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Biocontrol Agents for Managing Potato Pests and Diseases

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Abstract Potato cultivation faces significant challenges from various pests and diseases, including insect infestations, fungal infections, and viral diseases, which can severely impact yield and crop quality. This study provides a systematic review of the application of biological control agents (BCAs) as sustainable alternatives to chemical pesticides in managing potato pests and diseases. It outlines the types of microbial control agents (such as fungi, bacteria, and viruses), natural predators and parasitoids, with a focus on their mechanisms of action, including antagonism, induction of systemic resistance, and competitive exclusion. The study also evaluates the effectiveness of integrating BCAs into integrated pest management (IPM) programs through field trials and case studies. The research highlights the importance of biological control agents in promoting sustainable potato cultivation and provides practical recommendations to enhance crop resilience and reduce dependence on chemical pesticides.
Keywords Biocontrol agents; Potato pests and diseases; Integrated pest management (IPM); Antibiosis; Sustainable agriculture

1 Introduction

Potato (*Solanum tuberosum*) is a staple crop worldwide, but its production is significantly hampered by various pests and diseases. Among the most notorious pathogens are *Phytophthora infestans*, causing late blight, and Rhizoctonia solani, responsible for black scurf and stem canker (Wang and Long, 2023). Other significant pathogens include Streptomyces scabies, which causes common scab, and Fusarium species, which lead to dry rot (Steglińska et al., 2022). These diseases not only reduce yield but also affect the quality of the tubers, leading to substantial economic losses.

The conventional approach to managing potato pests and diseases has heavily relied on synthetic chemical pesticides and fungicides. While effective, these chemicals pose several challenges. They can lead to the development of resistant pathogen strains, negatively impact human health, and cause environmental degradation. Moreover, the stringent regulations and removal of various fungicides from the market further complicate disease management (Gush et al., 2023). The over-reliance on chemical control methods is increasingly seen as unsustainable, necessitating the exploration of alternative strategies (Cray et al., 2016; Feng et al., 2021).

Biocontrol agents (BCAs) offer a promising alternative to synthetic chemicals, aligning with the principles of sustainable agriculture. These agents, including bacteria, fungi, and their metabolites, can effectively suppress potato pathogens through various mechanisms such as competition, antibiosis, and induction of plant resistance. For instance, *Bacillus subtilis* EG21 has shown antagonistic potential against *P. infestans* and *R. solani*, while *Bacillus velezensis* K-9 has been effective against Streptomyces scabies (Ma et al., 2023). *Pseudomonas fluorescens* LBUM223 has demonstrated efficacy in controlling common scab through the production of phenazine-1-carboxylic acid (Arseneault et al., 2016). The integration of BCAs into pest management strategies not only reduces the dependency on harmful chemicals but also promotes environmental health and sustainability.

This study aims to explore the potential of biocontrol agents (BCAs) in managing potato pests and diseases, focusing on their mechanisms of action, efficacy, and practical applications. It seeks to provide a comprehensive understanding of how BCAs can be integrated into sustainable potato cultivation practices, including evaluating the effectiveness of various biocontrol agents and examining their interactions with pathogens to ensure the long-term viability of potato production.

2 Types of Biocontrol Agents in Potato Pest Management

2.1 Microbial biocontrol agents

Microbial biocontrol agents are microorganisms such as bacteria, fungi, and oomycetes that can suppress or inhibit the growth of potato pathogens. These agents work through various mechanisms, including the production of antimicrobial compounds, competition for nutrients and space, and induction of plant resistance.

Bacillus subtilis strains have shown significant potential in controlling potato pathogens. For instance, *Bacillus subtilis* EG21 has demonstrated strong antagonistic effects against *Phytophthora infestans* and *Rhizoctonia solani* through the production of cyclic lipopeptides and extracellular enzymes like cellulase, pectinase, and chitinase. Similarly, *Bacillus velezensis* K-9 has been effective in managing potato scab caused by Streptomyces scabies, reducing disease symptoms and increasing potato yield (Ma et al., 2023).

