SATSA Mukhapatra - Annual Technical Issue **30** : 2026 ISSN 0971-975X

Biocontrol Agents: An Important Tool for Eco-friendly Pest Management in Cereal Crops

Sunil Kumar Ghosh and Thakoor Pavan*

(Received : December 20, 2025; Revised : January 18, 2026; Accepted : January 24, 2026)

ABSTRACT

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 microorganisms 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. 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 mode 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.

Keywords : Beneficial microbes, Biopesticides, IPM, Ecological integrity, Environmentally sustainable

Department of Agriculture Entomology, Bidhan Chandra Krishi Viswavidyalaya, Mohanpur, Nadia, West Bengal-741252, India.
Corresponding Author E-mail: ghosh.sunil@bckv.edu.in; sg_bckv2014@rediffmail.com

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 as well as insect pests like stem borer, leaf roller, 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 strains, loss of biodiversity, and adverse effects on non-target organisms, including pollinators and beneficial soil microbes (Pimentel and 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 results in environmental degradation, population growth, pesticide residual issues in the soil and water, and pest 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). Biopesticidal control of insect pest is becoming increasingly popular as insect pathogens such as viruses, bacteria, fungi, nematodes, protozoa, and botanicals serve as biocontrol (Ghosh, 2022).

In light of these challenges, there has been increasing global interest in the development of sustainable and ecofriendly 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, hyperparasitism, and the induction of systemic resistance in host plants (Berg *et al.,* 2021).

Botanical extract derived from floral part of *Polygonum hydropiper* and pathogens like *Beauveria bassiana* and *Bacillus thuringiensis* caused significant lower mortality of the predator (less than 30 %) whereas the synthetic insecticides like profenophos, malathion, DDVP and methomyl caused significantly higher mortality (more than 52 %) (Ghosh, 2013; Ghosh, 2016). Ghosh *et al.* (2009) reported that microbial toxin *Streptomyces avermitilis* was found to be the best for suppression of mite population (83.42%). Abamectin (Vertimec), a microbial toxin originated from a soil Actinomycetes, proved its superiority over synthetic insecticides (Ghosh *et al.,* 1999). Though synthetic pesticides perform better in respect of pest control over biologically originated pesticides, abamectin was found to be more or less equally effective (Ghosh *et al.,* 2001). Abamectin is effective against whitefly, safer to human health and environment, and also effective against soft bodied insects and mites (Ghosh *et al.,* 2004). The concept of biological control is not new; however, recent advancements in microbial biotechnology, genomics, formulation science, and precision agriculture have significantly improved the efficacy 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 technology—such as microencapsulation, biofilm-based delivery, and seed coatings—have enhanced the stability, shelf-life, and field performance of these agents (Bhattacharyya and Jha, 2012). Such improvements are particularly relevant for cereal crops, which are cultivated over the vast areas and under highly variable agroecological conditions.

Furthermore, the growing adoption of integrated pest management (IPM) and organic farming systems across the globe has created new opportunities in large-scale for the deployment of BCAs 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 biopesticides neem is a species that combines two environment-friendly themes of current interest in the form of bio-pesticides and bio-diesel (Ghosh and Mandal, 2025).

Ghosh *et al.* (2012) reported that Jatropha is an important source of biofuel and neem is an important source of biopesticides. Ghosh (2020) reported that the mixed formulation of Azadiractin + *Polygonum*, microbial toxin spinosad, botanical pesticide Azadiractin, tobacco leaf extract and extracts of *Polygonum* floral parts gave moderate to higher control of aphids. Development of herbal insecticidal formulations may, therefore, serve as an effective 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 the farming communities and the extension workers. Addressing these barriers will require coordinated efforts involving multi disciplinary research, public-private partnerships, policy interventions, and farmer capacity building initiative. 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 system, presents successful case studies, and outlines future directions for research and policy making to promote the widespread use of biocontrol in cereal based 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 or pathogen and prevailing 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 and Jacques, 2008; Stein, 2005). For instance, *B. subtilis* has demonstrated efficacy against *Fusarium graminearum* and *Rhizoctonia solani* in wheat and rice ecosystem.

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 defence 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 and 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.

Nucleopolyhedrosis virus (NPV)

NPVs have been used to manage *Spodoptera frugiperda* (fall armyworm) 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 microorganisms—bacteria and fungi that live inside plant tissues-have gained recognition for their biocontrol potential. Species like *Bacillus velezensis*, *Burkholderia spp.*, and non-pathogenic strains of *Fusarium oxysporum* have shown promise in disease suppression and cereal crop health promotion (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 and 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 root.

