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RESEARCH ARTICLE

Evaluation Of Native Bacterial Antagonist Against *Fusarium Subacianum* In Potatoes

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A B S T R A C T

This study investigated the prevalence and impact of Fusarium dry rot, a significant postharvest disease of potatoes. The objectives of this research were to determine the primary *Fusarium* species causing dry rot in potato markets and to assess the antagonistic potential of selected bacterial biocontrol agents against the dominant pathogen. Market surveys revealed significant disease losses, with Islamabad exhibiting the highest incidence (17.2-19%). *Fusarium* species, particularly *F. subacianum* (62.50%), *F. oxysporum* (57.50%), and *F. solani* (56.25%), were identified as the primary pathogens. Pathogenicity tests confirmed the virulence of these isolates, with *F. oxysporum* (45 mm) demonstrating the highest aggressiveness. To explore biological control options, three bacterial strains (*Pseudomonas fluorescens*, *Bacillus velezensis*, and *Bacillus subtilis*) were evaluated for their *in vitro* and *in planta* antagonistic activity against *F. subacianum*. Their efficacy was assessed through *in vitro* dual-culture assays and *in planta* experiments on potato tubers using both preventive and curative application methods. *B. velezensis* exhibited the strongest *in vitro* inhibition of fungal growth (74.91%) and demonstrated the most effective disease control in both preventive (14.28%) and curative (16.82%) applications on potato tubers. The demonstrated efficacy of *B. velezensis* underscores its potential as a sustainable biocontrol tool, offering a viable strategy to reduce postharvest losses and minimize reliance on synthetic fungicides in potato storage systems.

Keywords: *Bacillus* spp., *Fusarium* spp., Postharvest disease, *Solanum tuberosum*, *Pseudomonas fluorescens*.

INTRODUCTION

Potato, a highly nutritious and economically significant crop with a high yield potential (Koch *et al.,* 2020: Ahmad *et al.,* 2023), plays a crucial role in food security, particularly in developing countries like Pakistan (Faucher *et al.,* 1992). While Pakistan produces 4.5 million tons annually of potatoes from 185,360 hectares, its production lags behind major producers like China and India (FAOSTAT, 2020). This low yield is attributed to various production constraints, including significant post-harvest losses due to diseases such as dry rot, caused primarily by *Fusarium oxysporum* (Rahman, 1969; Kamaluddin, 1970; Stevenson *et al.,* 2004). These losses can reach up to 60% of the harvested tubers (Stevenson *et al.,* 2004), with an estimated 2-9% loss annually in each storage facility (Rahman, 1969; Kamaluddin, 1970). In Pakistan, however, the specific causal agents and the extent of losses caused by Fusarium dry rot in contemporary storage systems are

not well-documented.

Traditional control methods, such as the use of synthetic fungicides like thiabendazole, have limitations. Inappropriate use of these chemicals can lead to environmental pollution and the development of fungicide-resistant strains of Fusarium. Moreover, while synthetic fungicides like thiabendazole have been used for control, their efficacy is often compromised by the emergence of resistant Fusarium strains, creating a critical need for alternative management strategies. This necessitates the exploration of alternative and sustainable control strategies (Desjardins *et al.,* 1993; Platt, 1997: Azeem *et al.,* 2020).

Biocontrol agents, such as *Pseudomonas* spp. and *Bacillus* spp., have shown promising results in controlling potato dry rot in field trials (Al-Mughrabi, 2010). These biopesticides offer a safer and more environmentally friendly approach to disease management compared to synthetic chemicals. Further research and implementation of biocontrol methods are crucial to mitigate post-harvest losses and enhance potato production in Pakistan. This study aimed to investigate the prevalence and causative agents of Fusarium dry rot in potatoes in selected markets of Pakistan, and to evaluate the *in vitro* and *in planta* efficacy of native bacterial antagonists—*Pseudomonas fluorescens*, *Bacillus velezensis*, and *Bacillus subtilis*—against *Fusarium subacianum* for the development of sustainable biocontrol strategies.

