Theme: Sustainable Agricultural Innovations for One Health and Environmental Resilience

RESEARCH ARTICLE Indian Journal of Agricultural Research, Volume 60 Special Issue: 32-38 (2026)

Growth Promotion and Biological Control of Fungal Dry Rot in Potato by Potential *Bacillus* Rhizobacterium

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10.18805/IJARe.A-6631

ABSTRACT

Background: Dry rot of potato (*Solanum tuberosum* L.) is often caused by *Fusarium sambucinum* and is a major factor accounting for loss of productivity of this economically important food crop. Repeated use of synthetic fungicides has led to worries about pollution risk and emergence of fungicide resistant populations of the pathogen, underscoring the importance of using biological methods as alternatives to chemistry. Both *Bacillus subtilis* MGM123 and its lipopeptides were tested in the present study for management of potato dry rot disease condition under green house.

Methods: A greenhouse experiment was conducted during 2025-2026 using potato variety Kufri Khyati in a completely randomized design with seven treatments comprising untreated control, *F. sambucinum*, *B. subtilis* MGM123, *Fusarium* + *Bacillus*, *Fusarium* + *Trichoderma*, *Fusarium* + Mancozeb and *Fusarium* + lipopeptides. Vegetative growth, defence-related enzymes (PAL, POD and PPO), total chlorophyll content, disease severity index (DSI) and tuber yield were recorded. Data were analysed using analysis of variance and treatment means were separated by Tukey's HSD test at $P \leq 0.05$.

Result: Significant differences were observed among treatments for vegetative growth, defence-related biochemical responses, disease severity and tuber yield. *Bacillus subtilis* MGM123 recorded the highest plant height (64.01 cm), shoot length (13.09 cm), root length (14.91 cm) and tuber yield (140.00 g plant^{-1}). Among the pathogen-challenged treatments, lipopeptides effectively reduced disease severity from a Disease Severity Index (DSI) of 4.67 in pathogen-inoculated plants to 1.67 at 28 DAT while increasing tuber yield to 129.00 g plant^{-1}. Biological treatments also enhanced phenylalanine ammonia-lyase (PAL), polyphenol oxidase (PPO) and peroxidase (POD) activities and maintained higher chlorophyll content than the pathogen-inoculated treatment. These findings demonstrate that *B. subtilis* MGM123 and its lipopeptides are promising environment-friendly alternatives to chemical fungicides for the sustainable management of potato dry rot.

Key words: *Bacillus subtilis*, Biological control, Defence enzymes, *Fusarium sambucinum*, Lipopeptides, Potato, Tuber yield.

INTRODUCTION

Potato (*Solanum tuberosum* L.) is one of the significant food crops following rice and wheat in terms of contribution for food and nutritional security around the world due to its high productivity, nutritive value and broad adaptability. Potato is the second most important crop in India besides that it has significant contribution to farm income as well as in vegetable processing industry. Potato cultivation is often faced with a number of biological threats including fungal diseases that contribute significantly to losses of yield, quality and storage life. *Fusarium sambucinum* is one of the most serious diseases with potato seed and storage tubers. The pathogen attacks the wounds of tubers and growing sprouts, causing decay and leading to sub-optimal sprouting, decreased establishment and decline in tub quality for storage and marketing (FAOSTAT, 2024; Larkin, 2024).

Chemical seed treatment and synthetic fungicides are the most important tools in disease management. These chemicals inhibit the growth of pathogens and have been used for long, but not much attention has been given to other issues involving contamination of the environment, development of fungicide resistance and residues of pesticide in agricultural ecosystems (Periyandavan *et al.*, 2025). Environment-friendly biological measures are, therefore, becoming more and more popular as disease management methods. *Bacillus subtilis* is a growth promoting rhizobacterium, which has come to light as an effective bio-control agent due to its ability to colonize the rhizosphere, produce various antimicrobial metabolites and promote plant growth in many ways (Kaushal and Wani, 2016). Moreover, cyclic lipopeptides like surfactin, iturin and fengycin are highly effective against fungi as active components involved in various types of antifungal activity, including cell membrane disruption and mycelial growth

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How to cite this article: Patil, P.S. and Gore, N.S. (2026). Growth Promotion and Biological Control of Fungal Dry Rot in Potato by Potential *Bacillus* Rhizobacterium. *Indian Journal of Agricultural Research.* **60(Special Issue):** 32-38. doi: 10.18805/IJARe.A-6631.

