



Efficacy of Biocontrol Agents as Potential Control Alternatives in Managing Blight Diseases of Potato (*Solanum tuberosum* L.)

Yvonne Hadzhi^{1,2} · Julia Sibiya^{1,3} · Lerato Matsaunyane² · Isack Mathew⁴



Received: 24 July 2025 / Accepted: 4 May 2026 / Published online: 29 May 2026
© The Author(s) 2026

Abstract

Late blight, caused by *Phytophthora infestans*, is one of the most important potato diseases globally, resulting in significant production losses. The pathogen is highly variable, adapting to newly developed cultivars and fungicides. In this study, several biocontrol agents and chemicals were evaluated in 2021 and 2022 seasons, for efficacy against blight disease in potato under field conditions. Treatments—applied individually and in combinations—included *Bacillus*, *Trichoderma*, Bioneem, *Lantana* extract, phosphite and mancozeb, and a water sprayed control (no chemical). Disease severity was higher in 2022 than in 2021, with slow progression observed between days 7 and 21, followed by a sharp increase from day 21 to day 28. Across the seasons, mancozeb consistently showed the lowest late and early blight infection rates (66.7–75.0%) by day 28, compared to 91–100% for other treatments. However, no significant differences ($p > 0.05$) in the area under disease progress curve (AUDPC) were observed among treatments due to the surge in disease severity during the final week of assessment. Among biocontrol options, *Trichoderma*, *Trichoderma* + *Bacillus* and Bioneem were the most effective in suppressing disease. *Lantana* extract also showed potential but requires further optimisation regarding dosage and application frequency. Whilst chemical control using mancozeb and phosphite remained superior, the combination of *Trichoderma* + *Bacillus* is recommended as a promising biocontrol alternative for managing blight diseases in potato production.

Keywords *Alternaria alternata* · Biocontrol · Botanical extracts · *Phytophthora infestans* · Synergism

Introduction

South Africa is one of the largest producers of potatoes in the world (Steyn et al. 2016). The potato industry plays an important role in the country's economy, providing employment opportunities and contributing to both local and international markets (Ortiz and Mares 2017). Potato cultivation in South Africa has increased over the years with a record high of over 2.5 million tonnes of production reported in 2020 (Statista 2023). Both small- and large-scale farmers currently produce potatoes (Apraku et al. 2021).

Despite its important contribution to food security, potato production across the world is challenged by several pests and diseases (Shimira et al. 2020). Late blight caused by *Phytophthora infestans* is one of the most devastating diseases of potato globally (Islam et al. 2018), infecting leaves, stems, and tubers at any stage of development (Islam et al. 2018). Rahman et al. (2008) reported that about 25 to 57% yield losses occur due to late blight depending on the degree of susceptibility of the cultivar, time of appearance, and age of the plant at infection. Epidemiological studies indicate that the disease is devastating at 12–25 °C and a relative humidity of more than 85% (Berhan 2021). Early blight, caused by *Alternaria solani*, is another important foliar disease of potatoes worldwide (Abuley and Nielsen 2019). The disease has been reported to cause yield losses between 24 and 54% in Denmark and Germany, respectively.

Several methods have been used to manage blight diseases of potatoes, with chemical fungicides being the most widely used strategy (Axel et al. 2012). However, over-reliance on chemical fungicides has led to resistance development by some pathogens. Apart from fungicide resistance, some of these chemicals have been linked to negative effects on human and animal health, and environmental impacts (Bisht and Chauhan 2020). Therefore, alternative and more sustainable control strategies are required to complement chemical control, whilst reducing the negative impacts.

There are proposals supporting the use of biocontrol and botanical extracts to replace chemical fungicides in potato production (Ab Rahman et al. 2018). Biocontrol involves the use of living organisms such as *Bacillus* bacteria, *Trichoderma* fungal spp., mycoviruses or plant-derived extracts to control plant diseases (Baker et al. 2020). Biological control of plant pests and pathogens is a low-cost, eco-friendly and sustainable strategy for crop protection (Ab Rahman et al. 2018). Biocontrol can be combined with other strategies like chemical control and agronomic practices, making it an attractive proposition for crop production.

Currently, *Trichoderma* has been the most commercialised biocontrol agent and reported to be effective against diverse range of plant pathogens (Mukhopadhyay and Kumar 2020). However, there is a need for more control options that are compatible across diverse cropping systems. For example, *Bacillus* spp., *Lantana* and Bioneem extracts have been tested and found to be effective against various pathogens in different crop species (Yaseen 2020; Lal et al. 2021). The main challenge limiting the use of biocontrol agents has been their relatively low activity and poor efficacy under field conditions (Tucci et al. 2011) due to both biotic

(mostly related to host plant and field microflora) and abiotic factors including texture and components of the soil, pH, temperature, moisture and combinations of other pesticide formulations used (Boro et al. 2022). There are also problems with developing effective and farm applicable formulations at commercial level (Tucci et al. 2011). It is not easy to find, develop, and implement biocontrol strategies that reduce pests and diseases to levels below the economic threshold (Lal et al. 2021). Therefore, continuous efforts are required to assess efficacy of different biocontrol agents individually and in combination with other control methods for effective control of blight diseases in potato production. Hence, the objective of this study was to determine the efficacy of biocontrol agents and chemical fungicides against blight diseases of field grown potato cultivars under natural blight infection.

Materials and Methods

Study Area

The experiment was conducted at the Agricultural Research Council-Vegetable Industrial and Medicinal Plants (ARC-VIMP), Roodeplaat, Pretoria, South Africa, in 2021 and 2022 seasons. The site is characterised by sandy loam soil type, with soil pH values within the range of 5.5 to 6.2. During the 2021 and 2022 seasons, Roodeplaat had an annual rainfall averaging 689 mm and average maximum and minimum temperatures of 25 °C and 10 °C, respectively, between September and December of both 2021 and 2022. These conditions are conducive for potato production.