MATERIALS AND METHODS

Potato sample collection survey and disease assessment: This study investigated the prevalence of dry rot in potato tubers across four arid zone districts in Pakistan: Islamabad, Chakwal, Rawalpindi, and Jhelum. Within each district, three distinct markets were selected for data collection. In Islamabad, these included the Srinagar Highway Market, the I-11/4 Fruit and Vegetable Market, and the G.B Food Goudown. Rawalpindi's study sites encompassed the Raja Bazar Market, the Rawalpindi Food Storage House, and the DK Khan Vegetable Market. Chakwal's investigation focused on the Rehmat Store, the Dhodial Market, and the Kaler Kahar Sabzi Mandi. Finally, in Jhelum, the study sites were the Sabzi Mandi Jhelum, the Tehsil Dina Market, and the Suhawa Market.

Data collection continued over a three-month period, spanning August to October 2021. Within each market, potatoes were observed in two primary forms: displayed for immediate sale and stored in gunny bags. These bags, typically containing 75-85 kg of potatoes, were either stacked on racks or piled together for storage. To ensure representative data, a random sampling process was employed, selecting four bags per potato cultivar or variety (cvs. Kuroda and Lady Rosetta) within each market.

The assessment of dry rot prevalence involved a meticulous examination of each sampled bag. The potatoes were carefully spread out on the floor, allowing for a thorough visual inspection. Diseased tubers exhibiting the characteristic symptoms of dry rot were identified and subsequently separated from the healthy ones. The weight of the diseased tubers was then recorded for each bag. This data collection procedure was systematically repeated on a weekly basis for every cultivar included in the study.

To assess disease-related losses, diseased tubers from sampled bags were weighed. The weight of these diseased tubers was then divided by the total weight of potatoes (cv. Kuroda) observed in the bags and multiplied by 100 to determine the percentage of loss due to disease, as outlined by Islam (1995). This calculation yielded the number of diseased tubers per bag, and subsequently, the total loss in each market within the Rawalpindi and Islamabad regions was calculated using the following formula: Disease Loss (%) = (disease tubers in bag) / (Total tubers observed in bag) x 100.

Furthermore, to determine disease prevalence, the total number of tubers and the number of infected tubers (cvs. Kuroda and Lady Rosetta) were counted, with disease prevalence calculated as the percentage of locations exhibiting disease out of the total number of locations surveyed. Disease Prevalence (%) = (number of infected tubers) / (total number of tubers surveyed) x 100 (Islam, 1995).

Pathogen identification: To isolate the causative agent, potato dextrose agar (PDA) media was utilized (pH = 6). The lesion area was surface-sterilized with a sprit swab. A small piece of surface tissue was removed to expose the necrotic edge, and a small fragment of the diseased tissue was excised using a sharp scalpel. Five such tissue pieces from different parts of the lesion were then aseptically placed onto the PDA media. The inoculated plates were incubated at room temperature (28 ± 2°C) for a period of seven days (Yaqoob *et al.,* 2024: Matloob *et al.,* 2025). From the fungal growth observed on the

PDA plates, a small fragment of mycelia was transferred to fresh PDA media for sub-culturing. This process involved transferring either a block of fungal mycelium or conidia to obtain pure cultures. Fungal identification was based on a comprehensive analysis of colony characteristics, including linear growth, color in the medium, and sporulation patterns, following the methods described by Singh (1982). Microscopic examination of slides prepared from the fungal cultures further aided in confirming the identification (Bulbul, 1990; Kumar *et al.,* 1992).

Pathogenicity assay: The pathogenicity test was performed for fungal isolates under *in vitro* conditions. *Fusarium* spp. grown on PDA for 7-10 days, then, one agar disc colonized by fungi was inoculated into wounds (5×5 mm^2) in potato tubers (Usman *et al.,* 2024). The inoculated potato tubers were incubated at 25°C and 90% relative humidity for three weeks. After the incubation period, inoculated tubers were evaluated for rot development (mm) (Azadvar *et al.,* 2007). Each treatment was repeated four times. Standard slice inoculation and the pinprick method, as described by Kumar *et al.* (1992), were employed to inoculate tuber slices.

***In vitro* evaluation of *Pseudomonas fluorescens*, *Bacillus velezensis* and *Bacillus subtilis* against *Fusarium subacianum*:** To assess antagonistic activity, bacterial isolates (Pseudomonas fluorescens, *Bacillus velezensis* and *Bacillus subtilis*) were initially grown on Nutrient Agar (NA) medium at 25°C for 24 hours to obtain fresh cultures. Concurrently, pathogenic fungal isolate, specifically *F. subacianum*, were cultivated on PDA at 25°C for 7 days. Subsequently, three equidistant sites on Petri dishes were inoculated with the bacterial isolates. Simultaneously, a 5-mm disc of the *F. subacianum* pathogen was placed at the center of each Petri dish. These inoculated plates were then incubated at 25°C for one week.