Submitted: 10-07-2026 **Accepted:** 29-07-2026 **Online:** 10-08-2026

inhibition (Patil and Gore, 2025). These metabolites also promote systemic resistance by boosting defence enzyme activity such as phenylalanine ammonia-lyase (PAL), peroxidase (POD) and polyphenol oxidase (PPO), which provide plant resistance to pathogen attack (Ongena and Jacques, 2008; Chowdhury *et al.*, 2015; Gulzar *et al.*, 2025).

Although the antagonistic potential of *Bacillus* species against soil-borne fungal pathogens has been widely reported, information on the efficacy of *Bacillus subtilis* MGM123 and its lipopeptides against *Fusarium sambucinum* causing potato dry rot remains limited. Therefore, the present investigation was undertaken to evaluate the effectiveness of *B. subtilis* MGM123 and its lipopeptides for the biological management of potato dry rot in potato variety Kufri Khyati under greenhouse conditions. The study further assessed their effects on vegetative growth, defence-related enzyme activities, chlorophyll content, disease severity and tuber yield to determine their potential as environmentally sustainable alternatives to conventional chemical fungicides.

MATERIALS AND METHODS

Pathogen and biocontrol agent

In the present study, the previously isolated and identified *Fusarium sambucinum* csnmgmu7 (GenBank Accession No. PQ814396) and *Bacillus subtilis* MGM123 (GenBank Accession No. PX788821) were used. The fungal culture was kept on Potato Dextrose Agar (PDA) and the bacterial culture was kept on Nutrient Agar till requirement.

Production and purification of lipopeptides

Bacillus subtilis MGM123 was submerged cultured for the production of antifungal lipopeptides. Extraction of lipopeptide done by using acid precipitation method and analysed by using thin-layer chromatography (TLC). The spots observed in TLC proceeded to check the antifungal activity against *Fusarium sambucinum* before its application in the greenhouse experiment (Dlamini *et al.*, 2020).

Experimental details

The efficacy of the *Bacillus subtilis* MGM123 and its lipopeptides was tested on potato dry rot caused by *Fusarium sambucinum* csnmgmu7 in the greenhouse experiment at the Institute of Biosciences and Technology, Mahatma Gandhi Mission University, Chhatrapati Sambhajinagar, Maharashtra, India during November 2025 to February 2026. Healthy seed tubers free from diseases of potato (*Solanum tuberosum* L.). Variety Kufri Khyati was chosen for the evaluation of biological disease management technique due to its commercial significance, high yield potential and widespread adaption in the Indian plains (Kumar *et al.*, 2009; Sadawarti *et al.*, 2024) whichwere collected from the Zonal Agricultural Research Station, Ganeshkhind, Pune, Maharashtra.

The tubers were surface sterilized with 1% sodium hypochlorite solution for 2-3 min, rinsed three times with sterile distilled water and air-dried under aseptic conditions before planting and thethree seed tuber per pot was planted. After getting good vegetative growth, only one tuber was selected for further study. Size of pot was 7 × 7-inch plastic pots filled with sterile soil. Three replications of each of the seven treatments were used in the experiment. During the winter, plants were kept in a natural greenhouse with natural light and all treatments received a consistent basal dose of NPK (120:80:100 kg ha^{-1} equivalent). Irrigation was provided on alternate days to maintain optimum soil moisture under greenhouse conditions.

The treatments consisted of untreated control (T_1), *Fusarium sambucinum* (T_2), *Bacillus subtilis* MGM123 (T_3), *F. sambucinum* + *B. subtilis* MGM123 (T_4), *F. sambucinum* + *Trichoderma* spp. (T_5), *F. sambucinum* + Mancozeb (T_6) and *F. sambucinum* + lipopeptides (T_7). In accordance with the appropriate treatment schedule, pathogen inoculation (1×10^6 spores mL^{-1}) and the application of *Bacillus subtilis* MGM123 (1×10^9 CFU mL^{-1}), lipopeptides (100 µg mL^{-1}), *Trichoderma* spp. and Mancozeb were performed after one month of planting by soil drenching. The yield of crop was recorded at harvesting stage, January-February, 2026.

