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# Beneficial Fungi and Bacteria as Biocontrol Agents against Fungal and Bacterial Plant Pathogens

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**Abstract:** *Plant diseases caused by fungal and bacterial pathogens pose significant threats to global agriculture, resulting in substantial yield losses and environmental concerns from chemical pesticide overuse. This review explores the role of beneficial bacteria (Bacillus, Pseudomonas, Streptomyces) and fungi (Trichoderma, Gliocladium, Beauveria) as biocontrol agents (BCAs) for sustainable disease management. Key mechanisms include antibiosis, competition for resources, enzyme secretion, mycoparasitism, and induction of systemic resistance in plants. The paper discusses applications in crop protection against pathogens like Fusarium, Rhizoctonia, and Phytophthora, highlighting advances in omics technologies and nanotechnology for enhancing BCA efficacy. Challenges such as field variability and limited commercialization are addressed, emphasizing the potential of BCAs in reducing chemical inputs and promoting eco-friendly farming practices. Future prospects focus on integrated approaches for resilient agricultural systems.*

***Keywords;*** *Biocontrol agents, Beneficial bacteria, Beneficial fungi, Plant pathogens, Antibiosis, Induced systemic resistance, Trichoderma, Bacillus, Sustainable agriculture, Omics technologies, Nanotechnology*

## 1. Introduction

Fungal and bacterial diseases are a major constraint in agriculture due to causing devastating effect on yield. Globally, they are responsible for annual losses of 20-40% in crop yields (Ayaz *et al*., 2023). Infectious diseases such as those caused by fungal pathogens are also dangerous when fungi become resistant to chemical treatments, and excessive application of the treatment causes pollution (M. Khan *et al*., 2021). For oomycete pathogens such as Phytophthora spp., which infect the plants including pepper and potato, chemical fungicides have been able to control the pathogen; however it has raises problems of environmental pollution and resistance induced by fungicide (Volynchikova & Kim, 2022). Additionally, chemical methods can disturb the healthy soil microbiota which is detrimental to maintaining agricultural sustainability (Tariq *et al*., 2020).

Biocontrol agents (BCAs) represent a sustainable alternative to traditional chemical pesticides, by which natural enemies or antagonists of plant pathogens are used to control them. The bacteria such as Bacillus What is Internet References and the fungus *Trichoderma* are known to be effective BCAs because of their antimicrobial metabolites production, competition with the pathogens, and induction of plant immunity (M. Khan *et al*., 2021; Volynchikova & Kim, 2022). These agents are ecologically friendly and can enhance plant growth and act as antagonists against pathogens which makes them applicable for organic farming (Tyagi *et al*., 2024).

Biocontrol may be executed by direct antagonism of the pathogen through competition for growth resources, or by production of antifungal metabolites or enzymes including chitinases that attack the fungal cell wall (Neeraja *et al*., 2010; Pandey *et al*., 2021). Moreover, BCAs such as Bacillus subtilis produced biosurfactants with antifungal properties which protect against fungal diseases on certain crops (Ben Khedher *et al*., 2020). In addition to their' potential, BCAs also suffer from limitations like variable activity under field conditions and a limited array of commercial microbial biopesticides available (Bonaterra *et al*., 2022). Nevertheless, to ensure the success of BCAs in sustainable crop disease management, consideration must be given to future research for enhancing the performance and efficacy of BCAs (Ayaz *et al*., 2023).