After this incubation period, the antagonistic activities of the bacteria were evaluated by measuring the inhibition zones surrounding the bacterial colonies. These measurements quantified the distance between the edge of the bacterial colony and the edge of the *F. subacianum* mycelial growth. To ensure reliable results, each treatment was replicated four times (Rhouma *et al.,* 2024).

The percentage of mycelial growth inhibition (MGI) was determined 7 days post-inoculation. This calculation was performed according to the formula described by Matrood and Rhouma (2021):

MGI (%) = (1 − Ce/Ct) × 100; where Ce represents the radial growth diameter of *F. subacianum* in the presence of the bacterial isolate, and Ct represents the radial growth diameter of *F. subacianum* in the absence of the bacterial isolate.

***E*valuation of *Pseudomonas fluorescens*, *Bacillus velezensis* and *Bacillus subtilis* against *Fusarium subacianum*:** To evaluate the antagonistic activity of bacterial strains (*P. fluorescens*, *B. velezensis* and *B. subtilis*) against *F. subacianum* on potato tubers, *in vitro* assays were conducted. Bacterial isolates were cultured on Nutrient Agar (NA) for 24-48 hours at 25°C and subsequently suspended in sterile distilled water. The cell suspension concentration was standardized to 108 CFU/mL. *Fusarium subacianum* was grown on PDA at 25°C for 7 days. Kuroda potato tubers were selected for the experiments. They were meticulously cleaned by washing under running water, surface-sterilized by immersion in 3% sodium hypochlorite for 10 min, thoroughly rinsed with sterile distilled water for 10 min, and then air-dried. *In planta* experiments were designed to assess both preventive and curative effects of bacterial antagonists. For the preventive assay, potato tubers were treated with bacterial cell suspensions 24 h prior to *F. subacianum* inoculation. In the curative assay, bacterial treatments were applied 24 h after fungal inoculation. In both assays, 5x5 mm wounds were created on the potato tubers. Each wound was inoculated with 25 microliters of bacterial suspension and a 5 mm diameter agar disc colonized by *F. subacianum*. Fungal mycelium discs alone served as positive controls. The inoculated tubers were incubated in a growth chamber at 25°C and high relative humidity for 21 days. Each treatment consisted of four replicates, with three tubers per replicate. The entire experiment was repeated twice. Following the incubation period, the tubers were longitudinally sectioned through the inoculation sites. The extent of dry rot caused by *F. subacianum* was assessed by measuring the maximal width (w) and depth (d) of the lesion. The pathogen penetration into the tubers was calculated using the formula of Lapwood *et al.* (1984): Penetration (%) = ([w/2+(d-6)])/2.

STATISTICAL ANALYSIS

Data analysis were conducted using SPSS version 20.0 (SPSS, SAS Institute, Cary, NC, USA). Mean values of the

replicates were employed for statistical analysis. Analysis of Variance (ANOVA) was performed to determine significant differences between treatments. Prior to ANOVA, the homogeneity of variances and normality of the data were assessed. Duncan's Multiple Range Test was subsequently applied to identify significant differences between treatment means. All statistical tests were conducted at a significance level of 5% ($p \leq 0.05$).

RESULTS

Disease assessment: Table 1 presented the disease loss of dry rot potatoes across three months (August, September, and October) in four different markets: Rawalpindi, Jhelum, Chakwal, and Islamabad. The data revealed significant variations in disease loss between markets and across months. Duncan's Multiple Range Test indicated significant differences ($p < 0.01$) in disease loss between markets within each month, as denoted by different superscripts. Islamabad consistently exhibited the highest disease loss throughout the three months, followed by Rawalpindi and Chakwal. Jhelum generally experienced the lowest disease loss. Notably, the P-value for Islamabad was not significant ($p \geq 0.05$), suggesting that disease loss in this market may not have varied significantly across the three months (Table 1).

Table 1. Disease loss of dry rot potatoes in three months.