Growth observations

Vegetative growth parameters such as plant height, shoot length, shoot diameter, root length, leaf length, leaf width and number of leaflets was measured at 30 days after treatment (DAT) from three randomly selected potato plants in each replication.

Biochemical and physiological analysis

Fresh leaf samples were collected at 0, 1, 2, 3, 5, 7 and 14 DAT for biochemical and physiological analysis. Phenylalanine ammonia-lyase (PAL), polyphenol oxidase (PPO) and peroxidase (POD) activities were determined spectrophotometrically following the methods of Dickerson *et al.* (1984), Hammerschmidt *et al.* (1982) and Mayer *et al.* (1965), respectively. Total chlorophyll content was estimated according to Arnon (1949) under physiological study.

Disease assessment and yield

Disease severity was recorded at 0, 7, 14, 21 and 28 DAT using a 0-5 disease rating scale and the Disease Severity Index (DSI) was calculated according to McKinney (1923). At harvest, tubers from each treatment were collected and tuber yield was expressed as g $plant^{-1}$.

Statistical analysis

The experimental data were analysed using IBM SPSS Statistics. Analysis of variance (ANOVA) was performed and treatment means were compared using Tukey's Honestly Significant Difference (HSD) test at $P \leq 0.05$.

RESULTS AND DISCUSSION

Analysis of variance (ANOVA) showed significant treatment effect on vegetative growth, biochemical responses in defence mechanisms, chlorophyll content, disease severity

and yield of tubers (Table 1-8). The treatments with *Bacillus subtilis* MGM123 and its lipopeptides proved effective under greenhouse conditions for supressing the *Fusarium sambucinum* csnmgmu7 and enhancing plant performance in potato variety Kufri Khyati.

Effect of different treatments on vegetative growth

Different treatments significantly affected the vegetative growth of Kufri Khyati (Table 1 and 2). Plants inoculated with *Fusarium sambucinum* alone (T_2) exhibited the poorest growth for all parameters, whereas biological treatments

Table 1: Effect of different treatments on vegetative growth of potato at 30 DAT.

Treatment	Plant height (cm)	Shoot length (cm)	Shoot diameter (cm)	Root length (cm)
T_1	47.51^{f}	10.43^{f}	3.52^{f}	11.02^{f}
T_2	40.06^{g}	9.02 ±^{g}	2.36^{g}	9.26^{g}
T_3	64.01^{a}	13.09^{a}	6.85^{a}	14.91^{a}
T_4	57.39^{b}	12.92^{b}	5.28^{b}	14.04^{b}
T_5	53.73^{d}	10.52^{e}	5.28^{b}	14.00^{b}
T_6	53.79^{c}	10.19^{f}	4.20^{c}	13.90^{c}
T_7	53.93^{c}	12.88^{b}	4.20^{c}”	14.22^{b}

Means followed by different lowercase letters within a column differ significantly according to Tukey's honestly significant difference (HSD) test at P≤0.05.

Table 2: Effect of different treatments on leaf growth of potato at 30 DAT.

Treatment	Leaf length (cm)	Leaf width (cm)	Number of leaflets
T_1	15.09^{f}	8.07^{f}	12.67^{d}
T_2	12.17^{g}	6.26^{g}	9.67^{e}
T_3	20.87^{a}	10.92^{b}	17.33^{a}
T_4	19.19^{b}	12.24^{a}	16.67^{b}
T_5	18.15^{d}	10.93^{b}	14.00^{c}
T_6	18.18^{c}	10.38^{c}	14.00^{c}
T_7	20.25^{a}	10.93^{b}	17.00^{a}

Means followed by different lowercase letters within a column differ significantly according to Tukey's Honestly Significant Difference (HSD) test at P≤0.05.

Table 3: Effect of different treatments on phenylalanine ammonia-lyase (PAL) activity (U g^{-1} FW) from 0-14 DAT.