**Table 1.1 Major Beneficial Bacterial Genera Used as Biocontrol Agents and Their Mechanisms of Action**

| **Bacterial Genus** | **Key Antagonistic Mechanisms** | **Major Antimicrobial/Defense Compounds** | **Target Pathogens** | **Supporting Studies** |
|---|---|---|---|---|
| ***Bacillus spp.*** | Antibiosis, ISR, competition for nutrients, lytic enzymes | Surfactin, Iturin, Fengycin, proteases, amylases | *Fusarium spp., Rhizoctonia spp., Phytophthora spp.* | Falardeau *et al*. (2013); Anckaert *et al*. (2021); Ben Khedher *et al*. (2020) |
| ***Pseudomonas spp.*** | Antibiosis, siderophore production, ISR activation, HCN production | Phenazines, DAPG, Pyoluteorin, Siderophores | Pythium spp., Fusarium spp., bacterial wilt pathogens | Chin-A-Woeng *et al*. (2003); Santoyo *et al*. (2012); Alattas *et al*. (2024) |
| ***Streptomyces spp.*** | Antibiotics, cell-wall-degrading enzymes, VOCs, competition | Streptomycin-like compounds, SHC-AMP peptides | *Fusarium spp., Curvularia spp.,* plant bacterial pathogens | Evangelista-Martínez (2013); Jeon *et al*. (2023) |
| **Actinobacteria** | ISR induction, competition, antibiosis | Chitinases, β-1,3-glucanases | Soilborne fungi (*Fusarium, Verticillium*) | Ebrahimi-Zarandi *et al*. (2022) |

## 2. Beneficial Bacteria as Biocontrol Agents

In general, beneficial bacteria (Pseudomonas, Bacillus and Streptomyces) display diverse capacities against plant pathogen via different modes of action, and are regarded as potential biocontrol agents for sustainable agriculture.

### 2.1. Bacillus

This genus synthesizes antimicrobial substances, especially cyclic lipopeptides (CLPs) such as surfactins, fengycins, and iturins that provide protection to the plants through membrane disruption of pathogen bacteria and fungi. These lipopeptides also trigger the systemic resistance in host plants and potentiate plant defense (Falardeau *et al*., 2013). Furthermore, there are reports that Bacillus strains (randomly mutated) have improved antagonistic activity along with enhanced plant defensive enzyme activation to counter diseases such as root rot and wilt (Manikandan *et al*., 2022).

### 2.2. Pseudomonas

This genus produces phenazines and phloroglucinols to function as biocontrol agents for their anti-fungal activities and for triggering systemic resistance in plants. [Psi] These metabolites also assist Pseudomonas species in better enhancing the competition of other microorganisms cohabiting with them within rhizosphere as to why Pseudomonas spp. are effective biological control agents (Chin-A-Woeng *et al.*, 2003). The interaction between Pseudomonas and Bacillus displays protection mechanisms such as the Type VI secretion system, which promotes plant co-colonization and safeguarding (Molina-Santiago *et al*., 2019).

### 2.3. Streptomyces

Soil-dwelling bacteria that manufacture numerous antimicrobial compounds with activity against both bacterial and fungal pathogens. A novel antimicrobial peptide from Streptomyces, SHC-AMP that exhibited strong activity against various plant pathogens was suggested as a biocontrol agent (Jeon *et al*., 2023). Streptomyces spp can be active against fungal pathogens, altering the course of various fungi including Fusarium and Curvularia in a wide spectrum of antagonist activities that may be employed for biocontrol (Evangelista-Martínez, 2013). These bacteria inhibit pathogen growth by competition for nutrients and space, antibiosis, activation of plant defenses, and also promote plant growth (Lee *et al*., 2023; Santoyo *et al*., 2012), making them a good choice as supplements or alternatives to chemical pesticides in sustainable agriculture. A) 1dBACs antibiosis, competition and ISR are considered among most important mechanisms involved in the control of bacterial biocontrol agents applied to agricultural systems.