Planting Materials, Chemical Fungicides, and Biological Agents

In both seasons, Lanoma, a potato variety moderately susceptible to blight diseases, was obtained from an agro-dealer and used for the assessment. Two chemical fungicides, mancozeb and phosphite, and four biological control agents, namely *Trichoderma* (Real IPM, South Africa), *Bacillus* (Real IPM and Bio grow, South Africa), Bioneem (Bio grow, South Africa) and *Lantana camara*, whilst *Lantana* is a naturally occurring plant species and extract, were evaluated individually and mixed in different combinations in both seasons to determine their effectiveness against late blight and early blight diseases (Murmu et al. 2015; Chauhan et al. 2017). This resulted in 12 treatments which were *Bacillus*, Bioneem, Bioneem + *Trichoderma* + *Bacillus*, mancozeb, *Lantana*, *Lantana* + phosphite, *Lantana* + *Trichoderma*, *Lantana* + *Trichoderma* + *Bacillus*, control (water spray), phosphite, *Trichoderma*, and *Trichoderma* + *Bacillus*. The active ingredients and formulations for the treatments are indicated in Table 1. All the biological agents used have been introduced in South Africa for registration.

The treatments were prepared by dissolving a specified amount of either the chemical or biological agent in plain distilled water as indicated in Table 1. Each of the treatments was mixed with 16 L of distilled water in a 20-L knap sack sprayer.

Table 1 Composition of biocontrol agents and chemical treatments tested against blight disease in potato plants

Treatment	Agents	Active ingredient	Dosage/m ²
Bioneem		By mass azadirachtin 1.5 g/ℓ	0.018 L/m ² Bioneem mixed with 16 L of water in a 20-L knap sack sprayer
Bacillus		<i>Bacillus methylothrophicus</i> 2 × 10 ⁹ CFU/mL	0.06 L/m ² <i>Bacillus</i> mixed with 16 L of water in a 20-L knap sack sprayer
Bioneem + <i>Trichoderma</i> + <i>Bacillus</i>		Bioneem: by mass azadirachtin 1.5 g/ℓ + <i>Trichoderma asperellum</i> Strain TRC900. + <i>Bacillus methylothrophicus</i> 2 × 10 ⁹ CFU/mL	0.018 L/m ² Bioneem, 0.05 L/m ² <i>Trichoderma</i> and 0.06 L/m ² <i>Bacillus</i> mixed with 16 L of water in a 20-L knap sack sprayer
Chemical mancozeb		A mixed product of zinc ion and manganese ethylene bisdithiocarbamate	60 g/m ² of mancozeb mixed with 16 L of water in a 20-L knap sack sprayer
<i>Lantana</i>		Triterpenoids like lactic acid and camaric acid, as well as compounds like germacrene-D, β-caryophyllene and β-cureumene	600 g/m ² diluted in 2.5 L/m ² of <i>Lantana</i> mixed with 16 L of water in a 20-L knap sack sprayer
<i>Lantana</i> + phosphite		Triterpenoids like lactic acid and camaric acid, as well as compounds like germacrene-D, β-caryophyllene and β-cureumene + potassium phosphite 560 g/L + phosphorous acid equivalent 400 g/L	600 g/m ² <i>Lantana</i> mixed on 2.5 L/m ² and 0.04 L/m ² of phosphite mixed with 16 L of water in a 20-L knap sack sprayer
<i>Lantana</i> + <i>Trichoderma</i>		Triterpenoids like lactic acid and camaric acid, as well as compounds like germacrene-D, β-caryophyllene and β-cureumene + <i>Trichoderma asperellum</i> strain TRC900	600 g/m ² diluted in 2.5 L/m ² of <i>Lantana</i> , 0.05 L/m ² <i>Trichoderma</i> —mixed with 16 L of water in a 20-L knap sack sprayer
<i>Lantana</i> + <i>Trichoderma</i> + <i>Bacillus</i>		Triterpenoids like lactic acid and camaric acid, as well as compounds like germacrene-D, β-caryophyllene and β-cureumene + <i>Trichoderma asperellum</i> strain TRC900 + <i>Bacillus methylothrophicus</i> 2 × 10 ⁹ CFU/mL	0.05 L/m ² <i>Trichoderma</i> and 0.018 L/m ² Bioneem, diluted in 2.5 L/m ² —mixed with 16 L of water in a 20-L knap sack sprayer
No chemical (water spray, control)		Water only	16 L/m ²
Phosphite		Potassium phosphite 560 g/L + phosphorous acid equivalent 400 g/L	0.04 L/m ² of phosphite mixed with 16 L of water in a 20-L knap sack sprayer
<i>Trichoderma</i>		<i>Trichoderma asperellum</i> strain TRC900	0.05 L/m ² <i>Trichoderma</i> mixed with 16 L of water in a 20-L knap sack sprayer
<i>Trichoderma</i> + <i>Bacillus</i>		<i>Trichoderma asperellum</i> strain TRC900 + <i>Bacillus methylothrophicus</i> 2 × 10 ⁹ CFU/mL	0.05 L/m ² <i>Trichoderma</i> and 60 mL <i>Bacillus</i> mixed with 16 L water in a 20-L knap sack sprayer

The control treatment consisted of distilled water only. Each treatment was applied manually using a 20-L knapsack sprayer. Spraying started 50 days after crop emergence, as soon as the blight diseases were visually observed on the moderately susceptible variety and repeated four times at 7-day intervals for 28 days.

Experimental Design and Plot Establishment

The experiments were laid out in a randomised complete block design (RCBD) with six replications per treatment (Box 1980; Stridh et al. 2022). Each plot comprised of four, 3.0-m-long rows with inter-row and intra-row spacings of 1.0 m and 0.3 m, respectively. Each row had 10 plants resulting in a total of 40 plants per plot. The field area planted was 30 m × 48 m, giving a total area of 1440 m². The plants were weeded three times at 30-day intervals. Ridging of rows was done twice throughout the growing season. Irrigation was scheduled two times a day during the first 14 days after planting, and from the third week after planting, the plants were irrigated once every day in the morning.

Data Collection

Disease severity data was collected based on the proportion of late and early blight symptoms on the plant foliage and stems. Leaf diseases severity was visually estimated and recorded according to the 6-point scale proposed by Messiha et al. (2007) and later modified by Bensaci et al. (2021). It consisted of recording the disease onset (DO) of both late blight and early blight, thereafter severity of each recorded on the foliage and the stem of the plant at 7-day intervals.