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, West Bengal, India. Observations include all the life stages of YSB (egg, larvae and pupa) and its important Hymenopteran parasitoids species. *Telenomus rowani*, Gahan (Scelionidae), *Tetrastichus schoenobii*, Ferriere (Eulophidae) and *Trichogramma chilonis,* Ishii (Trichogrammatidae) were identified as the three important egg parasitoids in this region. Highest parasitisation was observed during early vegetative stage (63.85%) and declined to 14.67% at the crop maturity (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 and Pell, 2003).
- Abamectin (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; 1 ml/L) and *Bacillus thuringiensis* Berliner (Biolep 5 x 107 spores/ml; 1 g/L) (Ghosh and 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 by PGPR such as *Pseudomonas* and *Bacillus* spp. enables efficient iron sequestration, thereby limiting iron availability to pathogens (Loper and Henkels, 1997). Rapid colonization of root surfaces and internal plant tissues by beneficial microbes restricts pathogen establishment and invasion.

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 defence mechanism against a wide range of pathogens and pests.

- This process, known as induced systemic resistance (ISR) or systemic acquired resistance (SAR), involves upregulation of defence-related genes, including those encoding for PR (pathogenesis-related) proteins, peroxidases, and phytoalexins (Pieterse *et al.,* 2014).
- *Pseudomonas fluorescens* and *Bacillus subtilis* are well-documented ISR inducers that prime plants for rapid defence responses. ISR is typically mediated through jasmonic acid and ethylene signalling pathways, whereas SAR is primarily regulated by salicylic acid.

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

Artificial Intelligence (AI) and machine learning (ML) tools are now being used to optimize BCA applications and predict their performance.

- ML models can predict the efficacy of specific BCA strains under various conditions, considering the 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 significantly improved the targeted and efficient delivery of BCAs, reducing 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 and seed-pelleting technologies allow BCAs to be directly embedded onto cereal seeds, ensuring early root colonization and disease suppression during germination (Harman *et al.,* 2004).
- Automated soil inoculation systems ensures uniform distribution and precise placement of BCAs at optimal depth, improving their establishment and survival.

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

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. These consortia are more resilient to environmental stress and exhibit synergistic interactions that enhance plant health (De Souza *et al.,* 2020).

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 proper utilization of biocontrol agent, early detection of insect and mite pest, diseases, and nutrient deficiency. Nano pheromones are used with sustained release of semiochemicals. E-nose nanotechnologies are now widely used for detection of insect infestation in storage. 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 and 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 production 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. Additionally, CA practices improve the soil organic matter content, 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 promote plant growth and suppress pathogens simultaneously (Vessey, 2003).
- Compost teas enriched with beneficial microbes can be applied 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) to climate change, 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 predator and spider population decrease with the rise of temperature, relative humidity and heavy rainfall. But in case of the predator ladybird beetle, population decreases with the rise of temperature, relative humidity and rainfall (Subba and 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, whereas relative humidity and sunshine hours showed a negative influence. Rainfall exerted 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.

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. 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.

Rice: Suppression of Sheath Blight and Blast Disease

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 and 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* resulted 20–30% yield increase while maintaining disease levels well below economic thresholds. These cases illustrate the synergy between BCAs and agroecological practices, especially under low-input conditions.

Maize: Control of Root Rot and Fall Armyworm

In Kenya, application of *Metarhizium anisopliae* resulted in a 60–70% reduction in fall armyworm (*Spodoptera frugiperda*) larval populations with minimal impact on beneficial insects. 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

Australian studies showed 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 variations in 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 handling and distribution, particularly 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 delayed response 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, geographic information systems (GIS), and Internet of Things (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 evaluated 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 challenges remain, gene-editing technologies such as CRISPR/Cas offer opportunities to develop safer and more efficient microbial strains and consortia tailored to 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 has become a priority. Heat- and UV-tolerant formulations, spore-based granules, and encapsulated microbes are being developed to withstand harsh field conditions. 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.

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 financial support for 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.

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 diverse mechanisms of action, ranging from direct antagonism and parasitism to induced systemic resistance and competition for nutrients, underscore their adaptability across varied agroecological 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 biocontrol strategies. To realize this potential, stakeholders must foster collaborative innovation, ensure access to quality bioinputs, and create enabling environments for safe and effective BCA use. By bridging the gap between ecological principles and modern crop management, BCAs 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.

