Advancement in Biocontrol Agent Performance for Sustainable Cereal Farming

Thakoor Pavan, Sunil Kumar Ghosh

Cereal crops such as rice, wheat, maize, and barley are central to global food systems, contributing to the dietary caloric intake of billions of people worldwide. However, these crops are constantly under threat from a wide range of biotic stresses, including fungal, bacterial, and viral pathogens, as well as insect pests. Traditionally, the management of these threats has relied heavily on synthetic chemical pesticides and fertilizers, which, while effective in the short term, have led to several unintended consequences. These include the emergence of pesticide-resistant strains, degradation of soil health, disruption of beneficial microbial communities, and contamination of water bodies and food chains. In response to these concerns, there has been a growing emphasis on the development and adoption of environmentally sustainable and ecologically sound alternatives, among which biocontrol agents (BCAs) are prominent. Biocontrol agents beneficial microbes such as bacteria, fungi, viruses, and nematodes exert their effects through multiple mechanisms, including antibiosis, parasitism, competition, and induction of host plant resistance. Recent advancements in biotechnology, microbiology, and precision agriculture have significantly enhanced the efficacy, reliability, and scalability of BCAs. Techniques such as genomic sequencing, strain improvement, synthetic biology, and nano-formulation technologies have enabled the development of robust, target-specific biocontrol solutions that are compatible with integrated pest management (IPM) strategies.

Keywords: *Beneficial microbes, Bio-pesticides, IPM, Ecological integrity, Environmentally sustainable*

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Publisher: Cornous Publications LLP, Puducherry, India.
Insect Pest Challenges in Cereal Crops: Current Scenario and Sustainable Management
Editors: Dr. Atanu Seni
ISBN: 978-81-993853-3-7
DOI: https://doi.org/10.37446/edibook212025/63-82

This chapter provides a comprehensive overview of the latest innovations in the field of biocontrol agent development and deployment, with a focus on cereal crop production. It examines the various types of BCAs in use, their modes of action, and the technologies that have improved their formulation, delivery, and field performance. Additionally, the chapter addresses the challenges that limit broader adoption such as regulatory hurdles, environmental variability, and knowledge gaps and outlines strategic directions for future research and policy support. By advancing the performance and reliability of BCAs, modern agriculture can move toward more sustainable, resilient, and climate-smart cereal farming systems that maintain productivity while safeguarding ecological integrity.

Introduction

Cereal crops primarily rice (*Oryza sativa*), wheat (*Triticum aestivum*), maize (*Zea mays*), barley (*Hordeum vulgare*), and sorghum (*Sorghum bicolor*) are essential to global food security, providing nearly 50% of the caloric intake and a significant proportion of protein for the global population (FAO, 2021). However, these crops are persistently challenged by a range of biotic stresses, including fungal diseases such as blast (*Magnaporthe oryzae*), sheath blight (*Rhizoctonia solani*), Fusarium head blight, rusts, and insect pests like stem borers, leaf roller and aphids and other sucking pests. These pathogens and pests are responsible for significant annual yield losses, often ranging from 20% to 40% in the absence of effective control measures (Savary et al., 2019). Historically, the use of synthetic pesticides and fungicides has been the mainstay of pest and disease management in cereal farming. While these chemical inputs have played a critical role in boosting crop yields, their indiscriminate use has led to a suite of environmental and health concerns. These include the accumulation of pesticide residues in soil and water bodies, development of resistant pest strains, loss of biodiversity, and adverse effects on non-target organisms, including pollinators and beneficial soil microbes (Pimentel & Burgess, 2014).

Furthermore, the high cost of chemical pesticides and the lack of sustainable input supply chains make them inaccessible to smallholder farmers in many developing regions. In order to rapidly eliminate these insect pests, chemical pesticides are being applied. However, overuse of these chemical pesticides frequently resulted in environmental degradation, population growth, pesticide residual issues in the soil and water, and bug resistance to these chemicals. Target specificity, self-perpetuation, and environmental safety make biological control highly regarded (Shaikh et al., 2024a and Shaikh et al., 2024b). Bio-pesticidal control of insect pest is becoming increasingly popular as insect pathogens such as viruses, bacteria, fungi, nematodes, protozoa, and botanicals serve as bio-control (Ghosh, 2022). In light of these challenges, there has been increasing global interest in the development of sustainable, ecologically friendly approaches to crop protection. Biocontrol agents (BCAs) comprising naturally occurring antagonistic microorganisms such as bacteria, fungi, viruses, and nematodes offer a viable and promising alternative. These agents can suppress pathogens and pests through multiple mechanisms, including antibiosis, competition, hyper parasitism, and the induction of systemic resistance in host plants (Berg et al., 2021).

Botanical extract, *Polygonum hydropiper* floral part, pathogens, *Beauveria bassiana* and *Bacillus thuringiensis* caused significant lower killing of the predator (less than 30 %) whereas the synthetic insecticides, profenophos, malathion, DDVP and methomyl caused significantly higher killing (more than 52 %) (Ghosh, 2013; Ghosh, 2016). Ghosh et al. (2009) reported that microbial toxin *Streptomyces avermitilis* was found best for suppression of mite population (83.42% suppression).