Treatment	0 DAT	1 DAT	2 DAT	3 DAT	5 DAT	7 DAT	14 DAT
T_1	16.80^{d}	19.04^{d}	18.21^{c}	19.09^{c}	18.30^{c}	20.20^{c}	20.62^{d}
T_2	41.61^{ab}	52.21^{a}	56.15^{a}	59.33^{a}	68.96^{a}	69.04^{a}	61.63^{a}
T_3	46.03^{a}	50.25^{ae}	49.05^{ab}	50.68^{ab}	50.42^{b}	57.17^{ab}	54.98^{ae}
T_4	37.19^{b}	40.52^{b}	41.55^{b}	41.40^{b}	42.20^{b}	45.43^{b}	45.70^{b}
T_5	38.13b	42.31^{be}	42.03^{b}	42.09^{b}	41.19^{b}	47.41^{b}	46.46^{be}
T_6	25.32^{c}	28.31^{c}	27.98^{c}	27.72^{c}	28.12^{c}	30.88^{c}	31.84^{c}
T_7	42.45ab	46.27^{ab}	46.62^{ab}	46.89^{b}	46.39^{b}	51.4^{b}	50.76^{be}

Means followed by different lowercase letters within a column differ significantly according to Tukey's Honestly Significant Difference (HSD) test at P≤0.05.

Table 4: Effect of different treatments on polyphenol oxidase (PPO) activity (U g^{-1} FW) from 0-14 DAT.

Treatment	0 DAT	1 DAT	2 DAT	3 DAT	5 DAT	7 DAT	14 DAT
T_1	25.82^{d}	28.09^{d}	27.42^{d}	28.49^{d}	27.62^{d}	31.76^{d}	31.48^{d}
T_2	56.22^{a}	67.35^{a}	72.20^{a}	78.84^{a}	90.46^{a}	91.04^{a}	82.28^{a}
T_3	57.99^{a}	63.62^{a}	64.97^{b}	63.82^{b}	63.38^{c}	71.76^{b}	70.01^{b}
T_4	50.62^{b}	54.65^{b}”	55.91^{c}	55.63^{c}	55.68^{b}	61.23^{c}	62.75^{c}
T_5	50.01^{b}	55.56^{b}	56.14^{c}	55.47^{c}	53.98^{b}	60.66^{c}	61.27^{c}
T_6	33.06^{c}	36.80^{c}	35.93^{d}	36.24^{d}	35.17^{c}	40.27^{d}	40.50^{d}
T_7	53.54^{b}	58.49^{b}	58.39^{c}	58.64^{c}	57.72^{b}	65.99^{c}	66.15^{c}

Means followed by different lowercase letters within a column differ significantly according to Tukey's honestly significant difference (HSD) test at P≤0.05.

significantly improved plant development. Among all treatments, *Bacillus subtilis* MGM123 (T_3) produced the best vegetative growth, while lipopeptides (T_7) and the combined *Fusarium* + *Bacillus* treatment (T_4) also alleviated the adverse effects of pathogen infection.

Plant height, shoot length, shoot diameter and root length differed significantly among treatments (Table 1). The highest plant height (64.01 cm), shoot length (13.09 cm), shoot diameter (6.85 cm) and root length (14.91 cm) were recorded in T_3, whereas T_2 recorded the lowest values (40.06, 9.02, 2.36 and 9.26 cm, respectively). Among the pathogen-challenged treatments, T_7 maintained higher plant height (53.93 cm), shoot length (12.88 cm) and root length (14.22 cm), while T_4 also showed substantial improvement over pathogen inoculation alone. Enhanced vegetative growth following *B. subtilis* application may be attributed to improved nutrient uptake, production of plant growth-promoting substances and suppression of pathogen development. Similar improvements in potato growth following *Bacillus*-based biological control have been reported by Larkin *et al.* (2024) and Serrão *et al.* (2024).

T_3 recorded the greatest leaf length (20.87 cm) and number of leaflets (17.33), whereas the widest leaflets were observed in T_4 (12.24 cm) (Table 2). In contrast, T_2 produced the shortest leaflets (12.17 cm), the narrowest leaflets (6.26 cm) and the fewest leaflets (9.67). Among the pathogen-challenged treatments, lipopeptides (T_7) maintained higher leaf length (20.25 cm) and leaf number (17.00 plant^{-1}), indicating better maintenance of canopy growth under pathogen stress. Improved leaf development in the biological treatments may be attributed to reduced disease severity and enhanced physiological activity, resulting in greater photosynthetic surface area and overall plant vigour. Similar improvements in leaf growth following the application of *Bacillus* spp. have been reported in potato and other crops (Chowdhury *et al.*, 2015; Larkin, 2024).