Lactic acid bacteria (LAB) such as Lactiplantibacillus plantarum KB2 LAB 03 have also been identified as effective biocontrol agents. This strain has shown a significant reduction in the infestation of multiple potato pathogens, including Pectobacterium carotovorum and Rhizoctonia solani, by producing organic acids and other antimicrobial metabolites (Steglińska et al., 2022).

Arbuscular mycorrhizal fungi (AMF) and endophytic fungi like *Epicoccum nigrum* ASU11 have been used to control blackleg disease caused by Pectobacterium carotovora. These fungi enhance plant growth and induce systemic resistance, reducing disease severity and improving potato yield (Bagy et al., 2019).

2.2 Natural predators and parasitoids

Natural predators and parasitoids are another group of biocontrol agents that can help manage potato pests. These organisms prey on or parasitize pest species, thereby reducing their populations and the damage they cause to potato crops. Various insects and mites can serve as biological control agents. For example, lady beetles (Coccinellidae) and lacewings (Chrysopidae) are known to prey on aphids, which are common pests in potato fields (Volynchikova and Kim, 2022). Similarly, parasitoid wasps can target and parasitize the larvae of potato tuber moths, reducing their impact on potato crops.

3 Mechanisms of Action of Biocontrol Agents

3.1 Antagonism and competition

Biocontrol agents (BCAs) often employ antagonism and competition to suppress potato pests and diseases. This involves the production of antimicrobial compounds, competition for nutrients and space, and direct parasitism of pathogens. For instance, *Bacillus subtilis* EG21 produces cyclic lipopeptides such as surfactins, which exhibit strong anti-oomycete and zoosporecidal effects against *Phytophthora infestans*. Rhizosphere bacteria isolated from resistant potato plants, including Streptomyces and Pseudomonas species, have shown significant inhibitory effects on the mycelium growth of *P. infestans* through the production of cellulase and catalase (Feng et al., 2021). These mechanisms highlight the potential of BCAs to outcompete and directly antagonize pathogens, thereby reducing disease incidence.

3.2 Induction of host plant resistance

3.2.1 Activation of systemic acquired resistance (SAR) in potato plants

Systemic acquired resistance (SAR) is a plant defense mechanism that is activated in response to pathogen attack, leading to enhanced resistance throughout the plant. The co-treatment of potato plants with *Bacillus thuringiensis* B-5351 and salicylic acid (SA) has been shown to significantly increase the transcriptional activity of SAR-related genes such as PR1 and PAL, which are crucial for the plant's defense against *P. infestans* (Sorokan et al., 2021). This combined treatment not only enhances the plant's resistance to late blight but also increases the population of beneficial bacteria within the plant tissues, further contributing to disease suppression.

3.2.2 Enhancement of the plant’s immune response

Biocontrol agents can also enhance the plant's immune response through the induction of induced systemic resistance (ISR) and mycorrhizal-induced resistance (MIR). For example, the dual inoculation of potato plants with Pseudomonas sp. R41805 and Rhizophagus irregularis MUCL 41833 has been shown to elicit the expression of ethylene response factor 3 (ERF3), which plays a significant role in pathogen defense (Velivelli et al., 2015). This enhancement of the plant's immune response through complex signaling networks involving salicylic acid, jasmonic acid, and ethylene, provides a robust defense mechanism against various pathogens.