Abamectin/vertimec (a synthetic analogue of a microbial toxin originated from a soil Actinomycetes) proved its superiority over Chemical pesticides (Ghosh et al., 1999). The chemical pesticides always perform better in respect of pest control over biologically originated pesticides but abamectin (a synthetic analogue of natural microbial toxin) is more or less equally effective (Ghosh et al., 2001). Ghosh et al., (2004) reported that abamectin is more effective against whitefly than chemical pesticides and it is also effective against soft bodied insects and mites. Advancements in microbial biotechnology, genomics, formulation science, and precision agriculture have significantly improved the effectiveness and commercial viability of BCAs in recent decades.

The integration of omics technologies has facilitated the discovery of novel strains and functional genes responsible for biocontrol activity (Mendes et al., 2011). At the same time, innovations in formulation such as microencapsulation, biofilm-based delivery, and seed coatings have enhanced the stability, shelf-life, and field performance of these agents (Bhattacharyya & Jha, 2012). Such improvements are particularly relevant for cereal crops, which are cultivated over vast areas and under highly variable agroecological conditions.

Furthermore, the growing adoption of integrated pest management (IPM) and organic farming systems across various countries has created new opportunities for deploying BCAs in large-scale cereal production (Chandler et al., 2011). National and international policy frameworks now increasingly promote the use of biopesticides and microbial inoculants as part of sustainable intensification strategies aimed at minimizing environmental impacts while maintaining high levels of productivity. Among bio- pesticides neem is a species that combines environment- friendly themes of current interest in the form of bio-pesticides (Ghosh & Mandal, 2025). Ghosh et al., (2012) reported that Jatropha is the important source of biofuel and neem is the important source of bio-pesticides. Ghosh (2020) reported that mixed formulation Azadiractin + polygonum, microbial toxin spinosad, botanical pesticide Azadiractin, tobacco leaf extract, extracts of Polygonum floral parts gave moderate to higher control of aphids.

Development of herbal insecticidal formulations may be as an alternative to harmful synthetic chemical insecticides and a step forward towards development of a promising eco-friendly technology in crop protection (Purkait et al., 2019). Despite the progress, several challenges still hinder the large-scale adoption of BCAs in cereal farming. These include inconsistent performance under field conditions, limited shelf-life, regulatory complexities, and insufficient awareness among farmers and extension workers. Addressing these barriers will require coordinated efforts involving multidisciplinary research, public-private partnerships, policy interventions, and farmer capacity building. This chapter explores the current landscape and recent advancements in the development and application of BCAs for sustainable cereal production. It examines the types and mechanisms of BCAs, evaluates innovations in formulation and delivery, presents successful case studies, and outlines future directions for research and policy to promote the widespread use of biocontrol in cereal farming systems.

Types of Biocontrol agents in cereal farming

Biocontrol agents (BCAs) are organisms or their derivatives used to suppress plant pathogens and pests through natural mechanisms. In cereal farming, they represent a crucial component of integrated pest and disease management systems. BCAs are broadly classified based on their biological nature into bacterial, fungal, viral, and nematode-based agents. Each group offers unique mechanisms of action and benefits, which can be strategically harnessed depending on the target pest/pathogen and environmental conditions.

Bacterial biocontrol agents

Bacterial BCAs are among the most widely studied and commercially utilized due to their ease of mass production, broad-spectrum activity, and compatibility with various agronomic practices.

***Bacillus* spp.:** Members of the genus *Bacillus*, especially *B. subtilis*, *B. amyloliquefaciens*, and *B. thuringiensis*, are extensively used as bio-pesticides. These Gram-positive, spore-forming bacteria produce a wide range of antimicrobial compounds including lipopeptides (iturins, surfactins, fengycins) and enzymes (proteases, chitinases) that inhibit fungal and bacterial pathogens (Ongena & Jacques, 2008; Stein, 2005). For instance, *B. subtilis* has demonstrated efficacy against *Fusarium graminearum* and *Rhizoctonia solani* in wheat and rice systems.

***Pseudomonas* spp.:** *Pseudomonas fluorescens* and *Pseudomonas putida* are commonly used plant growth-promoting rhizobacteria (PGPR) that exert biocontrol activity through siderophore production, competition, antibiosis, and induction of systemic resistance (Weller, 2007). In rice cultivation, *P. fluorescens* has been reported to control sheath blight and bacterial blight by enhancing host plant defense mechanisms (Mew and Rosales, 1986).

Actinobacteria: Species such as *Streptomyces* and *Micromonospora* have gained attention for their antibiotic-producing capabilities and soil persistence. *Streptomyces* spp. produces a wide range of secondary metabolites and has been shown to suppress *Fusarium* spp. and other cereal pathogens (Doumbou et al., 2001).

