

Evaluation of *Pseudomonas fluorescens*, *Trichoderma viride*, and Their Consortium for the Management of Potato Late Blight and Tuber Yield

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Abstract

Potato late blight, caused by *Phytophthora infestans*, remains a major constraint to potato production and is predominantly managed through repeated fungicide applications. Biological control offers a potential complementary strategy, but its field performance under natural epidemic conditions remains inconsistent. This study evaluated the comparative efficacy of *Pseudomonas fluorescens*, *Trichoderma viride*, and their consortium for suppressing potato late blight and maintaining tuber yield under natural disease pressure. A field experiment was conducted in 2026 at Mude, Sindhupalchok, Nepal (2500 m above sea level), using cv. Desiree in a randomized complete block design with four treatments and five replications. Disease severity was assessed at weekly intervals using the CIP 1–9 late blight scale and converted to percentage severity, while epidemic development was quantified using the area under the disease progress curve (AUDPC). Total tuber yield was recorded at harvest. Disease severity increased progressively across all treatments. *T. viride* produced the lowest overall estimated mean disease severity (37.0%), which was significantly lower than that of *P. fluorescens* (42.9%; $P = 0.0349$). It also recorded the lowest AUDPC (762.65), corresponding to a 7.41% reduction relative to the untreated control, although treatment effects on AUDPC were not significant ($P = 0.372$). The consortium resulted in a 2.70% numerical reduction in AUDPC, whereas *P. fluorescens* increased AUDPC by 7.75% relative to the control. Tuber yield was not significantly affected by treatment ($P = 0.286$), although *P. fluorescens* produced the highest numerical yield (8.51 kg plot⁻¹). Overall, *T. viride* demonstrated greater disease-suppressive potential than *P. fluorescens* and the consortium under the conditions tested, but the magnitude and consistency of suppression were insufficient to establish reliable field-level control. These findings indicate that *T. viride* may have value as a component of integrated late-blight management, warranting further evaluation of locally adapted strains, preventive application schedules, and integration with reduced-fungicide programs under multi-location and multi-season conditions.

1. Introduction

Potato (*Solanum tuberosum* L.) is the world's third most important food crop after rice and wheat (Devaux et al., 2021). Globally, potato is cultivated on approximately 17.8 million hectares, with an annual production exceeding 385 million tons (Food and Agriculture Organization of the United Nations [FAO], 2025). In developing countries like Nepal, people cultivate potato as both staple food and a high-value cash crop. However, potato productivity remains constrained by numerous biotic stresses, among which late blight, caused by the oomycete *Phytophthora infestans* (Mont.) de Bary, is the major one.

Late blight continues to impose severe economic losses despite plethora of researches on it following the Irish famine. The disease can destroy an entire potato crop within a few weeks under favorable environmental conditions. The yield losses ranging from 20% to complete crop failure in susceptible cultivars is very likely when effective control measures are not implemented. Late blight remains one of the costliest plant diseases worldwide. The annual global loss is estimated to exceed US\$6 billion (Fry et al., 2015; Maurya et al., 2026).

In Nepal, late blight remains the principal disease of potato across diverse agroecological zones. Severe outbreaks frequently occur during the main potato-growing season, resulting in heavy yield losses and increased production costs associated with repeated fungicide applications. The disease reduces the yield by 75% in the high hills and 50–90% in the Terai under favorable environmental conditions. At the national level, the disease is estimated to reduce potato production by approximately 15% annually, resulting in an economic loss of about US\$100 million (Shrestha, 2000; Sharma et al., 2011). The devastating nature of the pathogen is attributed to its polycyclic infection cycle, prolific sporangial production, efficient aerial dispersal, and remarkable evolutionary potential.

The epidemiology of late blight is strongly influenced by environmental conditions. Disease development is favored by moderate temperatures (15–22°C), prolonged leaf wetness, high relative humidity (> 90%), and frequent rainfall or fog. These conditions promote sporulation, infection, and rapid secondary spread. Climate change can alter the epidemiology and geographic distribution of plant diseases by modifying temperature, precipitation, humidity, and other environmental conditions that regulate pathogen development and infection (Juroszek & von Tiedemann, 2013).

Chemical fungicides remain the main tool for managing late blight in many potato-growing regions. However, repeated use of fungicides can place selection pressure on pathogen populations. Over time, this may reduce the sensitivity of the pathogen to fungicides with specific modes of action. Therefore, careful fungicide use and the integration of non-chemical management practices are becoming increasingly important for sustainable late-blight management (Ivanov et al., 2021; Dong & Zhou, 2022). Field studies in Nepal have shown that properly selected fungicides can substantially reduce disease development and improve tuber yield. At the same time, these studies highlight the continued reliance of potato production on repeated chemical protection (Khadka et al., 2020).