Description of the disease scale is as follows:

-
- 0 = no visible symptoms (immune),
 - 1 = 10% on the total leaf area and stems blighted, usually confined to the two bottom leaves (highly resistant),
 - 2 = 25% leaf area and stems infected (resistant),
 - 3 = 50% of the total plant area and stems infected (tolerant),
 - 4 = 75% of the total plant area infected (susceptible) and
 - 5 = leaves and stems on whole plant (100%) are blighted and plant is dead (highly susceptible)
-

Area under disease progression curve (AUDPC), which quantifies disease development over time, was also calculated from the estimated percentage of the area affected on the leaf and stems, recorded during different times of the growing season. This was based on the formula by Simko and Piepho (2012) shown below.

$$\text{AUDPC} = \sum_{i=1}^{n-1} \frac{y_i + y_{i+1}}{2} x(t_{i+1} - t_i)$$

where y_i is the disease severity (percentage, proportion or ordinal score, etc.) at time i (in days, hours, etc.); t_i is the time at which disease severity was measured, $\sum$

indicates summation over all time points and n is the total number of observations. The AREA ($y; x$) function that numerically integrates the curve running through the points specified by variates y and x using the trapezoidal method in Genstat for Windows was used to calculate the AUDPC.

Data Analysis

The general linear model procedure (PROC GLM) in SAS version 9.4 statistical software (SAS 2016) was used to analyse the data collected. Analysis of variance (ANOVA) was used to test the significance of treatment effects on controlling blight and severity. Fisher's protected t -least significant differences (LSDs) were calculated ($\alpha=0.05$) to compare means of significant effects (Ott 1998). A probability level of 5% was considered significant for all significance tests.

Results

Seasonal comparison showed that both late and early blight infections were higher in the 2022 growing season as compared to the 2021 growing season shown by the AUDPCs (Tables 2 and 3). Although the overall AUDPC did not show significant differences, in both 2021 and 2022 seasons, respectively, late blight disease development was lower for phosphite (AUDPC 670.8 and 845.8), mancozeb (AUDPC 688.3 and 886.5), *Trichoderma* (AUDPC 714.7 and 880.8) and *Trichoderma*+*Bacillus* (AUDPC 685.5 and 819.7), compared to the rest of the treatments. Similarly, for early blight disease, the AUDPCs in both 2021 and 2022 seasons were lower for *Trichoderma* (694.2, 778.8) and *Trichoderma*+*Bacillus* (685.5, 764.2), respectively. In addition, for early blight disease, the AUDPC for Bioneem+*Trichoderma*+*Bacillus* (723.3) was lower in 2021, and lower for phosphite (740.8) and mancozeb (822.5) in 2022 season. *Lantana* combinations (particularly with *Trichoderma* or phosphite) showed higher AUDPC values, indicating reduced efficacy.

In terms of late blight percentage infection (Table 2), all the treatments showed a gradual increase in disease severity from day 7 to day 21, followed by a rapid disease development from day 21 to day 28, except for mancozeb and phosphite treatments in 2021 season where a decrease in disease severity was observed from day 14 to day 21. Overall, mancozeb had lower percentage late blight disease infection by day 28 (66.7–75.0%) across the two seasons, whilst for the rest of the treatments, by day 28, percent disease severity was between 91 and 100%.

As shown in Table 3, early blight disease development showed a similar pattern as late blight. There was slow progress in disease development between days 7 and 21, followed by a sharp increase in disease severity from day 21 to day 28. A decrease in disease severity was observed for *Bacillus* and *Trichoderma* treatments in both seasons from day 14 to day 21, whilst *Lantana*+*Trichoderma* showed a decrease from day 14 to day 21 in 2022 before the rapid increase from day 21. As observed for late blight infection, the final disease severity for early blight was lower for mancozeb

Table 2 Treatment means from analysis of variance on percentage late blight infection in the 2021 and 2022 growing seasons

Treatment	Percentage late blight infection 2021*				Percentage late blight infection 2022*				AUDPC	AUDPC
	Day 7	Day 14	Day 21	Day 28	Day 7	Day 14	Day 21	Day 28		
<i>Bacillus</i>	15.0 ^a	29.2 ^{abc}	37.5 ^{abc}	95.8 ^a	37.5 ^a	32.5 ^a	41.7 ^a	95.8 ^a	854.7 ^a	989.0 ^a
Bioneem	10.0 ^b	12.5 ^a	36.7 ^{abcd}	95.8 ^a	21.7 ^a	36.6 ^a	41.7 ^a	95.8 ^a	714.5 ^a	959.7 ^a
Bioneem + <i>Trichoderma</i> + <i>Bacillus</i>	10.0 ^b	20.0 ^{ab}	30.8 ^{abcd}	100.0 ^a	17.5 ^a	30.8 ^a	47.9 ^a	100.0 ^a	740.8 ^a	962.3 ^a
Chemical (mancozeb)	10.0 ^b	30.8 ^{abc}	29.7 ^{bcd}	66.7 ^b	24.2 ^a	33.3 ^a	43.8 ^a	75.0 ^b	688.3 ^a	886.5 ^a
<i>Lantana</i>	10.0 ^b	25.8 ^{abc}	33.3 ^{abcd}	95.8 ^a	28.3 ^a	39.2 ^a	43.8 ^a	95.8 ^a	784.7 ^a	1015.2 ^a
<i>Lantana</i> + phosphite	10.0 ^b	20.0 ^{abc}	45.8 ^{ab}	91.7 ^a	25.0 ^a	45.0 ^a	48.7 ^a	91.7 ^a	816.8 ^a	1064.7 ^a
<i>Lantana</i> + <i>Trichoderma</i>	10.0 ^b	16.7 ^{abc}	50.0 ^a	100.0 ^a	16.0 ^a	39.2 ^a	52.9 ^a	100.0 ^a	851.7 ^a	1052.8 ^a
<i>Lantana</i> + <i>Trichoderma</i> + <i>Bacillus</i>	10.0 ^b	22.5 ^{bc}	37.5 ^{abc}	95.8 ^a	25.0 ^a	37.5 ^a	54.2 ^a	95.8 ^a	790.5 ^a	1064.5 ^a
No chemical	10.0 ^b	37.5 ^a	37.5 ^{abc}	95.8 ^a	25.0 ^a	35.2 ^a	50.8 ^a	95.8 ^a	895.5 ^a	1023.7 ^a
Phosphite	10.0 ^b	23.3 ^{bcd}	17.5 ^d	100.0 ^a	25.8 ^a	26.7 ^a	31.2 ^a	100.0 ^a	670.8 ^a	845.8 ^a
<i>Trichoderma</i>	10.0 ^b	20.0 ^{bcd}	29.2 ^{bcd}	95.8 ^a	24.2 ^a	24.2 ^a	43.7 ^a	91.7 ^a	714.7 ^a	880.8 ^a
<i>Trichoderma</i> + <i>Bacillus</i>	10.0 ^b	19.2 ^{cd}	25.8 ^{cd}	95.7 ^a	19.2 ^a	25.8 ^a	33.8 ^a	95.8 ^a	685.5 ^a	819.7 ^a
$F_{11,55}$	2.50	2.13	1.61	6.12	1.46	0.56	1.23	2.91	1.42	0.75
p value	0.0126	0.0330	0.1217	< 0.001	0.1733	0.8534	0.2912	0.0044	0.1921	0.6908
$LSD_{p = 0.05}$	2.59	13.22	-	10.27	-	-	-	11.18	-	-