Fungal biocontrol agents

Fungal BCAs play a significant role in the management of soil-borne and foliar diseases in cereals through mechanisms like parasitism, enzyme production, and competition.

***Trichoderma* spp.:** *Trichoderma harzianum*, *T. viride*, and *T. atroviride* are dominant fungal BCAs with proven efficacy against a wide array of pathogens including *Fusarium*, *Rhizoctonia*, and *Sclerotinia* spp. These fungi colonize plant roots, produce hydrolytic enzymes (e.g., cellulases, chitinases), and compete for nutrients, thereby suppressing pathogens (Harman et al., 2004). They also enhance root growth and induce systemic resistance in plants.

Mycorrhizal fungi: Arbuscular mycorrhizal fungi (AMF), particularly *Glomus* spp., form symbiotic relationships with cereal roots, improving nutrient uptake and stress tolerance while also suppressing certain soil-borne diseases (Smith & Read, 2008).

Viral biocontrol agents

Entomopathogenic viruses, especially *Baculoviruses*, are highly specific to insect pests and have been utilized in managing Lepidopteran pests in cereals, such as armyworms and stem borers.

***Nucleopolyhedro virus* (NPV):** NPVs have been used to manage *Spodoptera frugiperda* (fall army worm) in maize. They cause infection by ingestion, leading to liquefaction of the insect body, thereby curbing pest populations without harming non-target organisms (Moscardi, 1999).

Granuloviruses (GVs): These viruses have shown efficacy against early instar larvae of pests and are integrated into cereal IPM programs in some countries, though their commercial availability is still limited.

Nematode-based biocontrol agents

Entomopathogenic nematodes (EPNs), such as those belonging to *Steinernema* and *Heterorhabditis* genera, are biological agents that parasitize and kill insect pests. These nematodes carry symbiotic bacteria (*Xenorhabdus* and *Photorhabdus*) which release toxins inside the insect host. EPNs are used in managing root-feeding and soil-dwelling insect pests in cereal crops. They are especially useful in conservation agriculture systems where soil health is maintained (Gaugler, 2002).

Plant-derived and Endophytic biocontrol agents

Recently, endophytic micro-organisms bacteria and fungi that live inside plant tissues have gained recognition for their biocontrol potential. Species like *Bacillus velezensis*, *Burkholderia* spp., and *Fusarium oxysporum* non-pathogenic strains have shown promise in suppressing diseases and promoting cereal crop health (Hallmann et al., 1997; Hardoim et al., 2015). These endophytes may be particularly important in enhancing stress resilience under climate change scenarios and improving nutrient use efficiency in cereals.

Mechanisms of action of biocontrol agents

Biocontrol agents (BCAs) suppress plant pathogens and pests using a variety of direct and indirect mechanisms. Understanding these mechanisms is essential for the strategic deployment of BCAs in cereal farming systems and for enhancing their effectiveness through strain selection, formulation, and integration with other agricultural practices. The primary mechanisms include antibiosis, parasitism and predation, competition, induction of systemic resistance, and plant growth promotion. Many BCAs utilize more than one mechanism simultaneously, offering broad-spectrum and durable protection.

Antibiosis: Antibiosis refers to the production of antimicrobial compounds such as antibiotics, volatile organic compounds (VOCs), lipopeptides, and siderophores that inhibit the growth or metabolism of plant pathogens.

- *Bacillus* spp. produces diverse lipopeptides such as iturins, surfactins, and fengycins, which disrupt fungal cell membranes and inhibit spore germination (Ongena & Jacques, 2008).
- *Pseudomonas fluorescens* produces phenazine, pyrrolnitrin, and 2, 4-diacetylphloroglucinol (DAPG), which have fungistatic or fungicidal properties (Weller, 2007).
- Volatile compounds like hydrogen cyanide (HCN) and VOCs (e.g., acetoin and 2, 3-butanediol) also contribute to pathogen inhibition (Ryu et al., 2003).

These compounds can act at low concentrations and persist in the rhizosphere, offering a protective zone around cereal roots.

Parasitism and predation: Some BCAs directly attack and parasitize pathogens, particularly fungal pathogens, through mechanisms such as coiling around hyphae, penetration, and enzymatic degradation of the host's cell wall.