In this context, biological control is gaining attention as part of integrated late-blight management, with both bacterial and fungal agents showing potential against *Phytophthora infestans*. For example, *Pseudomonas fluorescens* strain LBUM636 showed antagonistic activity against *P. infestans* (Morrison et al., 2016, 2017). Likewise, *Trichoderma* spp. can suppress pathogens while promoting plant growth and strengthening plant defense responses (Wang & Long, 2023; Cournault et al., 2025). Combining these microorganisms in a consortium could provide complementary effects by bringing together the antibiosis and rhizosphere-colonizing ability of *P. fluorescens* with the antagonistic and defense-inducing effects of *Trichoderma*. However, their combined performance may vary depending on strain compatibility, environmental conditions, and application methods. Thus, the effectiveness of such consortia needs to be confirmed through field experiments rather than assumed from the performance of individual agents (Daaboub et al., 2022; Wang & Long, 2023).

Despite growing interest in the biological management of late blight, field-based evidence is still limited compared with laboratory studies. Wang and Long (2023) reported that many biocontrol agents show promising antagonistic activity under controlled conditions. However, their performance in the field is often lower and more variable. This issue is particularly relevant in Nepal, where environmental

conditions differ considerably across potato-growing regions and late-blight epidemics develop under naturally changing conditions. Recent studies in Nepal have shown the potential of *Trichoderma* isolates and other biological treatments. However, comparative field evaluation of *P. fluorescens*, *T. viride*, and their combined application under the same conditions remains limited (Rokaya et al., 2023; Adhikari et al., 2023).

Therefore, this study was conducted to evaluate the effectiveness of *Pseudomonas fluorescens*, *Trichoderma viride*, and their consortium for managing potato late blight under natural disease pressure. Disease development was recorded at regular intervals and assessed using disease severity and the area under the disease progress curve (AUDPC). Tuber yield and yield-related traits were also measured to determine whether disease suppression resulted in improved crop productivity. The study compared individual and combined microbial treatments with an untreated control. It also assessed their potential as biological components of sustainable late-blight management in potato.

2. Materials and methods

2.1. Experimental Site

The field experiment was conducted at the Potato Crop Development Centre, Mude, Sindhupalchok, Nepal (approximately 27.8° N, 85.7° E; 2500 m above sea level). The experimental site is characterized by a cool temperate climate with frequent cloud cover and high relative humidity, conditions highly favorable for the development of late blight. The experimental field has a history of recurrent late blight epidemics.

2.2. Plant Materials

Potato (*Solanum tuberosum* L.) variety Desiree was used as the plant material for evaluating the efficacy of microbial biocontrol agents against late blight. Healthy and uniform seed tubers weighing approximately 30–50 g were selected based on uniform size, physiological maturity, and freedom from visible pest and disease symptoms. The experiment was planted on 20 February 2026 under field conditions. Before planting, seed tubers were treated with Saaf® 75 WP (carbendazim 12% + mancozeb 63% WP) at a rate of 2 g kg⁻¹ seed to protect against seed- and soil-borne fungal pathogens.

2.3. Experimental Design and Treatments

The field experiment was conducted using a Randomized Complete Block Design (RCBD) with four treatments and five replications, resulting in a total of 20 experimental plots. Each plot measured 3.0 m × 2.4 m (7.2 m²), with plant spacing maintained at 60 cm between rows and 25 cm between plants within rows. The treatments consisted of an untreated control (T1), *Pseudomonas fluorescens* (T2), *Trichoderma viride* (T3), and a consortium of *P. fluorescens* and *T. viride* (T4). Treatments were randomly assigned within each replication to minimize the effects of field variability. No fungicide targeting late blight was applied during the experiment so that the efficacy of the microbial treatments could be evaluated under natural disease pressure. To ensure uniform disease pressure under natural epiphytotic

conditions, two border rows of the cultivar Desiree were planted around the experimental area as spreader rows.

2.4. Pesticides Application

The microbial biopesticides *Pseudomonas fluorescens* and *Trichoderma viride* were applied individually and as a consortium according to the assigned treatments. Before planting, the seed tubers were treated with the respective microbial formulations at a concentration of 100 mL L⁻¹ of water. The respective microbial biopesticides were also applied in the planting hills before planting at the rate of 10 mL L⁻¹. The first foliar application was made on 5 May 2026 by diluting 10 mL of the respective treatment formulation per liter of water. The microbial formulations contained approximately 2×10^8 CFU mL⁻¹ of *P. fluorescens* and 1×10^9 CFU mL⁻¹ of *T. viride*. A second application was made on 12 May 2026, followed by a third application on 19 May 2026, using the same application procedure. In the consortium treatment, both microbial biopesticides were applied together at their respective concentrations. The untreated control received no microbial biopesticide application. All applications were performed uniformly across the respective plots using a knapsack sprayer.