References

Altieri, M. A., Nicholls, C. I., Henao, A. and Lana, M. A. 2015. Agroecology and the design of climate change-resilient farming systems. *Agronomy for Sustainable Development* **35**(3): 869–890.

Backer, R., Rokem, J. S., Ilangumaran, G., Lamont, J., Praslickova, D., Ricci, E. and Smith, D. L. 2018. Plant growth-promoting rhizobacteria: context, mechanisms of action, and roadmap to commercialization of biostimulants for sustainable agriculture. *Frontiers in Plant Science* **9**: 1473.

Bakker, P. A. H. M., Pieterse, C. M. J. and de Jonge, R. 2020. The soil-borne legacy. *Cell* **183**(6): 1127–1128.

Berendsen, R. L., Pieterse, C. M. and Bakker, P. A. 2012. The rhizosphere microbiome and plant health. *Trends in Plant Science* **17**(8): 478–486.

Berg, G., Rybakova, D., Fischer, D. and Cernava, T. 2021. Microbiome-based products for sustainable agriculture. *Nature Reviews Microbiology* **19**(8): 497–498.

Bhattacharyya, P. N. and Jha, D. K. 2012. Plant growth-promoting rhizobacteria (PGPR): Emergence in agriculture. *World Journal of Microbiology and Biotechnology* **28**(4): 1327–1350.

Bithell, S. L., McKay, A. C. and Barnett, S. J. 2015. The impact of *Trichoderma* and *Pseudomonas* inoculants on barley yield under Rhizoctonia root rot pressure. *Crop and Pasture Science* **66**(9): 885–893.

Chakraborty, K., Ghosh. S. K. and Roy. G. C. 2015. Abundance of yellow stem borer *Scirpophaga incertulas* Walker egg parasitoids in relation to cultural practices in West Bengal, India. *Research Journal of Pharmaceutical, Biological and Chemical Sciences* **6**(1): 265-270. ISSN: 0975-8585

Chandler, D., Bailey, A. S., Tatchell, G. M., Davidson, G., Greaves, J. and Grant, W. P. 2011. The development, regulation and use of biopesticides for integrated pest management. *Philosophical Transactions of the Royal Society B: Biological Sciences* **366**(1573): 1987–1998.

Chandler, D., Davidson, G., Grant, W. P., Greaves, J. and Tatchell, G. M. 2011. Microbial biological control agents for integrated pest management: An overview. *Biocontrol Science and Technology* **21**(9): 847–872.

Chhipa, H. 2019. Nanofertilizers and nanopesticides for agriculture. *Environmental Chemistry Letters* **17**(1): 15–20.

Chowdhury, S. P., Hartmann, A., Gao, X. and Borriss, R. 2022. AI-driven systems for monitoring biocontrol performance in precision agriculture. *Frontiers in Sustainable Food Systems* **6**: 945230.

De Souza, R., Ambrosini, A. and Passaglia, L. M. 2020. Plant growth-promoting bacteria as inoculants in agricultural soils. *Genetics and Molecular Biology* **38**(4): 401–419.

Derpsch, R., Friedrich, T., Kassam, A. and Hongwen, L. 2010. Current status of adoption of no-till farming in the world and some of its main benefits. *International Journal of Agricultural and Biological Engineering* **3**(1): 1–25.

Doumbou, C. L., Hamby Salove, M. K., Crawford, D. L., Beaulieu, C. and Beaulieu, C. 2001. Actinomycetes, promising tools to control plant diseases and to promote plant growth. *Phytoprotection* **82**(3): 85–102.

FAO. 2021. *The State of Food and Agriculture 2021: Making agrifood systems more resilient to shocks and stresses*. Food and Agriculture Organization of the United Nations.

Fravel, D. R. 2005. Commercialization and implementation of biocontrol. *Annual Review of Phytopathology* **43**: 337–359.

Garbeva, P., Van Elsas, J. D. and Van Veen, J. A. 2004. Rhizosphere microbial community and its response to plant species and soil history. *Plant and Soil* **259**: 47–58.

Gaugler, R. 2002. Entomopathogenic Nematology. CABI Publishing.

Ghosh, J. Ghosh, S. K., Chattetjee, H. and Senapati, S.K. 1999. Pest constraints of okra under terai region of West Bengal. *Indian Journal of Entomology* **61**(4): 362-371.