Months	Rawalpindi Market	Jhelum Market	Chakwal Market	Islamabad Market
August	15.6a[a]	9c	12b	19a
September	10.3c	14b	16a	18.7a
October	12.3b	19.5a	10.1c	17.2a
P-value[b]	< 0.01	< 0.01	< 0.01	≥ 0.05

[a]Duncan's Multiple Range Test, values followed by different superscripts are significantly different at P ≤ 0.05

[b]Probabilities associated with individual F tests

This study examined the prevalence of dry rot disease in two potato varieties, Kuroda and Lady Rosetta, across four markets in Pakistan over three months. The results presented in Table 2 demonstrate a significant degree of variability in disease prevalence. Firstly, a notable observation is the consistent high prevalence of dry rot in the Islamabad market for both potato varieties throughout the study period. This suggests a potential market-specific factor, such as storage conditions, transportation practices, or climatic conditions, that contributes to increased disease pressure in Islamabad. In contrast, the Jhelum market consistently showed the lowest disease prevalence for both varieties. Secondly, the analysis revealed a significant difference in disease susceptibility between the two potato varieties. The Kuroda variety consistently exhibited higher disease prevalence compared to Lady Rosetta across all markets and months. This suggests that the Kuroda variety may be inherently more susceptible to dry rot infection than Lady Rosetta (Table 2).

Table 2. Disease prevalence of dry rot potatoes in three months.

Months	Varieties	Rawalpindi Market	Jhelum Market	Chakwal Market	Islamabad Market
August	Kuroda	14.5a[a]	10d	1f	18.6ab
	Lady Rosetta	15a	7e	18b	14.1c
September	Kuroda	13.9b	18.5b	12.7d	19.5a
	Lady Rosetta	10d	20a	15c	14.3c
October	Kuroda	11c	13c	11e	17.7b
	Lady Rosetta	10.7c	8e	19.9a	16.1b
P-value[b]		< 0.01	< 0.01	< 0.01	< 0.01

[a]Duncan's Multiple Range Test, values followed by different superscripts are significantly different at P ≤ 0.05

[b]Probabilities associated with individual F tests

Pathogens frequency: Table 3 provided an overview of the fungal pathogens detected within dry rot potato tubers of the Lady Rosetta cultivar. The data highlighted the dominance of *Fusarium* species, with three species – *F. subacianum*, *F. oxysporum*, and *F. solani* – exhibiting high frequencies of isolation. Specifically, *F. subacianum* was found in 62.50% of the analyzed tuber samples, indicating its significant prevalence. *F. oxysporum* and *F. solani* were also prevalent, occurring in 57.50% and 56.25% of the samples, respectively. Statistical analysis using Duncan's

Multiple Range Test revealed no significant differences in the frequencies of these three *Fusarium* species at the P ≤ 0.05 level. This suggested that these pathogens may be occurring with similar levels of incidence within the potato tuber population (Table 3).

Table 3. Frequency of pathogens isolated from potato tubers (cv. Lady Rosetta).

Fungal Isolates	Frequency of pathogen (%)
Fusarium oxysporum	57.50[a]
Fusarium solani	56.25
Fusarium subacianum	62.50
P-value[b]	≥ 0.05

[a]Duncan's Multiple Range Test, values followed by different superscripts are significantly different at P ≤ 0.05

[b]Probabilities associated with individual F tests

Pathogenicity assay: Figure 1 assessed the pathogenicity of three *Fusarium* species (*F. oxysporum*, *F. solani*, and *F. subacianum*) on potato tubers of the Lady Rosetta cultivar. Pathogenicity was evaluated by measuring the lesion diameter of tuber rot caused by each isolate. Results showed that *F. oxysporum* caused the highest level of tuber rot (45 mm), followed by *F. solani* (35 mm) and *F. subacianum* (30 mm). Duncan's Multiple Range Test revealed significant differences in pathogenicity among the three *Fusarium* species at the p ≤ 0.05 level, with *F. oxysporum* exhibiting significantly higher pathogenicity than both *F. solani* and *F. subacianum* (Figure 1).