Overall, *Bacillus subtilis* MGM123 (T_3) was the most effective treatment for promoting vegetative growth, while lipopeptides (T_7) were the most effective among the pathogen-challenged treatments, demonstrating their potential as sustainable biological alternatives for mitigating the adverse effects of *Fusarium sambucinum*.

Effect of different treatments on defence-related biochemical and physiological responses

Defence-related biochemical and physiological parameters were significantly influenced by different treatments throughout the observation period (Table 3, 4, 5 and 6). Activities of PAL, POD and PPO increased rapidly following pathogen inoculation, reaching peak levels between 5 and 7 DAT before declining slightly at 14 DAT. Biological treatments maintained higher enzyme activities than the untreated control and chemical fungicide treatment, indicating enhanced activation of host defence mechanisms against *Fusarium sambucinum*. Significant differences in total chlorophyll content were observed at 5, 7 and 14 DAT, indicating better maintenance of photosynthetic capacity under pathogen stress.

Table 5: Effect of different treatments on peroxidase (POD) activity (U g^{-1} FW) from 0-14 DAT.

Treatment	0 DAT	1 DAT	2 DAT	3 DAT	5 DAT	7 DAT	14 DAT
T_1	25.76^{d}	28.38^{d}	27.98^{d}	28.57^{d}	27.99^{d}	32.09^{d}	31.59^{d}
T_2	65.17^{a}	82.80^{a}	84.84^{a}	90.54^{a}	103.74^{a}	108.28^{a}	93.21^{a}
T_3	71.68^{a}	78.80^{a}	77.51^{a}	78.54^{b}	80.15^{b}	88.69^{b}	85.47^{b}
T_4	60.27^{b}	64.34^{b}	65.91^{b}	65.29^{c}	65.15^{c}	74.81^{c}	75.05^{c}
T_5	61.11^{b}	67.22^{b}	67.63^{b}	65.67^{c}	66.33^{c}	73.99^{c}	74.87^{c}
T_6	40.92^{c}	44.29^{c}	45.20^{c}	44.53^{d}	44.03^{d}	49.51^{d}	48.92^{d}
T_7	60.27^{b}	64.87^{b}	66.71^{b}"	65.35^{c}	66.49^{c}	74.87^{c}	76.89^{c}

Means followed by different lowercase letters within a column differ significantly according to Tukey's honestly significant difference (HSD) test at P≤0.05.

Table 6: Effect of different treatments on total chlorophyll content (mg g^{-1} FW) from 0-14 DAT.

Treatment	0 DAT	1 DAT	2 DAT	3 DAT	5 DAT	7 DAT	14 DAT
T_1	1.42^{f}	1.59^{f}	1.56^{f}	1.56^{f}	1.55^{f}	1.76^{f}	1.78^{f}
T_2	1.60^{e}	1.78^{e}	1.74^{e}	1.75^{e}	1.82^{e}	1.90^{e}	1.93^{e}
T_3	1.69^{d}	1.82^{d}	1.88^{d}	1.87^{d}	1.84^{e}	2.13^{d}	2.13^{d}
T_4	1.92^{c}	2.08^{c}	2.14^{c}	2.12^{c}	2.05^{d}	2.37^{c}	2.38^{c}
T_5	2.26^{a}	2.52^{a}	2.53^{a}	2.57^{a}	2.58^{a}	2.80^{a}	2.79^{b}
T_6	1.73^{d}	1.89^{d}	1.88^{d}	1.90^{d}	1.90^{e}	2.16^{d}	2.15^{d}
T_7	2.27^{a}	2.50^{a}	2.44^{b}	2.45^{b}	2.49^{b}	2.74^{b}	2.90^{a}

Means followed by different lowercase letters within a column differ significantly according to Tukey's honestly significant difference (HSD) test at P≤0.05.

Pathogen infection significantly induced PAL activity, especially in T, with a maximum activity of 7 DAT (69.04 U g^{-1} FW) thereby proving activation of phenylpropanoid pathway after fungal invasion (Table 3). The biological treatments with consistently higher PAL activity followed lipopeptides (T_7) indicative of effective induction of host defence response, amongst the biologicals explored *Bacillus subtilis* MGM123 (T_3). On the other hand, the PAL activity of T_6 (Mancozeb) was lower as compared to the rest of the time. Induced resistance by *Bacillus* has also been shown to enhance the activity level of PAL by, Chowdhury *et al.* (2015), Verma *et al.* (2024) and Bakki *et al.* (2024).