Ghosh, S. K. 2022. Bio-pesticides – A New Era for Controlling the Pests of Brinjal (Eggplant) and Related Vegetable Crops, and Development of IPM. *SATSA Mukhapatra - Annual Technical Issue* **26:** 39-60.

Ghosh, S. K. 2023. Prospect of Nano Technology in Applied Agriculture. *SATSA Mukhapatra - Annual Technical Issue,* **27:** 121-133.

Ghosh, S. K. 2013. Incidence of red spider mite (*Tetranychus urticae* Koch) on okra (*Abelmoschus esculentus* (L.) Moench) and their sustainable management. *Current Biotica* **7**(1&2): 40-50.

Ghosh, S. K. 2016. Harmful effect of insecticides against predator, *Coccinella sp*. (Lady bird beetle) on eggplant *(Solanum melongena* L.). *Uttar Pradesh Journal of Zoo*logy **36**(1): 17-23.

Ghosh, S. K. 2020. Aphid (*Aphis craccivora* Koch.) Management on Groundnut Crop (*Arachis hypogaea*) by using Biopesticides. *International Journal of Current Microbiology and Applied Sciences* **9**(10): 24-34. doi: https://doi.org/10.20546/ijcmas.2020.910.004

Ghosh, S. K. and Mondal, G. S. 2025. Sustainable Management of Insect Pests of Tree Borne Oilseed Species and Pesticide Properties of their Oil Extracted. *SATSA Mukhapatra - Annual Technical Issue* **29**: 98-108.

Ghosh, S. K. and Senapati, S. K. 2009. Seasonal fluctuation in the population of *Leucinodes orbonalis* Guen. Under the sub-himalayan region of West Bengal, India and its control on eggplant (*Solanum melongena* L.) *Precision Agriculture* **10**:443-449.

Ghosh, S. K., Chakraborty, K. and Mandal, T. 2013. Bio-Ecology of Predatory Coccinellid Beetle, Coccinella septempunctata (Coleoptera: Coccinellidae) and its Dynamics in Rice Field of Terai Region of West Bengal, India. *Internal Journal of Bio-resource and Stress Management* **4**(4): 571-575.

Ghosh, S. K., Chaudhuri, N., Ghosh, J., Chatterjee, H. and Senapati, S. K. 2001. Field evaluation of pesticides against the pest complex of cabbage under terai region of West Bengal. *Pestology* **25**(2) 40-43.

Ghosh, S. K., Karmakar, R., Pramanik, K. and Mandal, G. S. 2022. Application of Nanotechnology in Agriculture and Allied Sciences, Edited book published Futuristic Trend in Agriculture Engineering and Food Sciences published by IIP proceedings, Vol. 2, Book 9, Chapter 3, pp. 41-52, Print ISBN: 978-93-95632-65-2 . https://www.rsquarel.org/assets/docupload/rsl2023053D54063C7DD58.pdf

Ghosh, S. K., Laskar, N. and Chakraborty, G. 2012. Plant protection of tree borne oilseed species in North Bengal". (in) Tree borne oilseed species (Ecological and Economic Benefits), Book published by LAP LAMBERT Academic Publishing, Germany, Edited by S. Chakraborty. ISBN 978-3-659-25616-5. pp. 97-110.

Ghosh, S. K., Laskar, N. and Senapati, S. K, 2004. Seasonal fluctuation of *Aphis gossypii* Glov. on brinjal and field evaluation of pesticides from different origin against *A. gossypii* under terai region. *Indian Journal of Agricultural Research* **38**(3): 171-177.

Ghosh, S. K., Laskar, N., Basak, S. N. and Senapati, S. K. 2004. Seasonal fluctuation of *Bemisia tabaci* Genn. on brinjal and field evaluation of some pesticides against *B. tabaci* under terai region of West Bengal. *Environment and Ecology* **22**(4): 758-762.

Ghosh, S. K., Sonowal, M., Chakraborty, G. and Pal, P. K. 2009. Bio-efficacy of microbial formulation against red spider mite (*Tetranychus urticae* Koch.) infesting lady's finger (*Abelmoschus esculentus* L.) *Green Farming* **2**(10): 685- 688.

Glare, T. R., Caradus, J. R. and Gelernter, W. D. 2012. Have biopesticides come of age? *Trends in Biotechnology* **30**(5): 250–258.