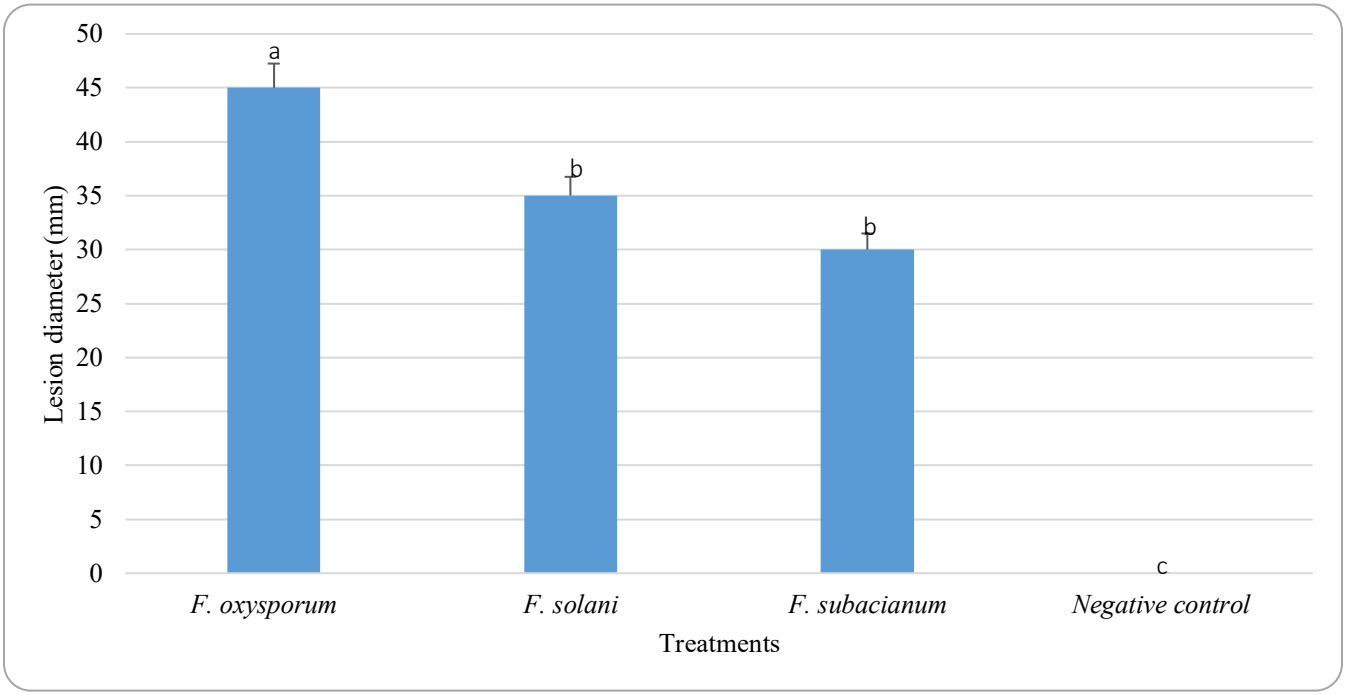

Figure 1. Pathogenicity on potato tubers (cv. Lady Rosetta) of *Fusarium* spp. Different letters above bars indicate statistically significant differences between treatments within the experiments (P ≤ 0.5) according to the Duncan's multiple range tests.

***In vitro* evaluation of *Pseudomonas fluorescens*, *Bacillus velezensis* and *Bacillus subtilis* against *Fusarium subacianum*:** Table 4 presented the outcomes of an experiment investigating the ability of three distinct bacterial species – *P. fluorescens*, *B. velezensis*, and *B. subtilis* – to suppress the growth of *F. subacianum*. The experiment measured mycelial growth inhibition (MGI) as a percentage, indicating the extent to which each bacterial strain hindered the growth of the fungus. The results demonstrate a clear hierarchy in the antifungal activity of these bacteria. *Bacillus velezensis* exhibited the most potent inhibitory effect, achieving an MGI of 74.91%. *Bacillus subtilis* demonstrated a moderate level of inhibition with an MGI of 55.16%. In contrast, *P. fluorescens* exhibited the least inhibitory activity among the three, with an MGI of 36.98%. Statistical analysis,

employing Duncan's Multiple Range Test, confirmed that the observed differences in MGI between the bacterial strains were statistically significant at a significance level of $p \leq 0.05$ (Table 4).

Table 4. Effect of *Pseudomonas fluorescens*, *Bacillus velezensis* and *Bacillus subtilis* on the mycelial growth inhibition (MGI) of *Fusarium subacianum* under laboratory conditions.