The pathogen inoculation also significantly raised the polyphenol oxidase (PPO) activity with the maximum (91.04 U g^{-1} FW) recorded in T_2 at 7 DAT (Table 4). The enzymatic defence response was efficient in the T_3 and T_7 treatments, which resulted in overall high PPO activity compared to T_6 amongst the management treatments. Presence of increased PPO leads to an increase in the generation of quinones, which are antimicrobial molecules that limit colonization by pathogens (Choudaker *et al.*, 2024; Serrão *et al.*, 2024).

The peroxidase activity exhibited the same pattern with maximum activity observed in T_2 at 7 DAT (108.28 U g^{-1} FW) and the maximum peroxidase activity among the biological treatments was observed in T_3 (88.69 U g^{-1} FW) (Table 5). Lipopeptides (T_7) also exhibited increased POD activity compared to Mancozeb, indicative of improved ability to remove ROS and strengthen barriers in the cell wall. Similar results have been seen in *Bacillus* treated plants attacked by fungal pathogens (Hammerschmidt *et al.*, 1982; Berendsen *et al.*, 2012).

Bacillus subtilis MGM123 and its lipopeptides activate induced systemic resistance (ISR), as seen by the increased PAL, POD and PPO activities seen in the biological therapies. By participating in the phenylpropanoid pathway, lignification, phenolic compound oxidation and plant cell wall fortification, these defence enzymes limit pathogen colonisation. On the other hand, rather than effective disease resistance, the pathogen-inoculated treatment's greatest enzyme activity probably represented a stronger stress response brought on by a severe infection. The biological treatments' mild but persistent enzyme activity suggests effective host defence priming along with a decrease in pathogen load (Bakki *et al.*, 2024; Verma *et al.*, 2024; Gulzar *et al.*, 2025).

The total chlorophyll content were significantly different for the different treatments during the experiment (Table 6). It was found that the amount of chlorophyll was utmost at T_5 (2.80 mg g^{-1} FW) at 7 DAT followed by T_7 (2.74 mg g^{-1} FW) and T_4 (2.37 mg g-1 FW), while T_1 exhibited the lowest chlorophyll level during observation. The chlorophyll content was higher in the biological treatment and was significantly higher than the pathogen treatment, signifying a better preservation of photosynthetic capacity when in disease stress. Chlorophyll content in plants after *Bacillus* spp. application was reported previously, which showed similar improvement (Chowdhury *et al.*, 2015; Siddika *et al.*, 2024).

Better preservation of photosynthetic ability under pathogen stress was evidenced by higher chlorophyll concentration in the biological treatments. Improved plant physiological state and less pathogen colonisation may have reduced chlorophyll breakdown, maintain photosynthetic efficiency and promote increased plant growth and output. Similar findings have been documented in plants treated with *Bacillus* under both biotic and abiotic stress (Siddika *et al.*, 2024; Verma *et al.*, 2024).

Effect of different treatments on disease severity and tuber yield

Disease severity

The severity of disease continued to rise as the days passed on pathogen-inoculated plants, but both biological and chemical treatments proved effective at reducing disease (Table 7). In the case of the *Bacillus subtilis* MGM123, disease symptoms were kept under check, remaining essentially negligible plants throughout the study; in the maximum points, 21 and 28 DAT, the DSI reached a maximum of 0.67, in the untreated control (T_1) received a few minimal symptoms. *Fusarium sambucinum*, as under greenhouse conditions, was found to have a very aggressive affect, with T_2 being the first control symptom group to appear at 7 DAT (DSI 1.67), followed by 2.67 at 14 DAT, 3.67 at 21 DAT and 4.67 at 28 DAT.

Among the disease-management treatments, lipopeptides ($T_{7)}$ and Mancozeb (T_6) were the most effective,

Table 7: Effect of different treatments on disease severity index (DSI) of at different DAT.