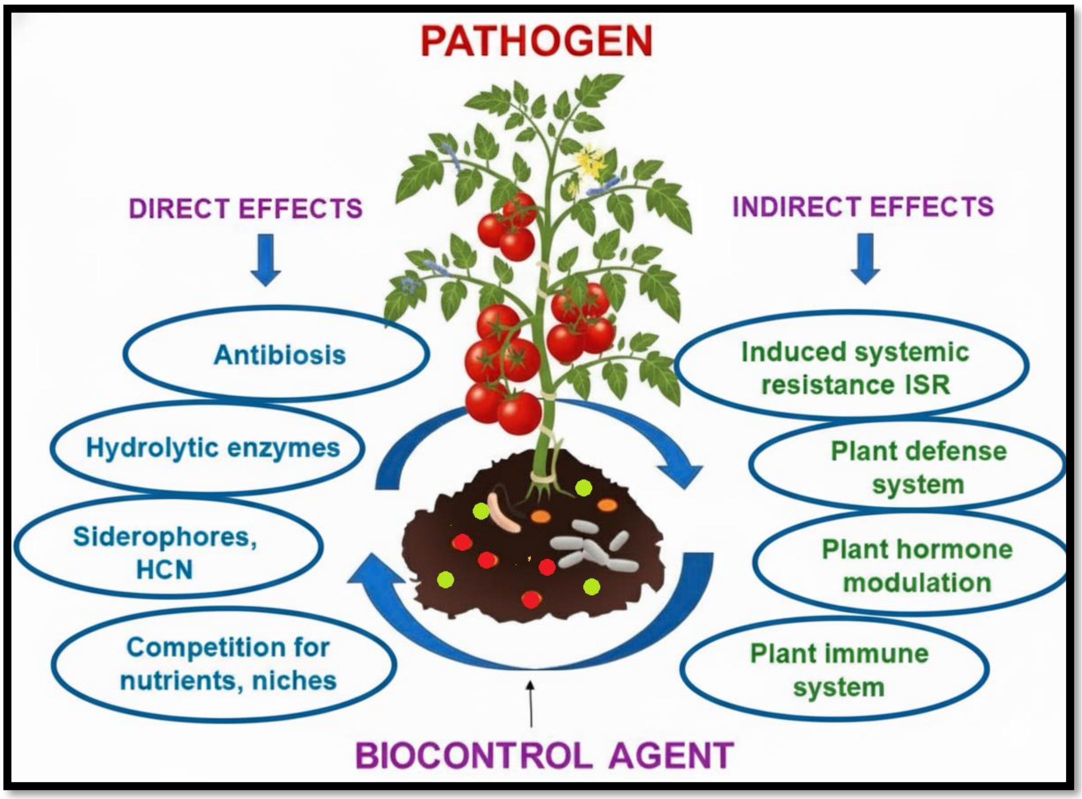
## 2.4. Antibiosis

This is the ability of bacteria to produce biologically active secondary metabolites (BSMs) capable of inhibiting or killing plant pathogens. For instance, *Bacillus spp*. are found to produce a variety of enzymes, proteins and small size BSMs which work antagonistically against phytopathogens (Anckaert *et al*., 2021). These molecules that are important enough to be named the barrier of its kind include antibiotics and other inhibitory compounds which play a primary role in restraining the growth and spread of pathogens.

## 2.5. Competition

Biocontrol agents may be able to compete more effectively than plant pathogens for resources that are critical, such as nutrients and space. In the rhizosphere, a region characterized by intense microbial interactions, biocontrol agents that grow faster or use resources more efficiently compete with pathogens for nutrients, thereby reducing limits to pathogen growth (Whipps 2001). However, this competition may be dependent on the substrate because some composts or organic matters might provide an optimal environment for biocontrol agents and thus their competitive advantage, in relation to pathogens could increase (Hoitink &Boehm, 1999). Induced Systemic Resistance (ISR): Priming bacteria can induce defense responses in plants which enhances the resistance against pathogens. In turn, by inducing systemic resistance in good connection with signaling pathways controlled by jasmonic acid, salicylic acid and ethylene, some soil Actinobacteria and Bacillus spp. may increase plant resistance (Ebrahimi-Zarandi *et al*., 2022). This priming condition enables the plant to respond more quickly and efficiently to pathogen challenge, and can be described as amplification of innate immune responses.