Treatments	MGI (%)
Pseudomonas fluorescens	36.98c[a]
Bacillus velezensis	74.91a
Bacillus subtilis	55.16b
P-value[b]	< 0.01

[a]Duncan's Multiple Range Test, values followed by different superscripts are significantly different at $P \leq 0.05$

[b]Probabilities associated with individual F tests

Table 5 showed a detailed assessment of the efficacy of different bacterial treatments (*P. fluorescens*, *B. velezensis*, and *B. subtilis*) in managing *F. subacianum* tuber infection. The study employed two experimental approaches: a preventive assay, where the bacteria were applied before *F. subacianum* infection, and a curative assay, where the treatments were administered after the pathogen was introduced. The results, analyzed using Duncan's Multiple Range Test, revealed statistically significant differences in disease control among the treatments in both assays. Notably, *B. velezensis* consistently demonstrated the highest efficacy in both preventive (14.28%) and curative (16.82%) scenarios. The disease incidence in plants treated with *B. velezensis* was significantly lower compared to those treated with *P. fluorescens*, *B. subtilis*, or left untreated (infected with *F. subacianum* alone; 76.92 and 82.71, respectively). While *P. fluorescens* and *B. subtilis* exhibited some level of disease suppression, their efficacy was significantly lower than that of *B. velezensis* (Table 5).

Table 5. Efficacy of preventive and curative treatments with *P. fluorescens*, *B. velezensis*, and *B. subtilis* against *F. subacianum* tuber infection.

Treatments	Preventive assay	Curative assay
P. fluorescens+ F. subacianum	31.33b	37.71b
B. velezensis+ F. subacianum	14.28d	16.82d
B. subtilis + F. subacianum	19.67c	26.82c
F. subacianum	76.92a	82.71a
P-value[b]	< 0.01	< 0.01

[a] Duncan's Multiple Range Test, values followed by different superscripts are significantly different at $P \leq 0.05$

[b] Probabilities associated with individual F tests

DISCUSSION

Fusarium dry rot poses a significant threat to potato tuber yield, causing substantial economic losses in the agricultural and food sectors. This postharvest disease can result in yield reductions ranging from 6 to 25% during the growing season and can escalate to devastating losses of up to 60% during storage. The growth of *Fusarium*, the causative pathogen, is highly sensitive to temperature fluctuations. Optimal growth occurs at temperatures below 10°C, while temperatures exceeding 5°C significantly restrict its development (Fry *et al.,* 2001). Our findings on the dominance of *F. subacianum*, *F. oxysporum*, and *F. solani* in Pakistani potato markets align with global reports identifying these species as key agents of Fusarium dry rot (Secor and Gudmestad, 1999; Peters *et al.,* 2008). However, the high relative frequency of *F. subacianum* (62.50%) observed in our study provides a crucial, region-specific insight, suggesting it may be a particularly dominant pathogen in the storage systems of Pakistan's arid zones, whereas other studies have often highlighted *F. sambucinum* or *F. oxysporum* as the primary species in different geographical contexts. This underscores the importance of identifying local pathogen populations to develop targeted control strategies (Desjardins *et al.,* 1993).

Recognizing the urgent need for sustainable and environmentally friendly disease management strategies, the application of Plant Growth-Promoting Rhizobacteria, or biocontrol agents, has emerged as a promising alternative to traditional chemical interventions. These beneficial microorganisms offer a multifaceted approach to enhancing crop health and productivity. Studies have

demonstrated that employing *Bacillus* spp. can significantly improve plant vigor by increasing the availability of essential nutrients within the rhizosphere, inhibiting the growth of harmful pathogens, and stimulating the plant's natural defense mechanisms (Garcia-Fraile *et al.,* 2015; Kang *et al.,* 2015).

The superior performance of *B. velezensis* in our study, both in vitro and in planta, offers a significant advance. While previous research has successfully demonstrated the efficacy of B. subtilis strains in reducing *Fusarium* growth by 25-50% (Lastochkina *et al.,* 2017), our isolate of *B. velezensis* achieved a notably higher inhibition rate. This finding is consistent with the broader antimicrobial potential of the *B. velezensis* (Zhang *et al.,* 2020) but crucially demonstrates its specific effectiveness against the locally dominant *F. subacianum* (Lastochkina *et al.,* 2020).