- Field study of both yellow stem borer (YSB) and its important parasitoids were carried out in the field of rice cultivar Swarna mashuri (MTU 7029) during four consecutive crop years (2005-2008) at Raiganj, India. Observations include all the life stages of YSB (egg, larvae and pupa) and its important Hymenopteran parasitoids species. *T. rowani*, Gahan (Scelionidae), *T. schoenobii*, Ferriere (Eulophidae) and *T. chilonis*, Ishii (Trichogrammatidae) were identified as the three important egg parasitoids in this region. High average parasitization at early vegetative stages (63.85%) decreased steadily and remained constant during mid-tillering stage (34.65%), and further declined during the ripening stage (14.67%). The overall egg mass parasitization (%) by *T. chilonis*, *T. rowani* and *T. schoenobii* was 18.23-71.67%, 15.56-67.34% and 10.23-52.56% respectively. Abundance of *T. chilonis* was highest in 37 standard meteorological weeks (SMW) and minimum in 30 SMW. Maximum number of *T. rowani* was recorded in 37 SMW and lowest in 30 SMW. Number of *T. schoenobii* was maximum in 37 SMW and minimum in 30 SMW (Chakraborty et al., 2015)

- *Trichoderma* spp. exhibit mycoparasitism, where they recognize pathogenic fungi, attach to their hyphae, and secrete cell wall-degrading enzymes such as chitinases, glucanases, and proteases (Harman et al., 2004). This process causes lysis of the target pathogen and prevents further spread.

- Entomopathogenic fungi like *Beauveria bassiana* and *Metarhizium anisopliae* infect insect pests directly by penetrating their cuticle and colonizing internal tissues, ultimately killing the host (Shah & Pell, 2003).

- Averrnectin (Vertimec 1.9 EC; 0.5 ml/L) was the most effective in suppressing dead heart caused by the pest, closely followed by *Beauveria bassiana* (Biorin 107 conidia/ ml; I ml/L) and *Bacillus thuringiensis* Berliner (Biolep 5 x 107 spores/ml; I g/L) (Ghosh & Senapati, 2009).

Competition for resources and niches: BCAs can out compete pathogens for nutrients (especially iron) and space, thereby preventing pathogen establishment in the rhizosphere or phyllosphere.

- Siderophore production is a key strategy among PGPRs like *Pseudomonas* and *Bacillus*, which sequester iron more efficiently than pathogens, making it unavailable for pathogen growth (Loper & Henkels, 1997).
- Rapid colonization of root surfaces or internal plant tissues by beneficial microbes blocks pathogen entry and suppresses infections.

In cereal crops, this competitive exclusion is particularly important in early growth stages when seedlings are vulnerable to soil-borne pathogens.

Induction of systemic resistance: Some BCAs trigger plant immune responses, enhancing the plant's natural defense mechanisms against a wide range of pathogens and pests.

- This process, known as induced systemic resistance (ISR) or systemic acquired resistance (SAR), involves upregulation of defense-related genes, including those encoding for PR (pathogenesis-related) proteins, peroxidases, and phytoalexins (Pieterse et al., 2014).

- *Pseudomonas fluorescens* and *Bacillus subtilis* are well-known ISR inducers, capable of priming the plant to respond more robustly to pathogen attack.

- ISR is usually mediated through jasmonic acid (JA) and ethylene signaling pathways, while SAR often involves salicylic acid (SA).

In cereals, ISR contributes to enhanced resistance against diseases such as rice blast, wheat rust, and maize downy mildew (Kloepper et al., 2004).

Plant growth promotion: Though not a direct antagonistic mechanism, plant growth promotion by BCAs indirectly contributes to disease resistance by improving plant vigor and resilience.

- PGPRs produce phytohormones such as indole-3-acetic acid (IAA), gibberellins, and cytokinins that enhance root development and nutrient uptake (Vessey, 2003).
- Some microbes also facilitate biological nitrogen fixation and phosphate solubilization, making nutrients more accessible to cereal crops.
- By alleviating abiotic stresses (e.g., drought, salinity), BCAs help maintain plant health, which in turn reduces the severity of biotic stress impacts.

Biofilm formation and colonization efficiency: An emerging mechanism is the formation of biofilms by certain microbial BCAs on root surfaces. These biofilms:

- Provide a stable microenvironment for microbial activity.
- Protect both microbes and plant roots from external stresses.
- Enhance the colonization efficiency of BCAs, ensuring consistent performance under field conditions (Raaijmakers et al., 2002).

Biofilm-forming strains of *Bacillus* and *Pseudomonas* have shown improved performance in cereal cropping systems under variable environmental conditions.

Technological advancements enhancing BCA performance

The effectiveness of biocontrol agents in cereal farming has historically been limited by environmental variability, inconsistent field performance, and formulation challenges. However, recent technological advancements have revolutionized the development, delivery, and monitoring of BCAs. These innovations are pivotal for scaling up biological control in commercial agriculture and ensuring its integration into sustainable cereal production systems.

Genomics and molecular characterization: The application of genomics and molecular biology has led to better understanding, identification, and enhancement of BCA strains.

- Whole-genome sequencing of beneficial microbes such as *Trichoderma harzianum*, *Bacillus subtilis*, and *Pseudomonas fluorescens* has revealed genes involved in antimicrobial compound production, stress tolerance, root colonization, and plant growth promotion (Berendsen et al., 2012; López-Bucio et al., 2007).

- CRISPR-Cas genome editing is being explored to modify specific genes in BCAs to enhance their antagonistic activity, persistence, or compatibility with chemical inputs (Wang et al., 2022).
- Omics-based approaches, including transcriptomics, proteomics, and metabolomics, are used to study plant-BCA-pathogen interactions at the molecular level, allowing the development of precision biocontrol strategies.