2.5. Crop Management

All other agronomic practices, including irrigation, fertilizer application, earthing-up, and manual weed control, were applied uniformly to all experimental plots according to the recommended potato production practices for the region. The crop was harvested in 8 June 2026.

2.6. Disease Assessment

Late blight development was monitored under natural disease pressure throughout the experimental period. Disease assessment was initiated when initial late-blight symptoms were observed in the experimental field. Disease severity was recorded at weekly intervals on 5, 12, 19, and 26 May 2026. Ten plants were randomly selected from each plot and tagged for repeated observations.

Disease severity was assessed using the 1–9 CIP late blight severity scale, where 1 = no visible symptoms and 9 = complete foliage destruction (Henfling, 1987). Disease scores were subsequently converted to percentage disease severity using the following formula:

$$\text{Disease severity (\%)} = [\Sigma \text{ Disease ratings} / (\text{Number of plants assessed} \times \text{Maximum disease rating})] \times 100$$

where: Σ Disease ratings = sum of the disease scores of all assessed plants in a plot, number of plants assessed = total number of plants evaluated per plot (10 in this study), maximum disease rating = 9 (CIP 1–9 late blight severity scale).

2.7. Area Under the Disease Progress Curve (AUDPC)

Disease severity data were used to calculate the Area Under the Disease Progress Curve (AUDPC) for each experimental plot using the trapezoidal integration method (Shaner & Finney, 1977):

$$AUDPC = \sum_{i=1}^{n-1} \left(\frac{Y_i + Y_{i+1}}{2} \right) (t_{i+1} - t_i)$$

where Y_i = disease severity (%) at the i^{th} observation; t_i = time (days) at the i^{th} observation; n = total number of disease assessments.

2.8. Weather

Daily weather data, including maximum and minimum air temperature, relative humidity, and rainfall, were obtained from the office weather system. These data were used to identify environmental conditions conducive to late blight development during the experimental period.

2.9. Statistical Analysis

Data on disease severity, area under the disease progress curve (AUDPC), and total tuber yield were subjected to statistical analysis according to the experimental design. Disease severity recorded at four assessment dates was analyzed using a linear mixed-effects model, with biopesticide treatment and assessment considered fixed effects, replication considered a random effect, and treatment $\times$ assessment included to determine whether disease development over time differed among treatments. The statistical model used was:

$$Y_{ijkl} = \mu + T_i + A_j + (TA)_{ij} + R_k + \varepsilon_{ijkl}$$

where Y_{ijkl} is the observed response; μ is the overall mean; T_i is the effect of the i^{th} biopesticide treatment; A_j is the effect of the j^{th} disease assessment; $(TA)_{ij}$ is the treatment $\times$ assessment interaction; R_k is the effect of the k^{th} replication; and ε_{ijkl} is the residual error.

AUDPC was calculated from disease severity assessments using the trapezoidal method. AUDPC and total tuber yield were analyzed using analysis of variance (ANOVA) based on the randomized complete block design (RCBD), with biopesticide treatment as the fixed factor and replication as the blocking factor. Whenever significant treatment effects were detected, treatment means were separated using Tukey's Honestly Significant Difference (HSD) test at the 5% significance level ($P \leq 0.05$) based on estimated marginal means.

Pearson's correlation analysis was performed to examine the relationship between AUDPC and total tuber yield, and simple linear regression analysis was conducted to describe the association between these variables.

All statistical analyses were performed using R software (version 4.5.2; R Core Team, 2025). Estimated marginal means and pairwise comparisons were computed using the emmeans package.

3. Results

3.1. Mean disease severity (%) of potato late blight among different treatments under protected field conditions

Disease severity increased progressively from the first to the fourth assessment in all treatments. At the final assessment, the lowest disease severity was recorded in *T. viride* (57.28%), while the highest was recorded in the untreated control (66.67%).

Table 1
Mean disease severity (%) of potato late blight

Treatment	Assessment 1	Assessment 2	Assessment 3	Assessment 4
T1 – Untreated control	16.67	24.89	51.11	66.67
T2 – <i>Pseudomonas fluorescens</i>	25.33	34.00	48.15	63.95
T3 – <i>Trichoderma viride</i>	20.67	23.56	46.42	57.28
T4 – Consortium	16.44	25.78	48.64	63.70

3.2. Effect of biopesticide treatments on disease development

The effect of the biopesticide treatments on overall disease severity was evaluated using a mixed-effects model, with treatment and assessment as fixed effects and replicate as a random effect. The overall mean disease severity differed significantly among treatments ($F_{3, 60} = 2.77$, $P = 0.0495$). *Trichoderma viride* recorded the lowest estimated mean disease severity (37.0%), while *Pseudomonas fluorescens* recorded the highest (42.9%). Tukey's multiple comparison showed that disease severity was significantly lower with *T. viride* than with *P. fluorescens* ($P = 0.0349$), whereas the other treatment comparisons were not significant.