Treatment	0 DAT	7 DAT	14 DAT	21 DAT	28 DAT
T_1	0.00^{f}	0.00^{f}	0.00^{f}	0.33^{f}	0.33^{f}
T_2	0.00^{a}	1.67^{a}	2.67^{a}	3.67^{a}	4.67^{a}
T_3	0.00^{f}	0.00^{f}	0.00^{f}	0.67^{f}	0.67^{f}
T_4	0.00^{b}	0.67^{b}	1.67^{b}	2.00^{b}	3.00^{b}
T_5	0.00^{c}	0.67^{b}	1.33^{c}	1.33^{c}	2.33^{c}
T_6	0.00^{d}	0.67^{b}	0.67^{d}	1.67^{d}	1.67^{d}
T_7	0.00^{e}	0.00^{f}	0.67^{d}	0.67^{e}	1.67^{d}

Means followed by different lowercase letters within a column differ significantly according to Tukey's honestly significant difference (HSD) test at P≤0.05.

Table 8: Effect of different treatments on tuber yield.

Treatment	Tuber yield (g plant^{-1})
T_1	76.00^{f}
T_2	48.00^{g}
T_3	140.00^{a}
T_4	107.00^{c}
T_5	103.00^{d}
T_6	103.00^{d}
T_7	129.00^{b}

Means followed by different lowercase letters within a column differ significantly according to Tukey's Honestly Significant Difference (HSD) test at P≤0.05.

each recording the lowest final DSI (1.67) at 28 DAT, followed by *Fusarium* + *Trichoderma* (T_5) (2.33) and *Fusarium* + *Bacillus subtilis* MGM123 (T_4) (3.00). The marked reduction in disease severity following application of *B. subtilis* MGM123 and its lipopeptides may be attributed to the combined effects of antifungal lipopeptide production and induction of host defence responses. Similar reductions in *Fusarium*-associated diseases through *Bacillus*-mediated biological control have been reported by Ongena and Jacques (2008), Chowdhury *et al.* (2015) and Gulzar *et al.* (2025).

Tuber yield differed significantly among treatments (Table 8). The highest yield was obtained with *Bacillus subtilis* MGM123 (T_3) (140.00 g plant^{-1}), followed by lipopeptides (T_7) (129.00 g plant^{-1}) and *Fusarium* + *Bacillus subtilis* MGM123 (T_4) (107.00 g plant^{-1}). *Fusarium* + *Trichoderma* (T_5) and Mancozeb (T_6) each produced 103.00 g plant^{-1}, whereas the pathogen treatment (T_2) recorded the lowest yield (48.00 g plant^{-1}), representing a substantial reduction compared with the untreated control (76.00 g plant^{-1}). The higher tuber yield obtained with the biological treatments reflects their ability to suppress pathogen infection while promoting healthier plant growth. Notably, lipopeptides produced a higher tuber yield than Mancozeb while maintaining comparable disease suppression, highlighting their potential as environmentally sustainable alternatives for potato dry rot management. Similar improvements in tuber yield following application of *Bacillus* spp. have been reported by Larkin *et al.* (2024) and Li *et al.* (2022).

Environmental heterogeneity in the field may affect the effectiveness of the biocontrol treatments, even if the current study showed encouraging disease suppression under greenhouse settings. Therefore, before promoting large-scale agricultural use, multilocation field evaluations are necessary.

CONCLUSION

The present study demonstrated that *Bacillus subtilis* MGM123 is an effective biological control agent for the management of potato dry rot caused by *Fusarium sambucinum* csnmgmu7 in potato variety Kufri Khyati under greenhouse conditions. Application of *B. subtilis* MGM123 significantly improved vegetative growth, enhanced defence-related biochemical responses and maintained higher chlorophyll content, resulting in negligible disease development and the highest tuber yield (140.00 g plant^{-1}). Lipopeptides also proved highly effective by reducing the Disease Severity Index (DSI) from 4.67 in pathogen-inoculated plants to 1.67 at 28 DAT, comparable to Mancozeb, while producing a higher tuber yield (129.00 g plant^{-1}) than the fungicide (103.00 g plant^{-1}). These findings indicate that *B. subtilis* MGM123 and its lipopeptides represent promising environment-friendly alternatives to chemical fungicides for the sustainable management of potato dry rot. Further validation through multi-location field trials is required to confirm their efficacy under diverse agro-climatic conditions and support their development as commercial biocontrol formulations.

ACKNOWLEDGEMENT

The present study supported by Institute of Biosciences and Technology, MGM University Chhatrapati Sambhajinagar and SARTHI Research and Training Institute, Pune, Maharashtra, India.

Disclaimers

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Informed consent

Not applicable.

Conflict of interest

The authors declare that there are no conflicts of interest regarding the publication of this article.

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