These technologies help screen and design highly potent, stress-resilient strains that perform reliably under varied agro-climatic conditions.

Formulation technology: The formulation of BCAs plays a critical role in their shelf-life, stability, ease of application, and field performance.

- Encapsulation techniques such as microencapsulation, nanoencapsulation, and alginate beads protect BCAs from UV light, desiccation, and microbial competition, thereby enhancing survival and controlled release (Rosas et al., 2018).
- Carrier-based formulations using talc, lignite, bentonite, or biochar ensure improved delivery and adherence to seeds or soil (Reddy et al., 2019).
- Liquid bioformulations with biofilms and stabilizers are increasingly being commercialized for easy application through drip irrigation or foliar sprays.

Improved formulations are essential for ensuring consistent colonization of BCAs on cereal roots and leaves in field conditions.

Artificial intelligence and data analytics: AI and machine learning (ML) tools are now being used to optimize BCA applications and predict their performance based on environmental and biological data.

- ML models can predict the efficacy of specific BCA strains under various conditions, taking into account variables like temperature, humidity, soil pH, and cropping patterns (Chowdhury et al., 2022).
- Decision support systems (DSS) and mobile apps integrated with remote sensing and GIS data can help farmers apply BCAs more effectively and at the optimal time.

These technologies make biocontrol practices more data-driven and adaptive to real-time field conditions.

Precision agriculture and smart delivery systems: Precision agriculture technologies have enabled targeted and efficient delivery of BCAs, reduced wastage and improving cost-effectiveness.

- Drones and unmanned aerial vehicles (UAVs) are being deployed for aerial spraying of microbial consortia over large cereal fields (Huang et al., 2018).
- Seed coating technologies allow BCAs to be directly embedded onto cereal seeds, ensuring early root colonization and disease suppression during germination (Harman et al., 2004).
- Soil inoculation via automated systems ensures uniform distribution and optimal depth placement of BCAs, improving their establishment and survival.

These methods are especially beneficial in large-scale commercial cereal farming where uniformity and timing are critical.

Synthetic biology and microbial consortia engineering: Synthetic biology offers the potential to design microbial consortia with tailored functionalities that surpass the performance of individual BCAs.

- Engineered microbial consortia can include combinations of bacteria and fungi that perform complementary roles such as pathogen suppression, nutrient solubilization, and hormone production (De Souza et al., 2020).
- These consortia are more resilient to environmental stress and exhibit synergistic interactions that enhance plant health.
- Efforts are underway to develop "designer consortia" for specific cereals like rice, wheat, and maize, targeting dominant regional pathogens.

Bioreactor-based mass production: The commercial viability of BCAs depends on cost-effective and scalable mass production systems.

- Industrial bioreactors are now used to produce high-quality microbial biomass with controlled nutrient and aeration parameters, enhancing spore viability and metabolite yield (Pandey et al., 2000).
- Advances in solid-state fermentation (SSF) and submerged fermentation (SmF) allow simultaneous production of microbial spores and bioactive compounds at a commercial scale.

These advancements have drastically reduced production costs and increased availability of BCAs for farmers.

Nanotechnology integration: Nanotechnology is being integrated into biocontrol systems to improve delivery, protection, and interaction with plant tissues.

- Nano-formulations of microbial BCAs allow for better penetration, adhesion, and sustained release of active compounds (Chhipa, 2019).
- Nanoparticles (e.g., silica, chitosan) are used to encapsulate BCA metabolites, enhancing their antimicrobial activity and persistence on crop surfaces.
- In case of plant health management, Nanotechnology can be applied for: A mechanism developed for proper utilization of bio-control agent. Early detection of insect pest, mite pest and other pest, diseases, and nutrient deficiency in the field and plant health. Nano pheromones are used with a sustained release of semiochemicals. E-nose nanotechnologies are now widely used for detection of insect infestation in storage. Thus far, it has been employed in cotton for stink bud detection, in pulses for pulse beetle detection, in wheat for mite detection, and also for storage pests of rice (Ghosh, 2023; Ghosh *et al.*, 2022)

This emerging field holds promise for creating highly effective, smart biocontrol systems.

Integration with sustainable farming practices

The integration of biocontrol agents (BCAs) into sustainable farming systems is critical for the long-term ecological and economic viability of cereal production. BCAs are a cornerstone of sustainable agriculture due to their environmentally benign nature, specificity, and potential to reduce the dependence on chemical pesticides. Their synergistic use with other agroecological practices enhances soil health, biodiversity, and resilience against biotic and abiotic stresses. This section highlights the main approaches to incorporating BCAs within sustainable farming practices.

Integrated Pest Management (IPM): BCAs are a fundamental component of Integrated Pest Management (IPM), a holistic strategy that combines biological, cultural, physical, and chemical tools to manage pests in an economically and ecologically sound manner.