Table 2
Effect of biopesticide treatments on overall mean disease severity of potato late blight

Treatment	Mean disease severity (%)	SE	Significance
T1 – Untreated control	39.8	3.07	ab
T2 – <i>Pseudomonas fluorescens</i>	42.9	3.07	a
T3 – <i>Trichoderma viride</i>	37.0	3.07	b
T4 – Consortium	38.6	3.07	ab

Note: Means are estimated marginal means averaged across the four disease assessments. Means sharing a common letter are not significantly different according to Tukey's test at $P \leq 0.05$.

3.3. Area under the disease progress curve (AUDPC)

AUDPC was calculated from the four disease assessments using the trapezoidal method. The mean AUDPC was highest in *Pseudomonas fluorescens* (887.53), followed by the untreated control (823.67), consortium (801.46), and *Trichoderma viride* (762.65) (Table 3). However, the differences among treatments were not statistically significant ($F_{3, 12} = 1.14$, $P = 0.372$). Thus, although *T. viride* showed the lowest numerical AUDPC, its AUDPC did not differ significantly from the other treatments.

Table 3
Area under the disease progress curve (AUDPC) of potato late blight under different biopesticide treatments

Treatment	Mean AUDPC	SE	Significance
T1 – Untreated control	823.67	37.06	a
T2 – <i>Pseudomonas fluorescens</i>	887.53	88.15	a
T3 – <i>Trichoderma viride</i>	762.65	93.54	a
T4 – Consortium	801.46	52.60	a
Note: AUDPC was calculated using the trapezoidal method with 7-day intervals between disease assessments. Means followed by the same letter are not significantly different at $P \leq 0.05$.			

3.4. Effect of biopesticide treatments on tuber yield

Biopesticide treatments did not significantly affect tuber yield ($F_{3, 12} = 1.42$, $P = 0.2862$). The highest mean yield was recorded with *Pseudomonas fluorescens* (8.51 kg plot⁻¹), followed by the untreated control (7.68 kg plot⁻¹), *Trichoderma viride* (7.51 kg plot⁻¹), and the consortium treatment (7.06 kg plot⁻¹) (Table 4). Tukey's multiple comparison test showed that none of the treatment pairs differed significantly ($P > 0.05$).

Table 4
Effect of biopesticide treatments on tuber yield of potato

Treatment	Tuber yield (kg plot ⁻¹)	SE	Significance
T1 – Untreated control	7.68	0.95	a
T2 – <i>Pseudomonas fluorescens</i>	8.51	0.47	a
T3 – <i>Trichoderma viride</i>	7.51	0.85	a
T4 – Consortium	7.06	0.96	a
Note: Treatment means were not significantly different according to Tukey's test ($P > 0.05$).			

3.5. Relationship between disease development and tuber yield

There was a weak, positive, and non-significant correlation between AUDPC and tuber yield ($r = 0.249$, $P = 0.291$). Linear regression similarly showed that AUDPC did not significantly explain variation in tuber yield ($R^2 = 0.062$, $F_{1, 18} = 1.19$, $P = 0.291$).

3.6. Biopesticide efficacy in reducing late blight

Compared with the untreated control, *Trichoderma viride* showed the highest numerical reduction in AUDPC (7.41%), followed by the consortium treatment (2.70%). In contrast, *Pseudomonas fluorescens* showed a 7.75% increase in AUDPC compared with the untreated control, indicating no reduction in disease development under the tested conditions.

Table 5
Efficacy of biopesticide treatments in reducing potato late blight based on AUDPC

Treatment	Mean AUDPC	Reduction in AUDPC (%)
T1 – Untreated control	824	0.00
T2 – <i>Pseudomonas fluorescens</i>	888	–7.75
T3 – <i>Trichoderma viride</i>	763	7.41
T4 – Consortium	801	2.70
Note: Reduction in AUDPC was calculated relative to the untreated control. Negative values indicate higher AUDPC than the untreated control.		

4. Discussions

Potato late blight developed progressively in all treatments during the experimental period, confirming that the experimental site at Mude, Sindhupalchok, provided favorable conditions for disease development. The cool, humid environment and recurrent late-blight history of the site likely supported repeated infection cycles of *Phytophthora infestans*. Late blight epidemics are strongly influenced by temperature, relative humidity, rainfall, leaf wetness, and the duration of favorable weather conditions. Consequently, even treatments with some suppressive activity may provide only partial protection when disease pressure is high and environmental conditions remain favorable for sporulation and infection.

4.1. Disease suppression by microbial treatments

Among the treatments, *Trichoderma viride* produced the most consistent numerical reduction in disease. Its overall estimated mean disease severity was 37.0%, compared with 39.8% in the untreated control, 42.9% in *Pseudomonas fluorescens*, and 38.6% in the consortium. Importantly, disease severity under *T. viride* was significantly lower than under *P. fluorescens*. This result suggests that *T. viride* was better adapted to the conditions of the experimental site or was more effective at suppressing disease under the application schedule used in this study.