Table 3 Treatment means from analysis of variance on percentage early blight infection in the 2021 and 2022 growing seasons

Treatment	Percentage early blight infection 2021 *				AUDPC		Percentage early blight infection 2022*				AUDPC	
	Day 7	Day 14	Day 21	Day 28			Day 7	Day 14	Day 21	Day 28		
<i>Bacillus</i>	15.0 ^a	37.5 ^a	32.5 ^{ab}	95.8 ^a	878.0 ^a		29.2 ^{ab}	37.5 ^a	32.5 ^a	95.8 ^a	927.7 ^a	
Bioneem	10.0 ^b	21.7 ^a	36.6 ^a	95.8 ^a	778.7 ^a		12.5 ^c	36.6 ^a	36.7 ^a	95.8 ^a	892.7 ^a	
Bioneem + <i>Trichoderma</i> + <i>Bacillus</i>	10.0 ^b	17.5 ^a	30.8 ^a	100.0 ^a	723.3 ^a		20.0 ^{bc}	30.8 ^a	30.8 ^a	100.0 ^a	852.0 ^a	
Chemical (mancozeb)	10.0 ^b	30.8 ^a	37.5 ^a	66.7 ^b	775.7 ^a		26.7 ^{ab}	33.3 ^a	37.5 ^a	66.7 ^b	822.5 ^a	
<i>Lantana</i>	10.0 ^b	28.3 ^a	39.1 ^a	95.8 ^a	843.0 ^a		25.8 ^{ab}	33.3 ^a	39.2 ^a	95.8 ^a	933.3 ^a	
<i>Lantana</i> + phosphite	10.0 ^b	25.0 ^a	45.0 ^a	91.7 ^a	845.7 ^a		20.0 ^{bc}	45.8 ^a	45.0 ^a	91.7 ^a	1026.8 ^a	
<i>Lantana</i> + <i>Trichoderma</i>	10.0 ^b	16.7 ^a	39.1 ^a	100.0 ^a	775.8 ^a		16.7 ^{bc}	50.0 ^a	39.2 ^a	100.0 ^a	1032.5 ^a	
<i>Lantana</i> + <i>Trichoderma</i> + <i>Bacillus</i>	10.0 ^b	22.5 ^a	37.5 ^a	95.8 ^a	790.5 ^a		25.0 ^{abc}	37.5 ^a	37.5 ^a	95.8 ^a	948.3 ^a	
No chemical	10.0 ^b	25.0 ^a	35.0 ^a	95.8 ^a	790.3 ^a		37.5 ^a	35.5 ^a	35.0 ^a	95.8 ^a	974.3 ^a	
Phosphite	10.0 ^b	25.8 ^a	26.7 ^a	100.0 ^a	752.5 ^a		23.3 ^{bc}	17.5 ^a	26.7 ^a	100.0 ^a	740.8 ^a	
<i>Trichoderma</i>	10.0 ^b	24.2 ^a	24.1 ^a	91.7 ^a	694.2 ^a		20.0 ^{bc}	29.2 ^a	24.2 ^a	95.8 ^a	778.8 ^a	
<i>Trichoderma</i> + <i>Bacillus</i>	10.0 ^b	19.2 ^a	25.8 ^a	95.8 ^a	685.5 ^a		19.2 ^{bc}	25.8 ^a	25.8 ^a	95.8 ^a	764.2 ^a	
$F_{11;55}$	2.50	1.71	0.58	2.91	0.62		2.01	1.56	0.58	6.12	0.82	
<i>p</i> value	0.0126	0.0964	0.8392	0.0044	0.8013		0.0445	0.1361	0.8392	<0.001	0.6184	
$LSD_{p=0.05}$	2.59	12	-	11.18	-		13.00	-	-	10.27	-	

*Means per column followed by the same letter are not significantly different at the 5% level

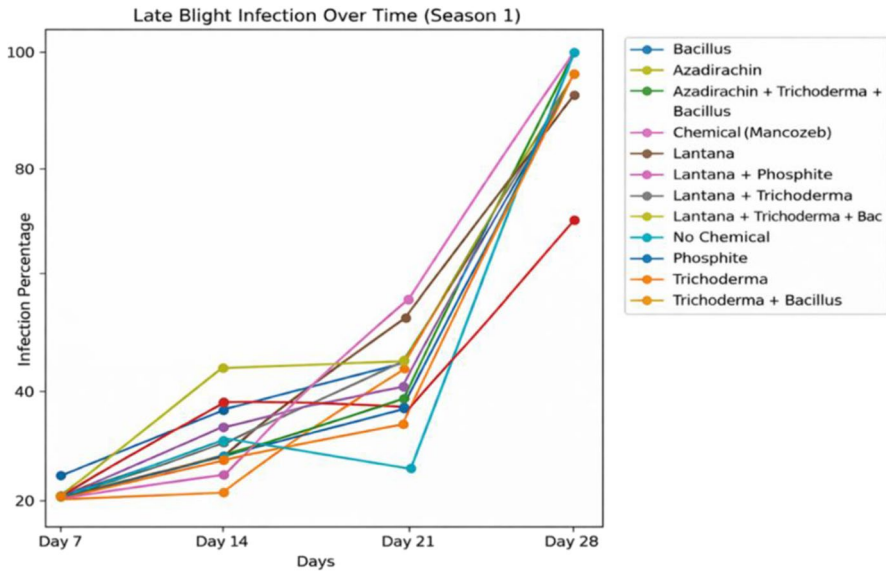


Fig. 1 Disease progression curves for late blight from the day of treatment application during season 1