- BCAs such as *Trichoderma*, *Pseudomonas*, and *Bacillus* spp. have been successfully incorporated into IPM programs to control cereal diseases like Fusarium head blight, downy mildew, and blast (Pretty & Bharucha, 2015).
- *Bacillus thuringiensis* can be used shortly before crop harvest without any residual effect (Ghosh et al., 2004).
- When combined with crop rotation, trap cropping, and resistant cultivars, BCAs enhance IPM effectiveness by creating multiple barriers against pathogen proliferation.
- The use of BCAs in IPM also reduces the selection pressure for pesticide-resistant pathogen strains, contributing to long-term pest suppression (Kumar et al., 2020).

Organic and low-input farming systems: BCAs are especially compatible with organic and low-input farming, where synthetic agrochemicals are limited or prohibited.

- In organic cereal systems, BCAs like *Beauveria bassiana* and *Trichoderma harzianum* serve as the primary agents for disease and pest control (Mäder et al., 2002).
- The promotion of soil biological diversity in organic systems enhances the natural establishment and efficacy of BCAs, particularly in the rhizosphere.
- Moreover, the integration of green manures, compost, and biofertilizers supports BCA survival and activity, creating a favourable soil microenvironment for their proliferation (Lori et al., 2017).

Conservation agriculture: Conservation agriculture (CA**)**, characterized by minimal soil disturbance, crop residue retention, and crop diversification, provides a conducive environment for BCAs.

- Reduced tillage preserves soil microbial habitats and promotes the persistence of BCAs such as *Paenibacillus* and *Streptomyces* spp. in cereal fields (Hobbs et al., 2008).
- Cover cropping and intercropping increase microbial diversity and support beneficial microbial consortia that include BCAs, enhancing disease suppression naturally.
- CA practices also enhance soil organic matter, which serves as a substrate for microbial growth and supports the establishment of rhizosphere-competent BCAs (Derpsch et al., 2010).

Use with biofertilizers and compost teas: The co-application of BCAs with biofertilizers, compost teas, and vermicompost contributes to nutrient cycling while also enhancing plant health and disease resistance.

- Biofertilizers such as *Azospirillum*, *Azotobacter*, and phosphate-solubilizing bacteria (PSB) can be co-inoculated with BCAs to simultaneously promote plant growth and suppress pathogens (Vessey, 2003).
- Compost teas enriched with beneficial microbes can act as foliar sprays or soil drenches to suppress foliar and soil-borne pathogens in cereals (Ingham, 2005).

Such combinations reduce input costs and environmental impact while improving soil fertility and plant resilience.

Compatibility with agroecological practices: BCAs align with agroecological principles such as enhancing biodiversity, promoting ecological balance, and reducing external inputs.

- Agroecology encourages the use of native or locally adapted BCAs, which tend to perform better under local environmental conditions and are more compatible with existing farming practices (Altieri et al., 2015).

- Encouraging beneficial insect habitats and field edge biodiversity indirectly supports BCAs by stabilizing microbial communities and promoting natural enemies of pests.

This systems-based approach ensures that BCAs are integrated not as standalone products but as part of a dynamic agroecosystem.

Role in climate-smart agriculture: BCAs are gaining importance in climate-smart agriculture (CSA), which aims to sustainably increase productivity, enhance resilience (adaptation), and reduce emissions.

- Many BCAs exhibit tolerance to drought, salinity, and temperature extremes and can help cereals maintain productivity under climate stress conditions (Backer et al., 2018).
- By reducing the reliance on synthetic inputs, BCAs contribute to lower greenhouse gas emissions and promote carbon sequestration in soils.
- Additionally, climate-resilient strains of BCAs are being developed to retain efficacy under changing environmental conditions, which is crucial for sustainable cereal farming in vulnerable regions.
- Correlation co-efficient studies revealed that activity predator spider population decrease with the rise of temperature, relative humidity and heavy rainfall. But in case of the predator ladybird beetle, population decrease with the rise of temperature, relative humidity and rainfall (Subba & Ghosh, 2016).
- Abiotic conditions such as minimum temperature, temperature gradient, maximum relative humidity and average relative humidity had significant positive influence on *C. septempunctata* population. In case of minimum relative humidity and sunshine hours, a negative influence was observed. In addition, other factors such as rainfall imparted insignificant positive effect on population development (Ghosh et al., 2013).

Case studies in cereal crops

The effectiveness of biocontrol agents (BCAs) in promoting sustainable cereal farming has been demonstrated across diverse agro-climatic regions and production systems. Case studies provide evidence of how BCAs can suppress diseases, enhance yield, and integrate successfully with ecological farming practices. This section outlines representative examples from key cereal crops wheat, rice, maize, and barley highlighting field-level success, challenges, and scalability.