The superiority of *T. viride* is also reflected in the disease progression data. At the final assessment, disease severity was 57.28% in the *T. viride* treatment, compared with 66.67% in the untreated control. Although the difference at the final assessment was numerically substantial, disease severity nevertheless increased over time in all treatments. This indicates that *T. viride* delayed or moderated disease development rather than completely preventing infection. The 7.41% reduction in AUDPC relative to the control further supports a modest disease-suppressive effect, although the difference was not statistically significant.

The present result is consistent with evidence from Nepal showing that the performance of *Trichoderma* against late blight depends strongly on the isolate. Rokaya et al. (2023) reported that selected native isolates reduced disease severity by approximately 30.4–40.2% under field conditions, and the best isolate increased tuber yield by 46.4–72.3% compared with the control. In contrast, other isolates did not provide satisfactory disease control or yield improvement. This variation indicates that species identity alone is insufficient for predicting biocontrol performance; strain-level antagonism, colonization ability, formulation quality, and adaptation to local environmental conditions are also important.

Several mechanisms may explain the performance of *Trichoderma*. These include competition for space and nutrients, production of antimicrobial metabolites and hydrolytic enzymes, mycoparasitism, rhizosphere colonization, and stimulation of host defense responses. In the case of an oomycete pathogen such as *P. infestans*, direct mycoparasitism may not fully explain disease suppression. Induced resistance, improved plant vigor, and alteration of the microbial environment around roots and foliage may also contribute to the observed effect. Recent reviews emphasize that biocontrol agents can act through multiple mechanisms, but that these mechanisms do not always translate into reliable field-level disease control because their activity is influenced by temperature, moisture, ultraviolet radiation, plant genotype, and application timing (Wang & Long, 2023; Cournault et al., 2025).

4.2. Performance of *Pseudomonas fluorescens*

In the present study, *P. fluorescens* did not suppress late blight. It recorded the highest overall mean disease severity, the highest AUDPC, and an AUDPC 7.75% greater than the untreated control. The numerical increase in disease development should not necessarily be interpreted as evidence that the bacterium stimulated pathogen infection. Rather, it suggests that the particular strain, formulation, dose, timing, or environmental conditions used in this experiment were inadequate for effective disease suppression.

The result contrasts with previous studies demonstrating that some *Pseudomonas* strains can inhibit *P. infestans*. For example, *P. fluorescens* LBUM636 produces phenazine-1-carboxylic acid, an antimicrobial compound associated with inhibition of pathogen growth and suppression of late-blight development. The wild-type strain also showed activity against tuber infection, whereas a mutant impaired in phenazine production did not provide the same level of protection (Morrison et al., 2017). Similarly, phenazine-1-carboxylic acid-producing *Pseudomonas* spp. have demonstrated potential for the biological control of potato late blight through tuber protection (Leger et al., 2021).

These findings highlight an important limitation of interpreting results at the species level. A commercial or field-applied product identified as *P. fluorescens* may not possess the same antagonistic traits as a strain demonstrated to be effective in laboratory or tuber assays. Effective performance may depend on the production of phenazines, siderophores, lytic enzymes, volatile compounds, or other metabolites. Root and leaf colonization are also essential because the bacterium must reach and persist near infection sites before it can influence pathogen development. Thus, future studies should identify the strain used in the formulation, verify its population density before application, and determine its ability to colonize potato roots and foliage under field conditions.

The timing of application may also have limited the effectiveness of *P. fluorescens*. The first foliar spray was made after disease symptoms had appeared. Biological agents often perform better when applied preventively, before substantial pathogen establishment. Once late blight has entered its exponential phase, rapid sporulation and secondary infection can exceed the suppressive capacity of a microbial treatment. More frequent application, use of an appropriate adjuvant, or integration with a reduced-risk fungicide may therefore be necessary.

4.3. Lack of consortium advantage

The consortium treatment did not outperform either individual microbial treatment. Its overall mean disease severity was 38.6%, and its AUDPC was 801.46, representing only a 2.70% reduction relative to the untreated control. Although the consortium performed numerically better than *P. fluorescens* alone, it was less effective than *T. viride*. These results do not support the assumption that combining two biocontrol agents automatically produces additive or synergistic disease suppression.

Microbial consortia can fail for several reasons. The organisms may compete for nutrients or space, produce inhibitory compounds that affect one another, or differ in their environmental requirements. The simultaneous application of the two products may also have reduced the population or activity of one organism. In addition, *P. fluorescens* and *T. viride* may have occupied different ecological niches, meaning that their combined application did not increase protection of the foliage during the critical stages of late-blight infection.