Beyond *Bacillus* spp., *P. fluorescence* has also shown considerable potential as a biocontrol agent. These bacteria, along with *B. subtilis* and *B. velezensis*, exhibit diverse mechanisms for combating tuber diseases, with their effectiveness varying across different plant species and genotypes. For effectively use these biocontrol agents, a thorough understanding of their specific modes of action and the environmental factors that influence their activity is crucial. This study aimed to evaluate the efficacy of *P. fluorescence*, *B. subtilis*, and *B. velezensis* in controlling Fusarium Dry Rot in potato tubers. *In vitro* experiments demonstrated significant pathogen-inhibiting properties in all three bacterial antagonists. Notably, *B. velezensis* exhibited the most potent inhibitory effect, achieving a 70% reduction in the growth of *F. subacianum*, the primary pathogens responsible for Dry Rot. *B. subtilis* and *B. cereus* also demonstrated moderate inhibitory activity, with respective inhibition rates. The successful implementation of biocontrol strategies for Fusarium Dry Rot requires careful consideration of environmental factors, particularly temperature and humidity. By meticulously controlling these parameters, we can create optimal conditions for biocontrol agents, which maximizes their effectiveness in suppressing disease and safeguarding potato yields. Numerous studies have demonstrated the efficacy of various bacterial strains in suppressing dry rot in potatoes, a disease primarily caused by species of *Fusarium*. For instance, *B. subtilis* strains BS 10-4 and BS 26D effectively reduced *F. oxysporum* growth by 50% and 25%, respectively, during potato storage (Lastochkina *et al.,* 2020). Similarly, *B. subtilis* V26 significantly decreased *Fusarium*-induced disease in potato plants. These findings align with previous research highlighting the potential of B. subtilis strains as biocontrol agents against plant pathogens, both in greenhouse and field conditions (Kumbar *et al.,* 2019).

Previous studies have shown that *B. velezensis* and *B. subtilis* can effectively suppress *Alternaria solani* and *Fusarium* species, respectively (Zhang *et al.,* 2020). However, in the current investigation, Bacillus cereus demonstrated superior performance compared to *B. subtilis*. Preventive treatments generally resulted in milder disease symptoms compared to curative treatments. In curative treatments, while both pathogen and biocontrol agent mycelia were observed, *Trichoderma asperellum* UDEAGIEM-H01 exhibited promising biocontrol activity against *F. oxysporum*, demonstrating both preventive and partial curative effects in mesocosm conditions (Carol Díaz-Guti´errez *et al.,* 2021).

Bacterial endophytes, including *Bacillus* species, are recognized for their biocontrol capabilities. These microorganisms colonize plants, competing with pathogens for resources and producing compounds that inhibit disease development (Kaouthar *et al.,* 2016). In a particular study, *Bacillus* sp. KL5 demonstrated efficacy in suppressing potato disease, likely through mechanisms such as competition and the production of inhibitory compounds (Lastochkina *et al.,* 2020). This supports the notion that endophytes offer broad-spectrum protection to host plants against various threats, including pathogens (Kanani *et al.,* 2020; Rhouma *et al.,* 2024; Rhouma *et al.,* 2025).

CONCLUSION

This study provides a comprehensive assessment of Fusarium dry rot in Pakistani potatoes, establishing *Fusarium subacianum* as the most frequently isolated species. The demonstrated efficacy of the native bacterium *Bacillus velezensis* as a potent antagonist against the dominant pathogen offers a concrete, sustainable solution for postharvest disease management. Its superior performance over *Pseudomonas fluorescens* and *Bacillus subtilis* in suppressing tuber infection underscores its significant potential as a biocontrol agent. Looking forward, these findings pave the way for several critical next steps. The immediate perspective involves formulating a stable and effective bio-product based on *B. velezensis* for large-scale

application. Subsequent research must validate these promising in planta results through pilot-scale trials in commercial storage facilities, where variables like temperature fluctuations and native microbiota can influence efficacy. Furthermore, elucidating the precise mode of action—whether through antibiosis, competition, or induction of host resistance—will be key to optimizing its application strategy. Integrating this potent biological control into an integrated pest management framework, alongside resistant cultivars and improved storage hygiene, represents the most promising pathway toward sustainably safeguarding potato yields and reducing economic losses in Pakistan and similar agro-climatic regions.

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COMPETING INTERESTS

The authors declare that they have no conflict of interest. This article does not contain any studies with human participants or animals performed by any of the authors. Informed consent was obtained from all individual participants included in the study. All authors have approved the manuscript for submission.

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