Wheat (management of fusarium head blight): Fusarium head blight (FHB), caused by *Fusarium graminearum*, is a major fungal disease affecting wheat globally, leading to yield loss and mycotoxin contamination. In Canada, researchers have tested strains of *Clonostachys rosea* and *Trichoderma harzianum* as biocontrol agents against FHB. When applied during the flowering stage, these agents reduced disease severity by up to 50% and lowered deoxynivalenol (DON) toxin levels significantly (Xue et al., 2014). Integration with resistant cultivars and timely application was essential for maximizing efficacy. Similarly, in Germany, field trials using *Bacillus subtilis*–based formulations (e.g., Serenade®) in an integrated pest management (IPM) program resulted in both disease suppression and improved grain quality, reinforcing the potential of BCAs in temperate wheat systems (Schisler et al., 2011).

Rice (suppression of sheath blight and blast disease): In Asia, where rice is a staple, fungal diseases such as sheath blight (*Rhizoctonia solani*) and blast (*Magnaporthe oryzae*) are major threats to productivity.

Field trials in Tamil Nadu, India, demonstrated that *Pseudomonas fluorescens* applied as a seed treatment and foliar spray effectively reduced sheath blight incidence by over 40% compared to untreated controls (Sundar & Vidhyasekaran, 2008). The treatment also promoted plant growth and tiller number due to the production of phytohormones and siderophores. In Vietnam and the Philippines, *Trichoderma asperellum* and *Bacillus amyloliquefaciens* were used under organic rice schemes, resulting in 20–30% yield increases while maintaining disease levels well below economic thresholds (Nguyen et al., 2019). These cases illustrate the synergy between BCAs and agroecological practices, especially under low-input conditions.

Maize (control of root rot and fall armyworm): Maize is vulnerable to both soil-borne pathogens and insect pests, including the recently invasive fall armyworm (*Spodoptera frugiperda*). In Kenya, the use of *Metarhizium anisopliae*, a fungal entomopathogen, was evaluated for fall armyworm control in smallholder maize systems. Applied as a biopesticide spray, it led to a 60–70% reduction in larval populations, with minimal impact on beneficial insects. Its adoption was facilitated through farmer field schools and extension services (Sisay et al., 2019). In Argentina, *Bacillus velezensis* was introduced to combat root and stalk rot diseases in maize caused by *Fusarium verticillioides*. In large-scale trials, this BCA enhanced root biomass and reduced disease severity by 45%, showing strong rhizosphere colonization and antagonism.

Barley (managing rhizoctonia root rot): Barley, often grown in rotation with wheat, is susceptible to *Rhizoctonia solani*, which causes root rot and reduces early plant vigor. Australian trials have shown that seed coating barley with *Trichoderma atroviride* and *Pseudomonas chlororaphis* leads to early suppression of *Rhizoctonia* spp., especially in minimum tillage systems. One study reported a 30% yield increase under conservation agriculture conditions, demonstrating how BCA efficacy is enhanced when aligned with soil health practices (Bithell et al., 2015).

Challenges and lessons learned: Despite promising results, several factors influence BCA success in the field:

- **Environmental variability:** Efficacy can decline under extreme temperatures, drought, or heavy rainfall, requiring strain selection for local conditions.
- **Formulation and delivery:** Liquid and granular formulations often perform better than dry powders, particularly for seed or soil applications.
- **Integration with farming practices:** BCAs show better performance when combined with crop rotation, organic amendments, or host resistance.
- **Farmer awareness and training:** Adoption is higher when farmers receive technical guidance and observe field-level benefits.

Challenges and limitations

Despite their numerous advantages, biocontrol agents (BCAs) face several practical, ecological, and economic challenges that constrain their widespread adoption and consistent performance in cereal farming systems.

Inconsistent field performance: One of the primary limitations of BCAs is their variable efficacy under field conditions. While many BCAs perform well in controlled environments, their effectiveness can fluctuate in the open field due to factors such as soil type, temperature, moisture, and UV radiation (Fravel, 2005). Unlike synthetic pesticides, BCAs are living organisms whose survival, colonization, and interaction with the host plant are influenced by external conditions.

Short shelf-life and formulation issues: BCAs often have a short shelf-life and require specific storage conditions (e.g., refrigeration or protection from desiccation), which complicates logistics in low-resource settings (Kumar et al., 2021). Additionally, the development of stable, user-friendly formulations particularly for spore-based or liquid inoculants is technically challenging. Some products may lose viability during transportation or when exposed to high temperatures.

Narrow spectrum of activity: Most BCAs have a narrow target range, meaning they are effective against specific pathogens or pests but may not provide broad-spectrum protection like chemical pesticides. This specificity requires accurate diagnosis of the pest or pathogen, which may not always be feasible for farmers lacking access to extension services or diagnostic tools (Chandler et al., 2011).

Slow action compared to chemicals: BCAs typically exhibit a slower onset of action, as they rely on colonization, antagonism, or induction of systemic resistance rather than immediate toxicity. This lag time can be a drawback in acute outbreak situations where rapid pest suppression is necessary (Garbeva et al., 2004). Farmers accustomed to the quick action of synthetic inputs may find BCAs less reliable for emergency interventions.