3.3 Direct pathogen and pest attack

BCAs directly attack pathogens and pests through mechanisms such as hyperparasitism, production of lytic enzymes, and release of antimicrobial compounds. For instance, *Bacillus subtilis* EG21 produces extracellular lytic enzymes, including cellulase, pectinase, and chitinase. Cellulase degrades the cellulose components in the cell walls of pathogens, disrupting their structural integrity. Pectinase acts by breaking down pectin in plant cell walls, further weakening the pathogen's adhesion to plant tissues. Chitinase is particularly crucial for degrading the main chitin component of fungal cell walls, demonstrating significant effectiveness against fungal pathogens. These enzymes cause extensive damage to the hyphae of Rhizoctonia solani and inhibit the infection of Phytophthora infestans. Experimental results indicate that the lytic enzymes secreted by *Bacillus subtilis* EG21 significantly inhibited the growth of Rhizoctonia solani in vitro. Microscopic observations revealed marked deformation, swelling, and rupture of the pathogen's hyphae, further confirming the critical role of lytic enzymes in disrupting the structure of the pathogens (Figure 1) (Alfiky et al., 2022). Similarly, microbial biopesticides can produce antimicrobial compounds that inhibit pathogen growth and virulence factors, thereby directly reducing disease incidence. These direct interactions between BCAs and pathogens are crucial for effective biocontrol in potato crops.

Figure 1 Representative images for A, potato tuber slices at 4 days postinoculation (dpi) as they were treated with bacterial cells (left), *Bacillus subtilis* EG21 culture filtrate (middle), and Luria Bertani broth as control (right), and then inoculated with *Rhizoctonia solani*. B, Lytic enzyme activities in EG21 for cellulase (left) and pectinase (right) (Adopted from Alfiky et al., 2022)

4 Application Strategies for Biocontrol Agents in Potato Cultivation

4.1 Soil and seed treatment

Soil and seed treatments are critical strategies for the effective application of biocontrol agents in potato cultivation. These treatments involve the introduction of beneficial microorganisms directly into the soil or onto the seed tubers to suppress soil-borne pathogens and enhance plant health. For instance, *Bacillus velezensis* K-9 has been shown to significantly reduce potato scab caused by Streptomyces scabies when applied to the soil, leading to improved tuber quality and increased yields (Gush et al., 2023). Similarly, *Brevibacillus laterosporus*

BL12 has demonstrated the ability to colonize the tuberosphere and rhizosphere soils, altering the soil bacterial community to suppress potato common scab (Li et al., 2021). The use of Fusarium oxysporum strain Fo47 as a soil treatment has also been explored, with successful re-isolation from inoculated plants in field trials, indicating its potential for large-scale application (Constantin et al., 2020). These examples highlight the importance of soil and seed treatments in establishing a protective microbial environment around potato plants.

4.2 Foliar application

Foliar application involves spraying biocontrol agents directly onto the leaves of potato plants to combat foliar pathogens. This method is particularly effective against diseases such as early blight caused by Alternaria solani. Azospirillum lipoferum AL-3, when applied as a foliar spray, significantly reduced early blight severity and increased tuber yield by inducing systemic resistance in potato plants (Mehmood et al., 2021). The foliar application of *Bacillus subtilis* EG21 has also shown promise, with its metabolites exhibiting strong anti-oomycete and zoosporecidal effects against *Phytophthora infestans*, the causative agent of late blight (Alfiky et al., 2022). These findings suggest that foliar application of biocontrol agents can be an effective strategy for managing foliar diseases in potato cultivation.

4.3 Integration with other pest management practices

Integrating biocontrol agents with other pest management practices is essential for achieving sustainable and effective pest control in potato cultivation. This integrated approach, known as Integrated Pest Management (IPM), combines biological, cultural, and chemical methods to manage pests and diseases. For example, combining biocontrol agents such as *Pochonia chlamydosporia* and *Purpureocillium lilacinum* with trap cropping using *Solanum sisymbriifolium* has shown promise in managing potato cyst nematodes (PCN) (Mhatre et al., 2022). The use of biocontrol agents like *Bacillus subtilis* EG21 in conjunction with other IPM strategies can enhance disease suppression and reduce reliance on synthetic chemicals. The integration of biocontrol agents with other pest management practices not only improves efficacy but also promotes environmental sustainability and reduces the risk of pathogen resistance.