**Figure.2.1 Direct and Indirect Effects of Biocontrol Agents on Plant Pathogen Suppression**



## 3. Beneficial Fungi as Biocontrol Agents

Beneficial fungi such as *Trichoderma, Gliocladium* and *Beauveria* have significant role to be used as biocontrol agents in the control of plant pathogens by various ways. These fungi have been preferred more than chemical pesticides because of their environmental safety and practical efficiency. *Trichoderma* has long been appreciated for its ability to suppress numerous plant pathogens. It does so in part by processes such as mycoparasitism, antibiosis and release of secondary metabolites that interfere with pathogen growth. Several *Trichoderma* Some reports also suggest that *Trichoderma* spp. inhibit soil-borne pathogens such as *Sclerotium rolfsii, Fusarium solani* and *Rhizoctonia solani* with the inhibition percentage reaching up to 100% (Bastakoti *et al*., 2017; M. Kumar & Ashraf, 2017). In addition, *Trichoderma* species have also been shown to function as endophytes and root colonizers of plants in order to promote growth and conferring resistance to biotic and abiotic stresses such as plant pathogens, insects, diseases limiting utilization of agrochemicals (Natsiopoulos *et al*., 2024).

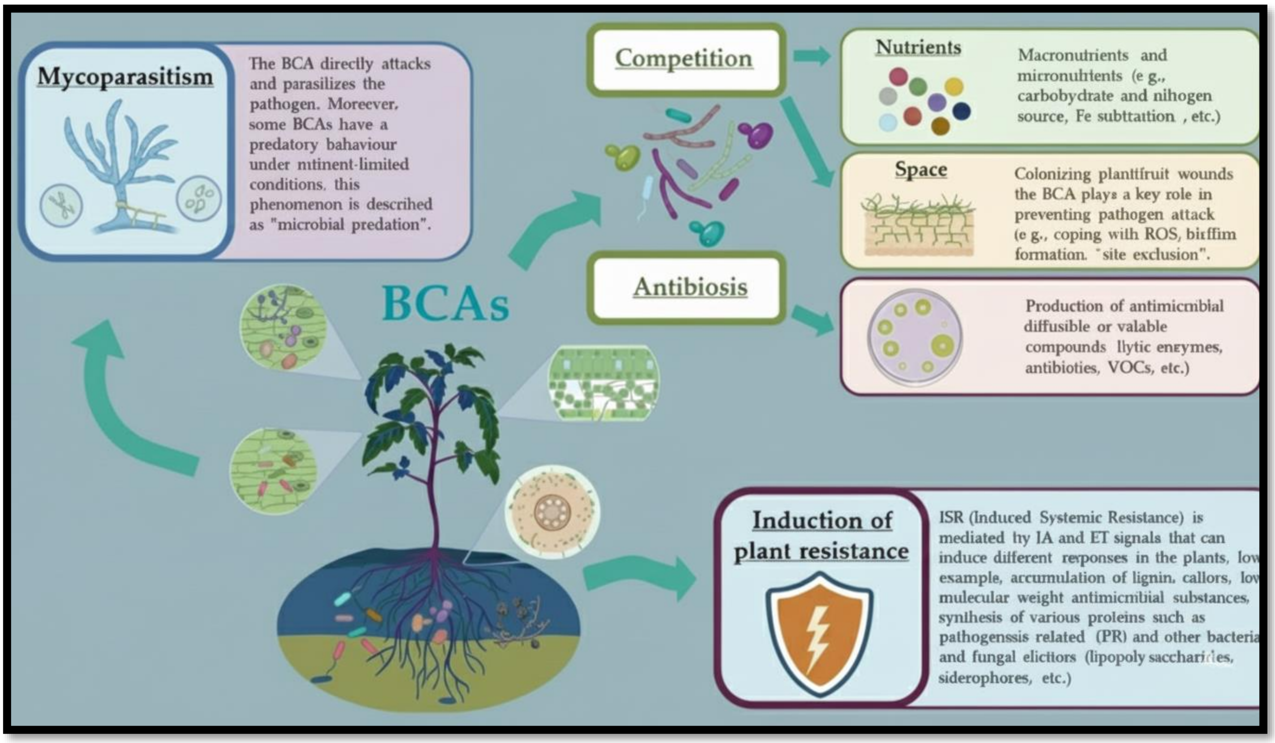
The genus Gliocladium, known to be used as a mycoparasite and endophyte that produces enzymes and antibiotics in its biocontrol action is often now referred to under the genus *Clonostachys*. *Gliocladium* spp. are good competitor in the rhizosphere for space and nutrients with pathogens, resulting in decreasing of pathogen (Manathunga *et al*., 2024). Beauveria, especially Beauveria bassiana is primarily recognized as an entomopathogenic agent against insect pests (Bamisile *et al*., 2018). Nevertheless, in recent works it is also being treated as a biocontrol against plant pathogens when used as an endophyte. Beauveria species as a colonizing plantcommensal is likely to contribute to the plant defense enhancemtn and growth boosting capacity of host plants, thus also contributing to sustainable agriculture (Bamisile *et al*.