Hallmann, J., Quadt-Hallmann, A., Mahaffee, W. F. and Kloepper, J. W. 1997. Bacterial endophytes in agricultural crops. *Canadian Journal of Microbiology* **43**(10): 895–914.

Hardoim, P. R., Van Overbeek, L. S. and Van Elsas, J. D. 2015. Properties of bacterial endophytes and their proposed role in plant growth. *Trends in Microbiology* **23**(12): 749–759.

Harman, G. E., Howell, C. R., Viterbo, A., Chet, I. and Lorito, M. 2004. Trichoderma species—opportunistic, avirulent plant symbionts. *Nature Reviews Microbiology* **2**(1): 43–56.

Hobbs, P. R., Sayre, K. and Gupta, R. 2008. The role of conservation agriculture in sustainable agriculture. *Philosophical Transactions of the Royal Society B: Biological Sciences* **363**(1491): 543–555.

Huang, Y., Reddy, K. N., Fletcher, R. S. and Pennington, D. 2018. Use of UAVs in precision agriculture for biocontrol application. *Precision Agriculture* **19**(1): 73–93.

Ingham, E. 2005. The compost tea brewing manual. Soil Foodweb Incorporated.

Kloepper, J. W., Ryu, C. M. and Zhang, S. 2004. Induced systemic resistance and promotion of plant growth by *Bacillus* spp. *Phytopathology* **94**(11): 1259–1266.

Kumar, S., Kaushik, N. and Dubey, R. C. 2021. Current trends in formulation and delivery of microbial biopesticides. *Environmental Sustainability* **4**(1): 59–67.

Kumar, S., Kaushik, N. and Singh, A. 2020. Recent trends in integrated pest management. *Indian Journal of Agricultural Sciences* **90**(4): 654–660.

Loper, J. E. and Henkels, M. D. 1997. Availability of iron to *Pseudomonas fluorescens* in rhizosphere and bulk soil evaluated with an iron-responsive biosensor. *Applied and Environmental Microbiology* **63**(1): 99–105.

López-Bucio, J., Campos-Cuevas, J. C., Hernández-Calderón, E., Velásquez-Becerra, C., Farías-Rodríguez, R., Macías-Rodríguez, L. I. and Valencia-Cantero, E. 2007. *Bacillus megaterium* rhizobacteria promote growth and alter root-system architecture through an auxin- and ethylene-independent signalling mechanism. *Plant Physiology* **142**(2): 620–631.

Lori, M., Symnaczik, S., Mäder, P., De Deyn, G. and Gattinger, A. 2017. Organic farming enhances soil microbial abundance and activity—A meta-analysis and meta-regression. *PLOS ONE* **12**(7): e0180442.

Mäder, P., Fliessbach, A., Dubois, D., Gunst, L., Fried, P. and Niggli, U. 2002. Soil fertility and biodiversity in organic farming. *Science* **296**(5573): 1694–1697.

Mendes, R., Garbeva, P. and Raaijmakers, J. M. 2011. The rhizosphere microbiome: significance of plant beneficial, plant pathogenic, and human pathogenic microorganisms. *FEMS Microbiology Reviews* **37**(5): 634–663.

Mew, T. W. and Rosales, A. M. 1986. Bacterization of rice plants for control of sheath blight caused by *Rhizoctonia solani*. *Crop Protection* **5**(5): 292–298.

Moscardi, F. 1999. Assessment of the application of baculoviruses for control of Lepidoptera. *Annual Review of Entomology* **44**(1): 257–289.

Mullins, J. G. L., Bailey, A. M. and Foster, G. D. 2021. Engineering enhanced biological control agents through synthetic biology. *Current Opinion in Biotechnology* **70**: 150–157.

Ongena, M. and Jacques, P. 2008. *Bacillus lipopeptides*: versatile weapons for plant disease biocontrol. *Trends in Microbiology* **16**(3): 115–125.

Pandey, A., Soccol, C. R. and Mitchell, D. 2000. New developments in solid state fermentation: I—bioprocesses and products. *Process Biochemistry* **35**(10): 1153–1169.

Pieterse, C. M., Van der Does, D., Zamioudis, C., Leon-Reyes, A. and Van Wees, S. C. 2014. Hormonal modulation of plant immunity. *Annual Review of Cell and Developmental Biology* **28**: 489–521.