5 Case Studies of Successful Biocontrol Implementation

5.1 Control of potato late blight (*Phytophthora infestans*)

Potato late blight, caused by *Phytophthora infestans*, is a devastating disease affecting potato crops worldwide. Traditional management relies heavily on synthetic fungicides, which pose environmental and health risks. Biocontrol agents offer a promising alternative. For instance, *Bacillus subtilis* H17-16 has shown significant potential in inhibiting *P. infestans* by producing protease, volatile compounds, and forming biofilms, which enhance plant resistance and promote growth. Field applications of H17-16, especially when combined with chitosan or chemical fungicides, have effectively reduced late blight incidence (Zhang et al., 2023). *Trichoderma* spp. have demonstrated multifaceted biocontrol strategies, including direct mycoparasitism, competition for nutrients, and antibiosis, significantly inhibiting *P. infestans* both in vitro and in planta (Alfiky et al., 2023). Essential oils (EOs) have also been explored for their anti-oomycete activities, showing promise as sustainable biopesticides (Martini et al., 2023). These biocontrol agents, when integrated into pest management programs, can significantly reduce the reliance on chemical fungicides and enhance sustainable agriculture practices.

5.2 Management of Colorado potato beetle (*Leptinotarsa decemlineata*)

The Colorado potato beetle (CPB) is a major pest of potato crops, notorious for its resistance to multiple insecticides. Innovative biocontrol strategies are being developed to manage this pest. Ledprona, a sprayable double-stranded RNA biopesticide, targets the proteasome subunit beta type-5 in CPB, triggering the RNA interference pathway. Laboratory and greenhouse trials have shown that Ledprona can achieve up to 90% mortality in CPB larvae, demonstrating efficacy comparable to traditional insecticides like spinosad (Rodrigues et al., 2021; Dzedaev et al., 2023).

Another approach involves the use of *Bacillus subtilis* 26DCryChS, which produces Cry1Ia toxin from *Bacillus thuringiensis*. A key advantage of *Bacillus subtilis* 26DCryChS is its ability to function as an endophytic bacterium, effectively colonizing the internal tissues of plants, particularly showing strong endophytic capabilities in potato plants. This strain can persist stably within plant tissues and is less affected by external environmental factors, such as UV radiation and rain wash-off, thereby ensuring its continuous action within the plant. The strain not only inhibits *Phytophthora infestans* but also exhibits insecticidal activity against the Colorado potato beetle (CPB). By expressing the Cry1Ia toxin, the strain demonstrates potent insecticidal activity against pests. When insects feed on plant tissues containing the 26DCryChS strain, the Cry1Ia toxin disrupts the insect's gut cells, causing severe intestinal damage and ultimately leading to insect death (Figure 2).