Fungal BCAs, particularly of the genus *Trichoderma* use a diverse array of mechanisms to inhibit the growth and promote health of plants against pathogens. Myco-parasitism, enzyme secretion and the promotion of plant growth are important strategies that increase their effectiveness. Direct mycoparasitism is defined as the attack of biocontrol agents on fungal pathogens. *Trichoderma* spp., for example, can sense and attach to the host pathogen resulting in the formation of infection structures. This mechanism consists in the release of lytic enzymes and antifungal metabolites that attack degrading the cell walls of pathogenic fungi, leading to host death by cellular breakdown (Omann & Zeilinger, 2010; Steyaert *et al*., 2003). This immediate antagonism results in pathogen lethality and inhibits its replication.

Enzyme excretion is also an important mechanism. Fungal BCAs secrete enzymes that degrade pathogen cell walls and therefore enough is done to stop their proliferation. *Trichoderma* has a well-established capability to secrete hydrolytic enzymes for example cellulases, proteases which degrade the cell wall and structural components of the pathogen contributing to mycoparasitism and other antagonistic interactions (Keswani *et al*., 2013; Manzar *et al*., 2022). Furthermore, exudation of secondary metabolites having antifungal activity augment the potential of biocontrol agents to protect plants by directly inhibiting pathogens growth and development (Manzar *et al*., 2022).

Plant-growth-promotion is one of the indirect modes for the biocontrol agents to enhance plant health. *Trichoderma* strains may stimulate plant growth enhancing root structure and nutrient absorption. These fungi secrete plant growth hormones and solubilize nutrients for plants to take up. This serves not only to promote plant growth (Diánez Martínez *et al*., 2015), but also contribute to the plant's ability to ward off disease organisms through increased health and vigor (Malus/hybrida 1). Furthermore, *Trichoderma* spp. are able to promote systemic resistance in plants via the activation of plant defense pathways, which prepares the immune system of a plant to provide enhanced protection when challenged by pathogens (Hermosa *et al*., 2013).

**Figure 3.1 Modes of Action of Biocontrol Agents (BCAs): Mycoparasitism, Competition, Antibiosis, and Induced Plant Resistance**



### 3.1. Applications in Crop Disease Management

Biocontrol agents have been effectively used to control bacterial blight, wilt, and spot diseases of different crops via diverse mechanisms which are ecofriendly options for chemical pesticides. An excellent example is the use of *Trichoderma* strains, that are other extensively researched as a well-characterized biocontrol agent with phytopathogen antagonistic and endophytic properties. Instead of solely being considered as biocontrol agents, these fungi have the ability to suppress pathogens and promote plant growth as well as tolerance against stresses, which make them valuable in decreasing disease severity and sustainability of agriculture (Natsiopoulos *et al*., 2024).

*Pseudomonas spp.* bacteria have also been employed in biocontrol of bacterial diseases, occupying a key place in rhizosphere microbiomes. They inhibit pathogens by competition for nutrients, production of antimicrobial compounds and induction of systemic resistance in the host plants. These isolates have been identified as controlling different diseases and providing benefits like reduced reliance on chemical pesticides, increased crop productivity; however, field performance continues to be inconsistent (Alattas *et al*., 2024).plant growth promoting rhizobacteria (PGPR) and fungi (PGPF) have shown potential as biocontrol agents. They control plant diseases through mechanisms such as induced systemic resistance, antibiotics and volatile compound production. PGPR and PGPF play a key role in minimizing the application of toxic chemicals for disease management, with obvious potential to be adopted on a large scale in agriculture (Verma *et al*., 2019). there are studies that suggest to use microbial stimulants to increase host-plants disease resistance capacity so those may have not only greater nutritional quality by more UPT of nutrients but also a greater stress tolerance against the various types of stresses such as pathogens. These mechanisms highlight the importance of mutualistic microbial interactions in preventing diseases of crop plants (Olowe *et al*., 2020). The biocontrol agents are environmentally safe and sustainable substitutes to chemical fungicides to control fungal diseases such as powdery mildew, rusts and wilts. These agents (fungi, bacterium, yeast) may control of the plant pathogens by different mechanisms.