Pimentel, D. and Burgess, M. 2014. Environmental and economic costs of the application of pesticides primarily in the United States. In *Integrated Pest Management*. pp. 47–71. Springer.

Pretty, J. and Bharucha, Z. P. 2015. Integrated pest management for sustainable intensification of agriculture in Asia and Africa. *Insects* **6**(1): 152–182.

Pretty, J., Toulmin, C. and Williams, S. 2018. Sustainable intensification in African agriculture. *International Journal of Agricultural Sustainability* **9**(1): 5–24.

Purkait, A., Biswas, S., Saha, S., Hazra, D. K., Roy, K., Biswas, P. K., Ghosh, S. K. and Kole, R. K. 2019. Formulation of plant based insecticides, their bio-efficacy evaluation and chemical characterization. *Crop Protection* **125:** 104907, 1-9.

Raaijmakers, J. M., Vlami, M. and De Souza, J. T. 2002. Antibiotic production by bacterial biocontrol agents. *Antonie van Leeuwenhoek* **81**(1): 537–547.

Reddy, P. P., Venkateswarlu, B. and Naidu, M. A. 2019. Bioformulations: Biotechnological Approaches for Sustainable Agriculture. Springer.

Rosas, S. B., Andres, J. A., Rovera, M. and Correa, O. S. 2018. Bio-encapsulation of PGPR in biopolymeric matrices for seed coating: benefits and perspectives. *Plant and Soil* **435**: 1–15.

Ryu, C. M., Farag, M. A., Hu, C. H., Reddy, M. S., Kloepper, J. W. and Paré, P. W. 2003. Bacterial volatiles promote growth in Arabidopsis. *Proceedings of the National Academy of Sciences* **100**(8): 4927–4932.

Savary, S., Willocquet, L., Pethybridge, S. J., Esker, P., McRoberts, N. and Nelson, A. 2019. The global burden of pathogens and pests on major food crops. *Nature Ecology and Evolution* **3**(3): 430–439.

Shah, P. A. and Pell, J. K. 2003. Entomopathogenic fungi as biological control agents. *Applied Microbiology and Biotechnology* **61**(5-6): 413–423.

Shaikh, S., Ghosh, S., Ghosh, S. K. 2024. Bio-control of Important Pests on Vegetable Crops by Using Microorganisms and Microbial Toxins. *SATSA Mukhapatra - Annual Technical Issue* **28**: 98-117.

Shaikh, S. I., Ghosh, S., Ghosh, S. K. and Mandal, G. S. 2024. "biological management of major vegetable insect pests with microorganisms for food safety and security", *Futuristic Trends in Agriculture Engineering & Food Sciences Volume 3 Book 3,IIP Series, Volume 3, Page no.16-30, e-ISBN: 978-93-5747-402-3, DOI/Link: https://www.doi.org/10.58532/V3BCAG3P1CH2*

Shamshiri, R. R., WSeltzien, C., Hameed, I. A., Yule, I. J., Grift, T. E., Balasundram, S. K., Pitonakova, L., Ahmed, D. and Chowdhary, G. 2018. Research and development in agricultural robotics: A perspective of digital farming. *International Journal of Agricultural and Biological Engineering* **11**(4): 1–14.

Smith, S. E. and Read, D. J. 2008. *Mycorrhizal Symbiosis* (3rd ed.). Academic Press.

Stein, T. 2005. *Bacillus subtilis* antibiotics: structures, syntheses and specific functions. *Molecular Microbiology* **56**(4): 845–857.

Subba, B. and Ghosh, S. K. 2016. Population dynamics of lady bird beetle and spiders in relation to weather factors in tomato (*Lycopersicon esculentum* l.). *Life Sciences International Research Journal* **3**(1): 35-37.

Sundar, A. R. and Vidhyasekaran, P. 2008. Biological control of sheath blight in rice with *Pseudomonas fluorescens*. *Phytoparasitica* **36**(2): 173–181.

Vessey, J. K. 2003. Plant growth promoting rhizobacteria as biofertilizers. *Plant and Soil* **255**(2): 571–586.

Wang, J., Wei, G., Li, Y., Li, X. and Li, B. 2022. CRISPR-mediated gene editing in biocontrol bacteria: emerging strategies to enhance efficacy and field adaptability. *Frontiers in Microbiology* **13**: 812304.

Weller, D. M. 2007. Pseudomonas biocontrol agents of soilborne pathogens: looking back over 30 years. *Phytopathology* **97**(2): 250–256.