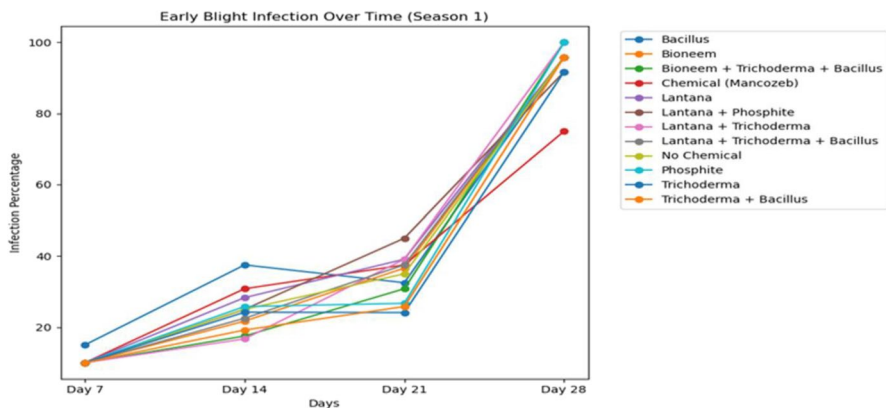


Fig. 2 Disease progression curves for early blight from the day of treatment application during season 1

(66.7–75.0%) across the seasons, whilst the rest of the treatments ranged between 91 and 100% across the seasons.

Distinct trends developed in treatment effectiveness and disease development as depicted by the disease progression over time graphs (Figs. 1, 2, 3 and 4), showing how each treatment performed across four time points for both late blight and early blight in the two seasons. In particular, the disease development slowed between day 14 and day 21 for most of the treatments. For late blight in 2021 (Fig. 1), phosphite and mancozeb showed the greatest disease suppression depicted by a sharp decrease between day 14 and day 21 (Fig. 1), whilst the rest of the treatments showed a less

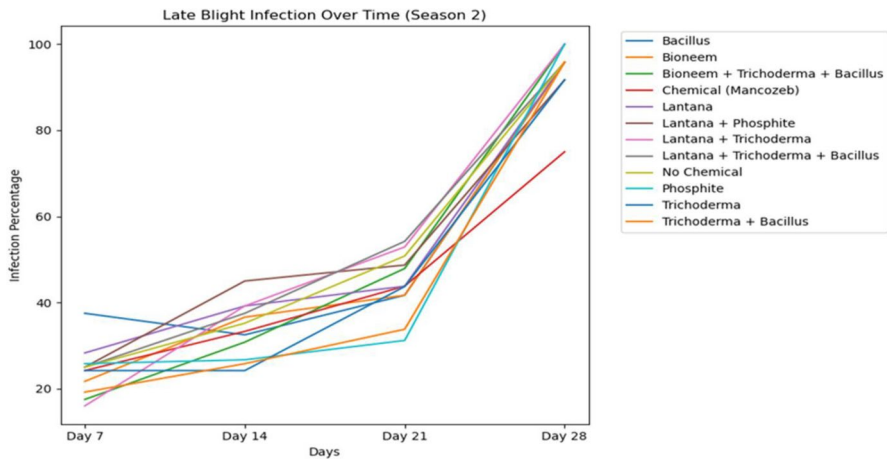


Fig. 3 Disease progression curves for late blight from the day of treatment application during season 2

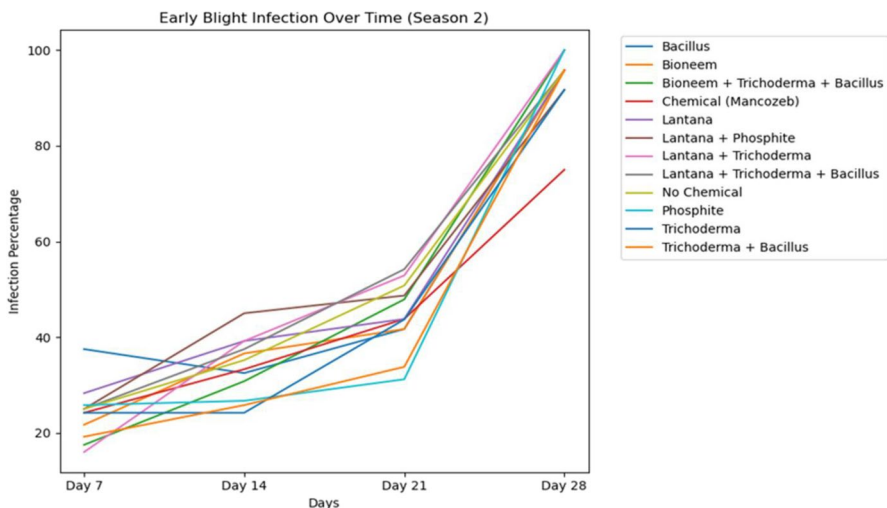


Fig. 4 Disease progression curves for early blight from the day of treatment application during season 2

marked decrease in the development of the disease. This trend showed the significance of the control intervention. Similarly, for early blight in season 1 (Fig. 2), *Trichoderma*, *Bacillus* and phosphite had a marked disease reduction between day 14 and day 21. Overall, biological treatments, particularly *Trichoderma* + *Bacillus*, outperformed chemical controls, and mid-season time points were critical for evaluating disease progression.

Trends in season 2 (Figs. 3 and 4) were more or less like what was observed in season 1. For late blight disease, there was a slight decrease observed from day 7 to day 14 for *Bacillus* and phosphite treatments. *Trichoderma* treatment showed no

change in disease between day 7 and day 14. The rest of the treatments showed a gradual increase in disease severity from day 7 to day 21, followed by the rapid increase from day 21 to day 28. For early blight disease (Fig. 4), *Trichoderma* and *Bacillus* had a slight decrease in disease severity between day 7 and day 14, whilst there was an insignificant change for phosphite treatment change between day 7 and day 14. The rest of the treatments showed a gradual increase in disease severity from day 7 to day 21, followed by a sharp increase from day 21 to day 28.