### 3.2. Antagonism and Direct Inhibition

Biocontrol agents such as species *Trichoderma* exert antagonistic activity against plant pathogens by synthesizing compounds which directly inhibit the pathogenic fungi such as Phytophthora capsici and a nd Phytophthora parasitica (Diánez Martínez *et al*.,2015). Also Pichia kudriavzevii demonstrated its potential since they reduced growth of fungi by secreted proteins and other antifungal activities (Elkhairy *et al*., 2023).

### 3.3. Induced Systemic Resistance (ISR)

A few biological control agents induce systemic resistance in the host plant. Bacillus, for example, are known to stimulate a plant’s immune system, and therefore raise its resistance level against pathogens such as F. oxysporum which is responsible for causing wilt (Boulahouat *et al*., 2023). This process doesn’t kill the pathogen directly, but it makes the plant better able to defend itself.

### 3.4. Competition for Resources

Biocontrol agents compete with pathogens for resources such as space and nutrients, which decreases the ability of the pathogen to survive. This kind of competitive exclusion reproduction is also a manner that agents, as Bacillus, handle diseases (Boulahouat *et al*., 2023).

### 3.5. Promoting Plant Health

Some biocontrol agents stimulate plant growth, which results in increased plant health and natural resistance to diseases. For instance, *Trichoderma saturnisporum* reduced the plant pathogens as well as improved the growth of plants (Diánez Martínez *et al*., 2015).

### 3.6. New Formulations and Adjuvants

New formulations of biocontrol agents have enhanced their capabilities in controlling foliar diseases under various different environmental conditions. Strategies such as the integration of biocontrol agents in antifungal fruit coatings promote their field survival and efficacy (Marín *et al*., 2017).

### 3.7. Control of multi-pathogens

There are biocontrol agents that play dual roles, in both insect control as well as in pathogen management. Isaria javanica is not only effective in aphids control but also can be used to provide control of fungi infection such as Colletotrichum gloeosporioides, indicating the versatile potential of biocontrol agent IJM43 is a good candidate for IPM technology application (Kang *et al*., 2018).

## 4. Advances and Future Prospects

Technologies in 'omics' have greatly advanced characterization of beneficial microbes and their functions in disease control. With the help of technologies such as genomics, proteomics, metabolomics and other omics-based approaches, scientists can reveal the complexity in plant-microbial interfacing systems and understand what determines these dynamics.

This is the main advantage of omics technologies, in that they offer a complete view of molecular interactions in the plant-microorganism system. For example, proteomics has contributed to the identification of symbiosis-specific proteins and post-translational modifications that are involved in beneficial plant-microbe interactions. Integration of proteomes with other omic layers is important to evaluate these hypotheses across the field of symbioses, ultimately improving microbe-assisted disease management approaches (Khatabi *et al*., 2019).

A multi-omics approach provides a broader picture, thereby offering the possibility of mechanistically understanding how environmental conditions impact plant-microbe interactions. Those are the sort of applications that are so valuable for developing predictive models: models to predict how plants and their microbial associates will respond to environmental stress, like climate change or an invading species. This predictive capability is important for improved plant disease control (Crandall *et al*., 2020).