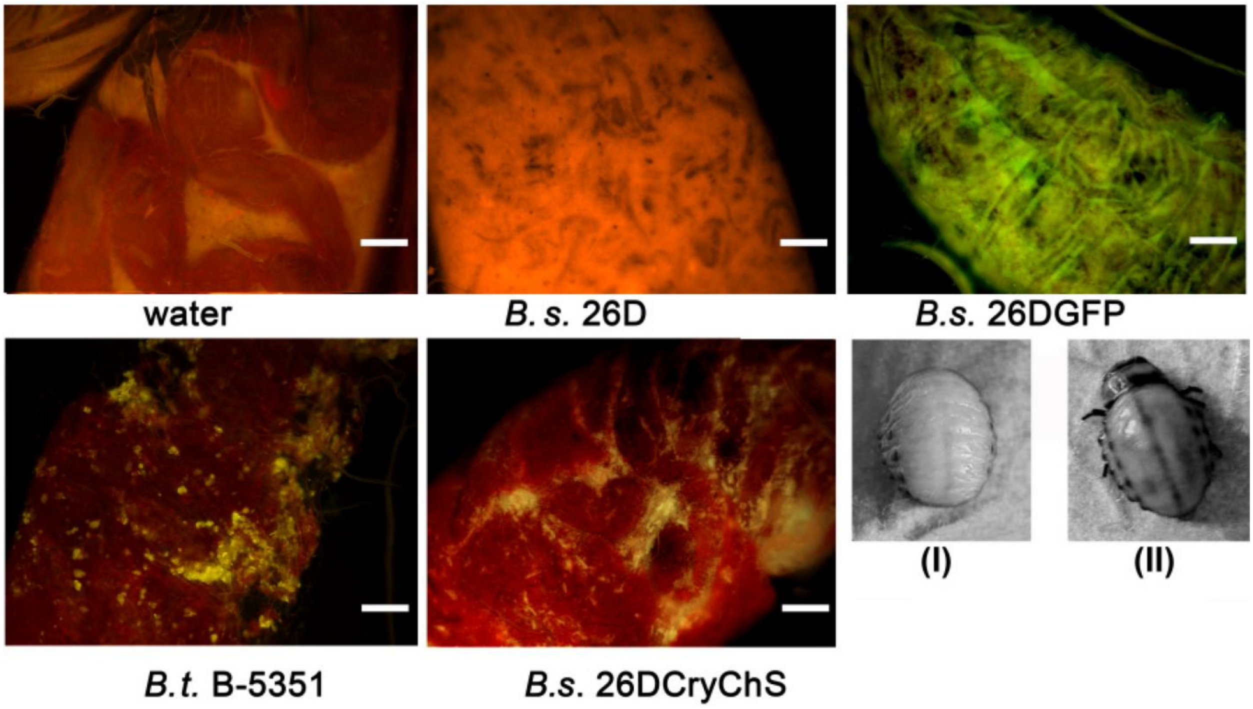

Figure 2 Mesenteron structure of *L. decemlineata* beetles 24 h after feeding of potato plants, which contained cells of *Bacillus* strains. Scale bars, 200 μm. (I) Healthy larva; (II) bacteriosis on alive larva on the 5th day after eating of plants containing *Bacillus* sp. (Adopted from Sorokan et al., 2020)

5.3 Control of rhizoctonia root rot

Rhizoctonia root rot, caused by Rhizoctonia solani, is another significant disease affecting potato crops. *Bacillus subtilis* EG21 has shown strong antagonistic potential against both *P. infestans* and *R. solani*. The strain produces cyclic lipopeptides, such as surfactins, which exhibit antifungal and anti-oomycete activities. Microscopic examinations have revealed extensive damage to *R. solani* mycelium upon interaction with EG21. The cell-free culture filtrate (CF) of EG21 has been found to be chemically stable and effective in inhibiting the growth of both pathogens under various conditions (Alfiky et al., 2022). Field applications of EG21 have confirmed its disease-inhibiting effects, making it a promising candidate for integrated pest management strategies aimed at controlling Rhizoctonia root rot and other potato diseases.

6 Challenges and Limitations of Biocontrol Agents

6.1 Variability in field performance

One of the primary challenges in the application of biocontrol agents for managing potato pests and diseases is the variability in their performance under field conditions. While laboratory and greenhouse experiments often show promising results, translating these findings to the field has proven problematic. For instance, biocontrol agents such as Bacillus sp. JC12GB43 have shown near-complete inhibition of pathogens in controlled environments but exhibited variable efficacy in the field due to differing environmental conditions (Cray et al., 2016; Yang, 2024). Similarly, the endophytic microbe Fusarium oxysporum 47 (Fo47) demonstrated effective biocontrol in laboratory settings, but its performance in large-scale field trials was inconsistent, highlighting the challenge of maintaining inoculum viability and effectiveness in diverse agricultural environments (Constantin et al., 2020). This variability necessitates extensive field trials and optimization of application methods to achieve reliable results.

6.2 Regulatory and commercialization hurdles

The regulatory landscape for biocontrol agents poses significant hurdles to their commercialization and widespread adoption. The process of obtaining regulatory approval for new biocontrol agents is often lengthy and complex, involving rigorous testing to ensure safety and efficacy. This can be a deterrent for companies looking to invest in the development and commercialization of biocontrol products. Additionally, the economic feasibility of biocontrol agents is influenced by the costs associated with their development and regulatory approval. For example, the introduction of biocontrol for wireworms in potato cultivation has been found to be economically viable, but the high costs and regulatory hurdles can limit the adoption of such strategies (Benjamin and Wesseler, 2016; Naqqash et al., 2020). These challenges underscore the need for streamlined regulatory processes and economic incentives to promote the use of biocontrol agents in integrated pest management (IPM) programs.