Discussion

The current study assessed the effects of different control methods on a moderately susceptible Lanoma potato cultivar in response to blight disease infection. The study demonstrated clear trends in treatment efficacy and important disease progression stages. Infections varied significantly between seasons with the 2022 season reporting high infection for both early and late blight diseases as compared to the 2021 season. This could be attributed to the continuous accumulation of sporangia with zoospores over time with the continuous production of the potatoes in the same fields from 2021 to 2022 seasons. Tubers were stored in isolated areas prior to planting to ensure proper preparation for the growing season and to prevent tuber blight. Integrated strategies for managing late blight in the future should focus on controlling primary inoculum sources, adjusting fungicide applications to prevailing weather conditions, and selecting resistant cultivars as key priorities.

Variations in blight infection can also be linked to weather factors like temperature, rainfall, dew and humidity, all of which significantly influence the onset and progression of late blight epidemics (Gautam et al. 2013; Narouei-Khandan et al. 2020; Boro et al. 2022). The mancozeb, phosphite, *Trichoderma*, *Trichoderma* + *Bacillus* combination and Bioneem treatments all showed lower AUDPCs compared to the control (water spray) treatment. Infection rates of late blight were greater the 2022 growing season compared to 2021. Early blight infection was also significantly higher in the 2022 growing season than in the 2021 growing season. High rainfall and cool weather conditions contribute to the infection of blight diseases as they are more favourable for the diseases to occur in open fields. In this study, high rainfall was experienced causing the increased severity of the blight diseases.

In 2021 for late blight disease, phosphite and mancozeb had low AUDPC, indicating greater disease suppression than the other treatments, particularly after a high reduction from day 14 to day 21. The untreated controls had the highest AUDPC, demonstrating the significance of no control treatment. Day 21 was critical as treatments diverged greatly, affecting the overall AUDPC.

Trichoderma and the combination of *Trichoderma* with *Bacillus* emerged as the most effective biological treatments, consistently showing lower AUDPC values across both seasons and demonstrating superior disease suppression throughout the 4-week evaluation period. *Trichoderma* could have a significant part in integrated

pest management (IPM) strategies. Biocontrol characteristics have been isolated from many different kinds of *Trichoderma*.

The least effective treatments were *Lantana*+phosphite and *Lantana*+*Trichoderma*+*Bacillus*, which had amongst the highest AUDPCs. *Lantana*+*Trichoderma* and the untreated control (water spray only—no chemical) both were significantly lower than the other treatments, indicating inadequate control.

Mancozeb, phosphite, *Trichoderma*+*Bacillus* combination, *Trichoderma* and Bioneem treatments, although not significantly different, showed a reduction of late blight disease when compared to the untreated plots (no chemical control treatment), especially between day 14 and day 21. Chemical efficacy in the study corroborates with previous studies that have shown that it is the most reliable strategy compared to other methods of disease management (Figueroa et al. 2018). The results also highlighted the significance of mid-season time points (days 14 and 21), which had the largest correlations with disease development, making them critical for monitoring and altering methods of treatment.

Overall, the findings suggest integrated biological approaches to blight management, which are more successful and sustainable. The combinations of treatments such as *Trichoderma*+*Bacillus* and Bioneem+*Trichoderma*+*Bacillus* that had lower AUDPC values would provide sustainable, environmentally beneficial alternatives to chemical fungicides. They may be considered additional, but not primary, treatments.

Chemical fungicides have high efficacy because they have been specifically developed to target different components or mechanisms of the fungal cell, including respiration, nucleic acid metabolism, cell membrane integrity, protein synthesis, signal transduction and cell mitosis (Ons et al. 2020). Chemical control in this study had an extended suppression-duration-effect, surpassing 4 weeks compared to the rest of the treatments, as depicted by the low disease severity by day 28. This is because fungicides have longer residual persistence unlike biocontrol extracts whose efficacy decreases rapidly due to their biodegradable nature (Norris and Coats 2017). This is why, in this study, a surge in disease was observed from day 21 for all the biologicals compared to the chemical (mancozeb) treatment. The trend analysis results indicate that the frequency of application is very crucial to improve or maintain the efficacy of biocontrol treatments.

Phosphite chemical also showed potential in suppressing disease progression compared to the other treatments as it is formulated to suppress the growth of blight pathogens on potato crops. *Bacillus* treatment did not show any significant differences with the control treatment (no chemical), showing its inefficiency against late blight on potato. In contrast, other reports have shown that *Bacillus* is effective against *Phytophthora* infection on wheat and soybean and *Capsicum* (Liu et al. 2019; Bhusal and Mmbaga 2020). This difference in results is expected as the efficacy of a control strategy depends on various factors including environmental effects on the tripartite interaction amongst the host plant, control method and pathogen (Alford 2008; Latz et al. 2018). The combination of *Trichoderma*+*Bacillus*, however, performed better than the respective individual treatments. This corroborates other studies which reported that a combination of *Trichoderma virens* (Tvien6) and *Bacillus velezensis* (X5) was more effective at controlling tomato bacterial wilt

disease than a single agent (Maketon et al. 2008; Yobo et al. 2011; John et al. 2016; Pertot et al. 2017).

Despite *L. camara* extracts not showing a significant control effect on blight diseases in this study, there was some level of disease suppression observed between day 7 and day 21. Other studies have shown that *Lantana* extracts contain strong antimicrobial activity (Girish 2017). *L. camara* extract is rich in total phenolics, flavonoids and alkaloids which are strong antimicrobial compounds capable of suppressing both human and plant diseases (Mansoori et al. 2020; Owusu 2022), making it a potential biocontrol agent to incorporate in an integrated pest management programme. The study conducted by Mansoori et al. (2020) showed that methanol extracts of *L. camara*'s leaves and flowers exhibit significant antioxidant and antibacterial properties. Many phytochemical components evaluated were found in variable amounts in both extracts, indicating variances in antioxidant and free radical scavenging capabilities. There was a positive connection between phenolic content and free radical scavenging capabilities (Mansoori et al. 2020). It should be noted that the good benefits and economic applications may outweigh the negative effects, which requires additional research studies on cost–benefit considerations for its management; however, the application was not 100% effective, and this might be because of heavy rains and more cool mornings during the plants' growth seasons.