Regulatory and commercialization barriers: The regulatory framework for BCAs is often unclear or overly complex in many countries, creating delays in product registration and market entry. Unlike synthetic agrochemicals, BCAs may not fit well into existing regulatory categories, leading to inconsistencies in approval processes (Glare et al., 2012). Furthermore, small and medium enterprises developing BCAs often lack the financial capacity to meet regulatory requirements or conduct long-term field trials.

Limited farmer awareness and technical support: Adoption of BCAs is hindered by limited awareness among farmers and insufficient extension services. Many farmers are unfamiliar with proper application methods (e.g., seed coating, soil drenching, foliar spraying) or the ecological principles underlying biocontrol. This gap leads to misuse or underuse, further reducing perceived efficacy (Pretty et al., 2018).

Future perspectives

As global agriculture transitions toward sustainability and resilience, biocontrol agents (BCAs) are poised to play an increasingly vital role in cereal crop protection. While significant advancements have been made, future developments must address current limitations and capitalize on emerging technologies to realize the full potential of BCAs. The following perspectives outline promising directions for research, development, and implementation.

Precision agriculture and digital tools: Integrating BCAs with precision agriculture technologies such as remote sensing, GIS, and IoT-based monitoring systems can significantly enhance their deployment. Early detection of pathogens and site-specific application of BCAs can reduce wastage and improve consistency. Smart spraying systems and drone-based delivery are already being tested for large-scale BCA applications, particularly in rice and wheat systems (Shamshiri et al., 2018).

Synthetic biology and genetic enhancement: Synthetic biology offers new tools to improve BCA traits such as environmental tolerance, persistence, and mode of action. For instance, genetically engineered strains of *Pseudomonas fluorescens* and *Trichoderma* spp. have shown enhanced antifungal activity and colonization ability (Mullins et al., 2021). Although regulatory and public acceptance hurdles remain, gene editing tools like CRISPR/Cas could facilitate the design of safer, more efficient microbial consortia tailored for specific cereal crops.

Development of microbial consortia: Future strategies are shifting from single-strain BCAs to multi-strain or multi-species microbial consortia, which offer broader spectrum activity, functional redundancy, and ecological stability. Research shows that such consortia can mimic natural rhizosphere communities and adapt better to fluctuating environmental conditions (Bakker et al., 2020). The challenge lies in identifying compatible strains and ensuring consistent performance across diverse field conditions.

Climates-resilient BCA formulations: As climate variability increases, developing climate-resilient BCAs is crucial. Heat- and UV-tolerant formulations, spore-based granules, and encapsulated microbes are under development to withstand harsher field environments. Advances in carrier materials such as biochar, nanomaterials, or biodegradable polymers can improve the shelf-life and delivery efficiency of BCAs, particularly in tropical cereal-growing regions (Singh et al., 2019).

Policy support and capacity building: The future success of BCAs also depends on supportive policy frameworks, harmonized regulatory procedures, and investment in farmer training. International collaboration is needed to develop science-based registration protocols, promote public-private partnerships, and fund long-term field trials in smallholder farming systems. Extension services must be strengthened to build farmer awareness and encourage adoption through demonstration trials and participatory research.

Integration into holistic agroecological models: BCAs should not be viewed as standalone solutions but as integral components of agroecological intensification. Their efficacy can be enhanced when combined with practices such as crop rotation, conservation tillage, organic amendments, and intercropping. Future research must focus on designing holistic, region-specific models that embed BCAs within broader sustainability goals (Wezel et al., 2020).

Conclusion

The growing demand for sustainable agricultural practices has placed biocontrol agents (BCAs) at the forefront of environmentally friendly crop protection strategies, especially in cereal farming. As conventional chemical inputs face increasing scrutiny due to their environmental impacts, human health concerns, and the emergence of resistant pests and pathogens, BCAs offer a biologically sound alternative that aligns with the principles of agroecology and sustainable intensification. Throughout this chapter, we have highlighted the diversity of BCAs including bacteria, fungi, viruses, and natural enemies and their multifaceted roles in suppressing cereal crop diseases and pests. Their mechanisms of action ranging from direct antagonism and parasitism to induced systemic resistance and competition for nutrients demonstrate their versatility in various agro-ecological settings. Technological innovations such as genomics, microbial consortia, precision agriculture, and improved formulations have further enhanced the efficacy and reliability of BCAs, paving the way for broader adoption. The integration of synthetic biology, digital tools, climate-resilient formulations, and agroecological models will likely define the next generation of biocontrol solutions.

To realize this potential, stakeholders must foster collaborative innovation, ensure access to quality bioinputs, and create enabling environments for safe and effective BCA use. In summary, biocontrol agents represent a pivotal element in the transition to sustainable cereal farming. By bridging the gap between ecological principles and modern crop management, they offer a viable pathway to reduce dependence on synthetic chemicals, enhance soil and plant health, and contribute to global food security in a climate-resilient manner.

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