) emerged as the most effective treatment for enhancing growth and managing *Phytophthora* disease in black pepper. This formulation demonstrated considerable potential as a sustainable alternative to chemical fungicides, supporting the growing demand for environmentally friendly agricultural practices.

To further confirm its applicability, multi-locational field trials should be conducted across various crops and agro-climatic zones. These trials will provide insights into its effectiveness against diverse diseases and under different farming conditions. Additionally, long-term studies focusing on its effects on soil health, microbial diversity, and crop productivity are essential to understand its broader implications in agriculture.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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