6.3 Compatibility with conventional agricultural practices

Integrating biocontrol agents into conventional agricultural practices presents another set of challenges. Biocontrol agents must be compatible with existing farming practices and other pest management strategies to be effective. For instance, the use of *Bacillus subtilis* EG21 and its metabolites has shown promise in controlling potato pathogens, but its integration into conventional farming systems requires careful consideration of its interactions with other agricultural inputs and practices (Alfiky et al., 2022). The success of biocontrol agents often depends on their ability to work synergistically with other methods in IPM programs. The combination of multiple biocontrol agents or their integration with chemical treatments can enhance efficacy, but this requires a thorough understanding of their modes of action and potential interactions (Wang and Long, 2023). Ensuring compatibility with conventional practices is crucial for the successful adoption and implementation of biocontrol strategies in potato cultivation.

7 Innovations in Biocontrol Agent Development And Deployment

7.1 Discovery of novel biocontrol strains

The discovery of novel biocontrol strains has been pivotal in advancing sustainable agricultural practices. For instance, *Bacillus subtilis* EG21 has shown significant antagonistic potential against potato pathogens *Phytophthora infestans* and *Rhizoctonia solani*, producing stable antifungal metabolites such as cyclic lipopeptides. Similarly, Bacillus sp. JC12GB43 has demonstrated near-complete inhibition of Phytophthora and Fusarium species under specific environmental conditions, although it can also stimulate pathogen proliferation under certain stress conditions (Cray et al., 2016; Yang and Fu, 2024). Another promising strain, *Bacillus velezensis* K-9, has been effective in managing potato scab, significantly reducing disease symptoms and increasing potato yield (Ma et al., 2023). *Brevibacillus laterosporus* BL12 has been shown to suppress potato common scab by altering the soil bacterial community, promoting beneficial bacteria that aid in disease control.

7.2 Advanced formulation techniques

Advanced formulation techniques are crucial for enhancing the efficacy and stability of biocontrol agents. The metabolites produced by *Bacillus subtilis* EG21, for example, have been found to be stable under high-temperature/pressure treatments and extreme pH values, making them suitable for various agricultural applications (Alfiky et al., 2022). The combination of arbuscular mycorrhizal fungi (AMF) and endophytic strain Epicoccum nigrum ASU11 has also been effective in controlling potato blackleg, with the biocontrol agents promoting systemic plant resistance and enhancing potato growth (Bagy et al., 2019). The complete genome sequencing of *Streptomyces angustmyceticus* CQUSa03 has provided insights into its potential for producing a variety of antagonistic compounds, providing a basis for the development of robust biocontrol formulations (Luo et al., 2022).

7.3 Data-driven optimization of biocontrol application

Data-driven approaches are essential for optimizing the application of biocontrol agents. For instance, the population dynamics and gene expression of *Pseudomonas fluorescens* LBUM223 have been studied to understand its biocontrol efficacy against potato common scab. High populations of LBUM223 and increased expression of the phenazine-1-carboxylic acid biosynthetic gene were associated with effective disease control

(Arseneault et al., 2016). The use of multiple bacterial strains isolated from the rhizosphere of resistant potato plants has shown significant inhibition of *Phytophthora infestans*, with field trials indicating enhanced microbial diversity and reduced pathogen abundance (Feng et al., 2021). These findings underscore the importance of integrating biocontrol agents with data-driven strategies to achieve optimal pest and disease management in potato cultivation.

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Conflict of Interest Disclosure

The author affirms that this research was conducted without any commercial or financial relationships that could be construed as a potential conflict of interest.

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