The present findings are consistent with broader evidence that field performance of biocontrol agents is often lower and more variable than performance under laboratory or greenhouse conditions. A recent review identified inconsistent field efficacy as one of the main barriers to the adoption of biological control for late blight (Daaboub et al., 2022). In field trials conducted across multiple locations, biological products reduced disease in some environments but generally did not match the performance of synthetic fungicides, with environmental variability identified as a major factor affecting efficacy. Therefore, consortium development should be based on compatibility testing, population monitoring, independent optimization of application timing, and replicated multi-environment field trials rather than simply mixing available products.

It is also possible that the consortium would perform better if the two agents were applied separately. For example, *T. viride* could be applied to seed tubers or soil to promote root colonization, while *P. fluorescens* could be applied to foliage as a preventive treatment. Such temporal or spatial separation may reduce direct microbial competition and allow each organism to act in its preferred ecological niche.

4.4. AUDPC and disease progression

Although *T. viride* recorded the lowest AUDPC, treatment differences were not statistically significant. AUDPC integrates disease intensity over time and is therefore more informative than a single final disease assessment. The lack of a significant AUDPC effect suggests that the numerical reduction produced by *T. viride* was not sufficiently large or consistent among replications to establish a clear treatment effect.

The nonsignificant AUDPC result may be explained partly by the short assessment period and the small number of observations. Disease was assessed on only four dates at weekly intervals. Under rapidly developing late blight, substantial changes can occur between assessments, and four observations may not fully describe the disease curve. In addition, the experiment had five replications, which may have provided limited statistical power for detecting relatively small treatment differences. Variation in microclimate, inoculum distribution, plant growth, and microbial establishment could also have increased experimental error.

The disease progression curves show that all treatments eventually experienced considerable disease development. This is important because biological treatments may delay epidemic development without preventing late-season infection. A delay in epidemic onset can still be agronomically useful if it protects foliage during tuber initiation and bulking. However, to establish this benefit, future studies should begin disease assessment before symptom appearance and continue until natural senescence or harvest. More frequent assessments would also improve AUDPC estimation.

4.5. Tuber yield response

The microbial treatments did not significantly affect tuber yield. The highest numerical yield occurred in the *P. fluorescens* treatment at 8.51 kg plot⁻¹, followed by the untreated control at 7.68 kg plot⁻¹, *T. viride* at 7.51 kg plot⁻¹, and the consortium at 7.06 kg plot⁻¹. Because the differences were not statistically significant, the numerical ranking should be interpreted cautiously.

The absence of a yield response is understandable because disease suppression was limited and inconsistent. Potato tuber yield depends on the duration of healthy foliage, crop establishment, nutrient availability, soil moisture, cultivar characteristics, temperature, and harvest timing. A modest reduction in late-blight severity may not be sufficient to increase yield if disease remains severe during tuber bulking. Moreover, the crop was harvested on 8 June, and the disease assessment period may not have captured the full effect of treatments on canopy retention and tuber development.

The lack of yield improvement also indicates that the biological treatments did not produce a strong plant-growth-promoting effect under the conditions of this trial. Some *Trichoderma* and *Pseudomonas* strains can enhance nutrient acquisition, root growth, stress tolerance, and induced resistance. However, these effects are strain-specific and may depend on soil properties, nutrient status, temperature, and plant developmental stage. In Nepalese field trials, selected native *Trichoderma* isolates increased plant growth and tuber yield substantially, but those results were obtained with isolates specifically selected for local performance and over multiple seasons (Rokaya et al., 2023). The commercial or experimental formulations used in the present study may require further optimization before similar benefits can be expected.

4.6. Relationship between disease and yield

The relationship between AUDPC and tuber yield was weak, positive, and nonsignificant ($r = 0.249$, $P = 0.291$); AUDPC explained only 6.2% of the variation in yield. This positive direction was unexpected because greater late-blight development would generally be expected to reduce yield by decreasing photosynthetic leaf area. However, the result should not be overinterpreted. The correlation was not significant, and the small sample size, limited disease observations, and variation among plots may have obscured the expected negative relationship.

Several biological explanations are also possible. Disease severity may have increased after the most important period of tuber bulking, when foliage loss would have had a smaller effect on final yield. Alternatively, yield may have been influenced more strongly by plant stand, soil fertility, irrigation, seed-tuber vigor, or plot-level variability than by the differences in AUDPC. The use of disease ratings based on tagged plants may also have introduced a mismatch between measured disease and the disease status of the entire plot.

Future experiments should record yield components, including number of tubers per plant, average tuber weight, marketable yield, and tuber size distribution. Repeated measurements of canopy cover and green-leaf duration would help clarify whether a treatment protects the crop long enough to influence tuber bulking. It would also be useful to analyze the relationship between yield and disease severity at specific growth stages rather than relying only on total-season AUDPC.