Effective fungicides are crucial in control efforts, but there is political pressure to decrease their impact, particularly on the environment. Several fungicides that have been newly licenced in Europe for late blight management are generally effective at lower application rates and have less environmental negative effects (Cooke et al. 2011). Furthermore, whilst these fungicides provide more control options, the need for anti-resistance management has resulted in most being approved only in mixtures with existing fungicides. Since most cultivars grown have limited blight resistance, the demand for resistant potato varieties is increasing (Cooke et al. 2011). Breeding new potato cultivars with durable resistance to late blight combined with desirable agronomic traits is thus recommended. Although developing these varieties remains a slow process, the strategy is effective and may be accelerated using molecular markers.

Conclusion

The findings of this study showed that chemicals such as mancozeb and phosphate remain the most effective control strategy compared to biocontrol agents. However, inclusion of biocontrol agents that showed potential, as part of an integrated disease management to reduce the number of chemical sprays, is recommended. Using different combinations of biocontrol agents was more effective than the respective individual biocontrol agents. Hence, future research on biocontrol agents should focus on investigating the compatibility of pest and diseases integration practices in addition to the efficacy of the combinations. Biological control of plant pests and pathogens is a cost-effective, environmentally friendly

and long-term crop protection strategy and it can be integrated with other practices, such as chemical control and agronomic practices, making it an effective crop production method. AUDPC is more appropriate to evaluate the impact of disease that develop during plant growth.

Acknowledgements This study is part of a PhD research project undertaken by the first author at the University of KwaZulu-Natal, South Africa, and sponsored by the Agricultural Research Council-Vegetable Industrial and Medicinal Plants, executing all the research work.

Author Contribution All authors read, reviewed and approved the final manuscript.

Funding Open access funding provided by University of KwaZulu-Natal. This research was supported by the Agricultural Research Council.

Data Availability Data shall be made available upon request.

Declarations

Conflict of interest The authors declare no competing interests.

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by/4.0/>.

References

- Ab Rahman SFS, Singh E, Pieterse CM, Schenk PM (2018) Emerging microbial biocontrol strategies for plant pathogens. *Plant Sci* 267:102–111
- Abuley IK, Nielsen BJ (2019) Integrating cultivar resistance into the TOMCAST model to control early blight of potato, caused by *Alternaria solani*. *Crop Prot* 117:69–76
- Alford DV (2008) Pest and disease management handbook, 2nd edn. John Wiley & Sons, Inc, Hoboken, NJ
- Apraku A, Morton JF, Gyampoh BA (2021) Climate change and small-scale agriculture in Africa: does indigenous knowledge matter? Insights from Kenya and South Africa. *Sci Afr* 12:e00821
- Axel C, Zannini E, Coffey A, Guo J, Waters DM, Arendt EK (2012) Eco-friendly control of potato late blight causative agent and the potential role of lactic acid bacteria: a review. *Appl Microbiol Biotechnol* 96:37–48
- Baker BP, Green TA, Loker AJ (2020) Biological control and integrated pest management in organic and conventional systems. *Biol Control* 140:104095
- Bensaci OA, Beghami R, Gouaref K (2021) First report of *Apiognomonina errabunda* on *Quercus ilex* in Algeria. *Folia For Pol Ser A Lesn* 63(1):10–20
- Berhan M (2021) Review on epidemiology, sampling techniques, and management strategies of late blight (*Phytophthora infestans*) of potato and its yield loss. *Asian J Adv Res* 4(1):199–207
- Bhusal B, Mmbaga MT (2020) Biological control of *Phytophthora* blight and growth promotion in sweet pepper by *Bacillus* species. *Biol Control* 150:104373
- Bisht N, Chauhan PS (2020) Excessive and disproportionate use of chemicals cause soil contamination and nutritional stress. *Soil Contamination-Threats and Sustainable Solutions*, pp 1–10