A case in point is the genomics, transcriptomics and metabolomics research on the biocontrol fungi *Trichoderma* spp., from which new insights with valuable applications for agriculture have arisen. These findings have been clearly translated into new crop management strategies, demonstrating the transformative impact of omics-driven research (Lorito *et al*., 2010). In addition, omics tools have revolutionized research in microbial biofilms, which are vital to perceive the resistance of microbial populations from pathogens. Transcriptomic, proteomic and metabolomics have been used in biofilm biology to understand more widely ranging tools for the study of what is perhaps the most complex of such systems on Earth through shedding light on molecular markers that can be targeted in disease management strategies aimed at inhibiting pathogenic biofilm development (Seneviratne *et al*., 2020).

Nanotechnology is increasingly contributing to the improvement of delivery systems used in biocontrol agents in agriculture. Nanotechnology applications in biopesticides and biocontrol formulations Some studies have reported on the advantages of incorporating nanotechnology to biopesticide and biocontrol formulations. nanotechnology offers the opportunity to create nano-biopesticides that consists of bio derived active materials combined with nanoparticles. These can be entrapped in appropriate polymers for successful end-use as a pest control agent. These nanoformulations improve the stability and shelf life of the microbial agents, important for applications in sustainable agriculture (P. Kumar *et al*., 2021). The Indian In other words, combination of nano pesticides are able to minimize the percentage of agrochemicals to be used and ensure timed release and efficient distribution of nutrients and pest agents (Dwivedi *et al*., 2016). Nanoparticles also have unique characteristics compared to larger materials such as increased solubility, surface functionalizability and multivalency (Mcneil, 2005). These features of the nanomaterials render them a promising material for precision agriculture, facilitating the development of bio-conjugated formulations, which will assure that the biological/metabolite is targeted to be delivered without causing any harm to non-target organisms (S. S. Khan *et al*., 2024). Also, green nanotechnology (eco-friendly synthesis of nanoparticles from plants and microorganisms) is useful. This process overcomes the shortcomings of chemical synthesis and increases the purity and biocompatibility of nanoparticles used in agriculture (Sundararajan *et al*., 2023).

**Table 4.1 Omics and Nanotechnology Contributions to Modern Biocontrol Development**

| Technology | Contribution to Biocontrol | Key Insights/Advantages | Supporting Studies |
|---|---|---|---|
| **Genomics** | Identification of beneficial strains, antifungal genes | Discovery of BCA gene clusters | Lorito *et al*. (2010) |
| **Transcriptomics** | Expression profiling under pathogen stress | *Trichoderma* ISR gene activation maps | Crandall *et al*. (2020) |
| **Proteomics** | Characterization of defense proteins & metabolites | Plant–microbe signaling proteins identified | Khatabi *et al*. (2019) |
| **Metabolomics** | Analysis of antifungal metabolites, VOCs | Detection of new antibiotic molecules | Seneviratne *et al*. (2020) |

| | | | |
|---|---|---|---|
| **Nanotechnology** | Nano-bioformulations improving stability & delivery | Controlled release, improved field survival | Kumar *et al*. (2021); Dwivedi *et al*. (2016) |
| **Green Nanotechnology** | Eco-friendly nanoparticle production | Reduces toxicity, improves compatibility | Sundararajan *et al*. (2023) |

## 5. Conclusion

In conclusion, beneficial bacteria and fungi serve as promising biocontrol agents for combating fungal and bacterial plant pathogens, offering environmentally sustainable alternatives to chemical pesticides. Through mechanisms such as antibiosis, competition, mycoparasitism, and induced systemic resistance, genera like Bacillus, Pseudomonas, Streptomyces, and Trichoderma effectively suppress diseases while enhancing plant growth and soil health. Advances in omics technologies have deepened our understanding of microbial interactions, enabling the identification of key genes, proteins, and metabolites for improved BCA strains. Similarly, nanotechnology has revolutionized formulation and delivery systems, enhancing stability and targeted efficacy in field applications. Despite challenges like inconsistent performance and regulatory hurdles, the integration of BCAs into integrated pest management strategies holds immense potential for reducing crop losses, minimizing environmental pollution, and supporting global food security. Future research should prioritize multi-omics integration, green nanotechnology, and large-scale field trials to fully harness these agents for resilient and sustainable agriculture.

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