4.7. Implications for integrated management

Overall, the results indicate that *T. viride* has potential as a component of integrated late-blight management at the Mude site, but it should not yet be considered a stand-alone replacement for fungicides. The treatment produced the lowest disease severity and AUDPC numerically, and its mean disease severity was significantly lower than that of *P. fluorescens*. Nevertheless, the absence of significant differences in AUDPC and yield demonstrates that the level of protection was insufficiently consistent under the disease pressure encountered in this experiment.

Biological products may be more useful when incorporated into an integrated program involving resistant or moderately resistant cultivars, disease forecasting, sanitation, suitable planting dates,

optimized irrigation, and judicious fungicide use. Previous field research has shown that formulated microbial agents can sometimes reduce the number of fungicide applications required, even when they do not provide complete control alone (Islam et al., 2022). Such an approach could reduce chemical inputs while maintaining adequate disease protection.

For Nepal, locally adapted strains deserve particular attention. The positive performance of native *Trichoderma* isolates in Nepal suggests that future work should compare the present *T. viride* formulation with locally selected isolates, determine the most effective dose and spray interval, and evaluate treatment performance across different potato-growing regions. Multi-season experiments are especially important because disease pressure and weather conditions can vary considerably between years.

5. Limitations and future research

The study provides useful field-based evidence, but several limitations should be considered:

1. The experiment was conducted at one location during one growing season, limiting the generalization of the results.
2. Disease was assessed on four dates only, which may not fully represent a rapidly developing epidemic.
3. The microbial treatments were applied after disease onset, whereas preventive application may have produced stronger protection.
4. The study did not quantify microbial survival, colonization, or compatibility in the consortium.
5. The trial used a single cultivar, dose, formulation, and application interval.
6. The experiment did not include a standard fungicide treatment, so the relative performance of the biological treatments against conventional management could not be evaluated.
7. Yield was measured as total plot yield without detailed analysis of marketable yield or tuber-size classes.

Future research should evaluate locally adapted strains, preventive and curative application schedules, and separate versus simultaneous application of the two microorganisms. Molecular or culture-based monitoring of microbial populations would help determine whether poor performance resulted from inadequate establishment. Studies should also include a fungicide standard and integrated treatments in which biopesticides are combined with reduced fungicide programs. Multi-location and multi-year trials, together with disease forecasting and economic analysis, will be necessary to determine whether *T. viride* can provide reliable and economically meaningful protection under Nepalese production conditions.

Declarations

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Competing interests

The authors declare that they have no competing interests.

Authors' contributions

Rajan Dhamaniya conceived and designed the study, conducted the field experiment, collected and analyzed the data, and drafted the manuscript. All authors reviewed and approved the final manuscript.

Data availability

The datasets generated and/or analyzed during the current study are available from the corresponding author on reasonable request.