- Boro M, Sannyasi S, Chettri D, Kumar Verma A (2022) Microorganisms in biological control strategies to manage microbial plant pathogens: a review. *Arch Microbiol* 204:666. <https://doi.org/10.1007/s00203-022-03279-w>
- Box JF (1980) RA Fisher and the design of experiments, 1922–1926. *Am Stat* 34(1):1–7
- Chauhan S, Ranjan A, Jindal T (2017) Biological control agents for sustainable agriculture, safe water and soil health. *Paradigms in pollution prevention*. Springer International Publishing, Cham, pp 71–83
- Cooke LR, Schepers HTAM, Hermansen A, Bain RA, Bradshaw NJ, Ritchie F, Shaw DS, Evenhuis A, Kessel GJT, Wander JGN, Andersson B (2011) Epidemiology and integrated control of potato late blight in Europe. *Potato Res* 54:183–222
- Figuerola M, Hammond-Kosack KE, Solomon PS (2018) A review of wheat diseases a field perspective. *Mol Plant Pathol* 19(6):1523–1536
- Gautam HR, Bhardwaj ML, Kumar R (2013) Climate change and its impact on plant diseases. *Curr Sci* 105(12):1685–1691
- Gitish K (2017) Antimicrobial activities of *Lantana camara* Linn. *Asian J Pharm Clin Res* 10(3):57–67
- Islam S, Raihan A, Nahiyan ASM, Siddique M, Rahman L (2018) Field screening and marker assisted selection of late blight resistant potato lines. *Int J Plant Soil Sci* 25:1–12
- John CJ, Jishma P, Arathy GB, Anisha C, Radhakrishnan EK (2016) Identification of plant growth promoting rhizosphere *Bacillus* sp. WG4 antagonistic to *Pythium myriotylum* and its enhanced antifungal effect in association with *Trichoderma*. *Journal of Soil Science. Plant Nutrition* 16:578–590
- Lal M, Chaudhary S, Rawal S, Sharma S, Kumar M, Chakrabarti SK (2021) Evaluation of bio-agents and neem based products against late blight disease (*Phytophthora infestans*) of potato. *Indian Phytopathol* 74(1):181–187
- Latz MA, Jensen B, Collinge DB, Jørgensen HJ (2018) Endophytic fungi as biocontrol agents: elucidating mechanisms in disease suppression. *Plant Ecol Divers* 11(5–6):555–567
- Liu D, Li K, Hu J, Wang W, Liu X, Gao Z (2019) Biocontrol and action mechanism of *Bacillus amyloliquefaciens* and *Bacillus subtilis* in soybean *Phytophthora* blight. *Int J Mol Sci* 20(12):2908
- Maketon M, Apisitsantikul J, Siriraweeul C (2008) Greenhouse evaluation of *Bacillus subtilis* ap-01 and *Trichoderma harzianum* ap-001 in controlling tobacco diseases. *Braz J Microbiol* 39:296–300
- Mansoori A, Singh N, Dubey SK, Thakur TK, Alkan N, Das SN, Kumar A (2020) Phytochemical characterization and assessment of crude extracts from *Lantana camara* L. for antioxidant and antimicrobial activity. *Front Agron* 2:582268
- Messih NA, van Bruggen AH, van Diepeningen AD, de Vos OJ, Termorshuizen AJ, Tjou-Tam-Sin NNA, Janse JD (2007) Potato brown rot incidence and severity under different management and amendment regimes in different soil types. *Eur J Plant Pathol* 119(4):367–381. <https://doi.org/10.1007/s10658-007-9167-z>
- Mukhopadhyay R, Kumar D (2020) *Trichoderma*: a beneficial antifungal agent and insights into its mechanism of biocontrol potential. *Egypt J Biol Pest Control* 30(1):1–8
- Murmu S, Dey S, Chakraborty A (2015) Management of early blight of potato using bio control agents and plant extracts. *J Appl Nat Sci* 7(2):860–864
- Narouei-Khandan HA, Shakya SK, Garrett KA, Goss EM, Dufault NS, Andrade-Piedra JL, Asseng S, Wallach D, Bruggen AHV (2020) BLIGHTSIM: a new potato late blight model simulating the response of *Phytophthora infestans* to diurnal temperature and humidity fluctuations in relation to climate change. *Pathogens* 9(8):659
- Norris EJ, Coats JR (2017) Current and future repellent technologies: the potential of spatial repellents and their place in mosquito-borne disease control. *Int J Environ Res Public Health* 14(2):124
- Ons L, Bylemans D, Thevissen K, Cammue BP (2020) Combining biocontrol agents with chemical fungicides for integrated plant fungal disease control. *Microorganisms* 8(12):1930
- Ortiz O, Mares V (2017) The historical, social, and economic importance of the potato crop. *The Potato Genome*, pp 1–10
- Ott RL (1998) *An Introduction to Statistical methods and data analysis*. Duxbury Press, Belmont, California, pp 807–837
- Owusu GA (2022) Antioxidant and insecticidal potency of essential oil extract from *lantana camara* growing in Central Region of Ghana. Doctoral dissertation, University of Education Winneba, Ghana
- Pertot I, Giovannini O, Benanchi M, Caffi T, Rossi V, Mugnai L (2017) Combining biocontrol agents with different mechanisms of action in a strategy to control *Botrytis cinerea* on grapevine. *Crop Prot* 97:85–93

- Rahman MM, Dey TK, Ali MA, Khalequzzaman KM, Hussain MA (2008) Control of late blight disease of potato by using new fungicides. *Int J Sustain Crop Prod* 3(2):10–15
- SAS Institute Inc. (2016) SAS® 9.4 Language Reference: Concepts, Sixth Edition. SAS Institute Inc., Cary, NC
- Shimira F, Afloukou F, Maniriho F (2020) A review on challenges and prospects of potato (*Solanum tuberosum*) production systems in Rwanda. *J Hortic Postharvest Res* 3(Special Issue-Abiotic and Biotic Stresses):97–112
- Simko I, Piepho HP (2012) The area under the disease progress stairs: calculation, advantage, and application. *Phytopathology* 102:381–389
- Statista (2023) Production of potatoes in South Africa from 2000 to 2020. <https://www.statista.com/statistics/1310115/potato-production-in-south-africa>. Retrieved on 27–04–2023
- Steyn JM, Franke AC, Van der Waals JE, Haverkort AJ (2016) Resource use efficiencies as indicators of ecological sustainability in potato production: a South African case study. *Field Crops Res* 199:136–149
- Stridh LJ, Mostafanezhad H, Andersen CB, Odilbekov F, Grenville-Briggs L, Lankinen Å, Liljeroth E (2022) Reduced efficacy of biocontrol agents and plant resistance inducers against potato early blight from greenhouse to field. *J Plant Dis Prot* 129(4):923–938
- Tucci M, Ruocco M, De Masi L, De Palma M, Lorito M (2011) The beneficial effect of *Trichoderma* spp. on tomato is modulated by the plant genotype. *Mol Plant Pathol* 12(4):341–354
- Yaseen S (2020) Analysis of anti-fungal activity of selected medicinal plant extracts against *Alternaria* leaf blight of bottle gourd. Doctoral dissertation, University of Agriculture, Faisalabad
- Yobo KS, Laing MD, Hunter CH (2011) Effects of single and combined inoculations of selected *Trichoderma* and *Bacillus* isolates on growth of dry bean and biological control of *Rhizoctonia solani* damping-off. *Afr J Biotechnol* 10(44):8746–8756

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Authors and Affiliations

Yvonne Hadzhi^{1,2}  · Julia Sibiya^{1,3} · Lerato Matsaunyane² · Isack Mathew⁴

✉ Yvonne Hadzhi
HadzhiY@arc.agric.za

¹ School of Agricultural, Earth and Environmental Sciences, University of KwaZulu-Natal, Private Bag X01 Scottsville, Pietermaritzburg 3209, South Africa

² Agricultural Research Council-Vegetable Industrial and Medicinal Plants, Private Bag x293, Pretoria 0001, South Africa

³ International Maize and Wheat Improvement Center (CIMMYT), P.O. Box 1041–00621, Nairobi, Kenya

⁴ Department of Plant & Soil Sciences, University of Venda, FESA, P. Bag X5050, Thohoyandou, South Africa