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Figures

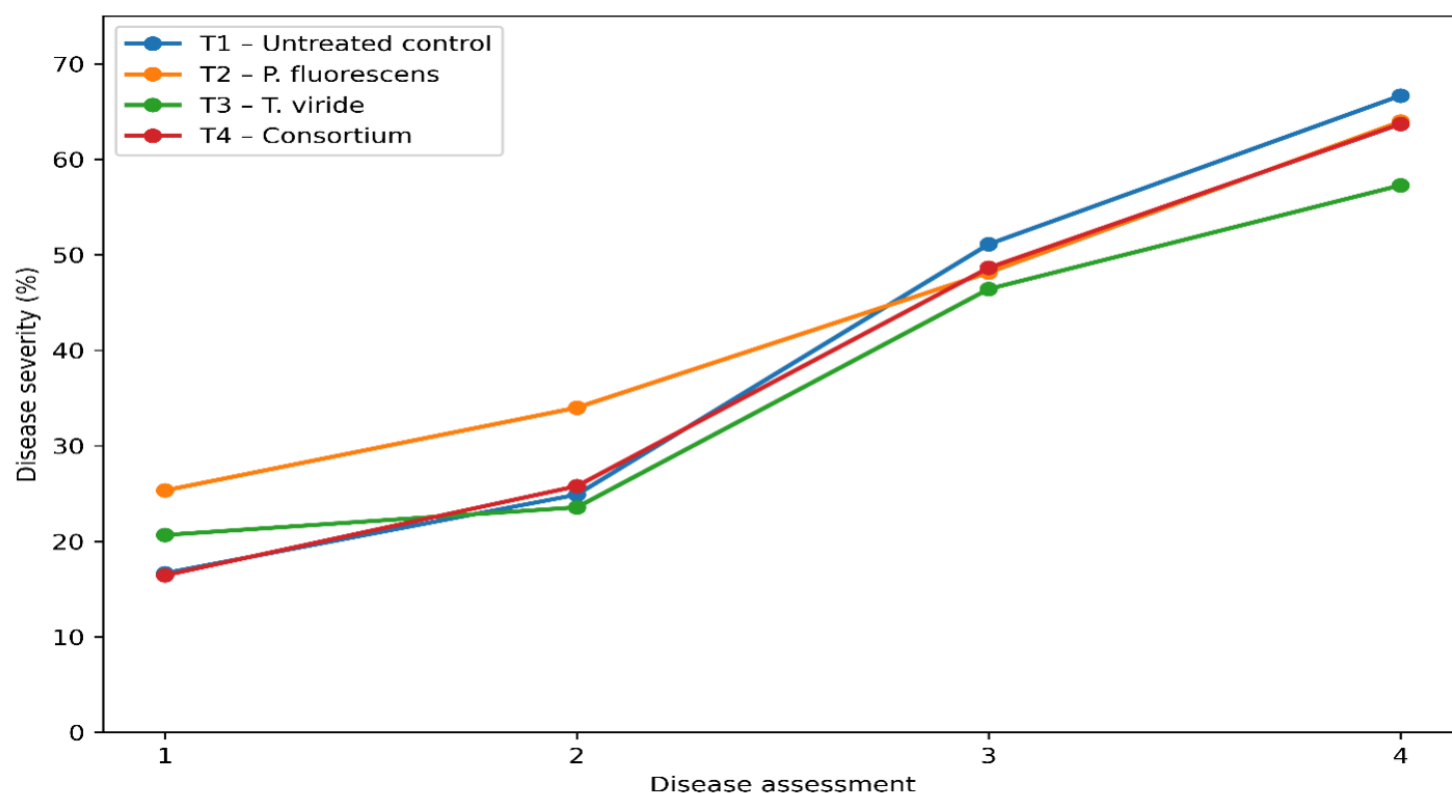


Figure 1

Disease progression curve showing mean disease severity (%) of potato late blight under protected field conditions across four disease assessments.

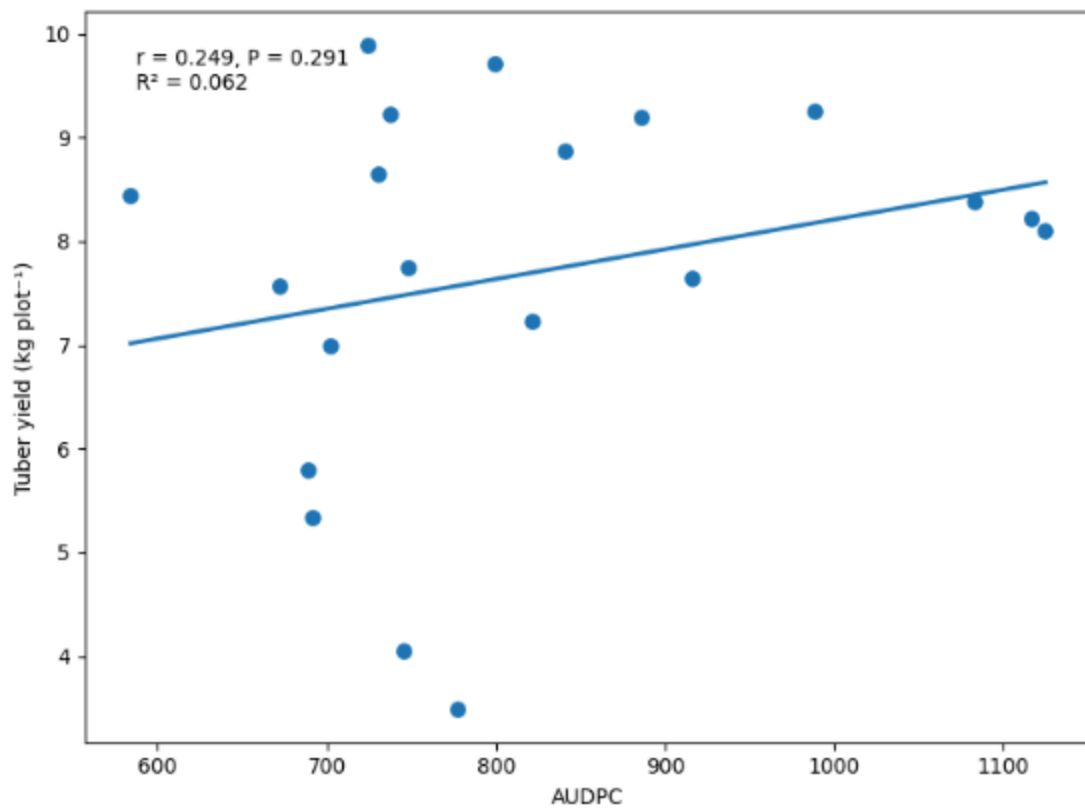


Figure 2

Relationship between AUDPC and tuber yield of potato under different biopesticide treatments.