Medical and Life Sciences (2026) 5(1): 22–30
ISSN (E): 2976-7245

Major Biocontrol Agents Against Plant Pathogens: Mechanisms and Applications

Muhammad Asif Shabbir[1]
Muhammad Usman Ghani[2]
Sonum Bashir[1]
Iram Bilqees[1]
Muhammad Hamza Saeed[1]

How to cite this article:
Shabbir, M. A., Ghani, M. U., Bashir, S., Bilqees, I., & Saeed, M. H. (2026). Major biocontrol agents against plant pathogens: Mechanisms and applications. *Medical and Life Sciences*, *5*(1), 22–30.

Received: 15 November 2025 / Accepted: 28 February 2026 / Published Online: 10 April 2026

Abstract

Phytopathogens endanger global food security and this threat necessitates the development of disease management frameworks that are accurate, scalable and real-time. Gold standards are the application of synthetic pesticides; however, chemical residues degrade soil microbiomes and promote pathogen resistance. The evolution of current technologies in agriculture has been dependent on biological control mechanisms. This paper describes the architecture of microbial agents deployed against viral, bacterial, nematode and fungal plant pathogens. The classification of biocontrol strategies is achieved by evaluating specific antagonistic mechanisms. Fungal endophytes induce systemic resistance to suppress viral replication. Bacteriophages demonstrate high efficacy in digesting bacterial cell walls and suppressing virulence genes. Nematode eradication happens by lytic enzyme secretion and secondary metabolite toxicity. Mycoparasitism and cyclic lipopeptide production serve fast neutralization of phytopathogenic fungi. The above interactions are dictated by environmental variables and host-pathogen dynamics. Field deployment necessitates the development of stable formulations. This study deduced that microbial consortia and spray-induced gene silencing represent robust pathways for sustainable crop protection.

Keywords: Biocontrol Agents; Mycoparasitism; Bacteriophages; Plant Parasitic Nematodes; Induced Systemic Resistance

1 Introduction

1.1 Biocontrol Architecture in Plant Pathology

Agricultural productivity has been dependent on aggressive chemical interventions to suppress infectious diseases. Intensive monoculture systems favor the rapid dissemination of phytopathogens. Fungi, bacteria, viruses and nematodes cause severe systemic damage to crops. Synthetic agrochemicals endanger non-target organisms and contaminate groundwater reservoirs. Biocontrol agents provide natural mechanisms for pathogen suppression. The architecture of the rhizosphere

[1]Virtual University of Pakistan, Raiwind Road Campus, Lahore, Pakistan
Corresponding Author: naureen.anwar@vu.edu.pk
[2]College of Agriculture, University of Sargodha, Sargodha, Pakistan

microbiome regulates plant health. Microorganisms leverage specific biochemical pathways for pathogen neutralization. Biological control is a synthesis of multiple ecological interactions. Direct antagonism involves the physical destruction or chemical inhibition of the pathogen (Stenberg et al., 2021). Indirect antagonism happens by altering the host plant physiology. Induced systemic resistance primes plant defenses against future infections. Root colonization by beneficial microbes excludes pathogens from critical nutrient zones (Liu et al., 2024). The deployment of single-strain inoculants often fails under fluctuating field conditions. Field efficacy requires robust environmental adaptation. The continuous evaluation of microbial interactions discerns the precise mechanisms of disease suppression as shown in table 1 (Niu et al., 2020). Formulations must adapt to ultraviolet radiation, desiccation and temperature extremes. Advanced diagnostic tools evaluate the genomic and metabolomic profiles of biocontrol agents (Agrawal, 2024). Multi-omics approaches extract critical data regarding secondary metabolite production (Palazzotto & Weber, 2018). The above methods typically do not address the needs of immediate field application but provide foundational knowledge for product development. Commercialization necessitates the development of consortia that exhibit superior resilience. Consortia leverage synergistic interactions for broad-spectrum disease control (Yadav et al., 2025). The transition toward sustainable agriculture relies on integrating these biological tools into existing farming architectures (Das et al., 2023). In this study, major biocontrol agents are defined based on their widespread application in agriculture, consistent efficacy across laboratory and field conditions, and their recognized importance in commercial and research-based plant disease management strategies, as shown in figure 1.

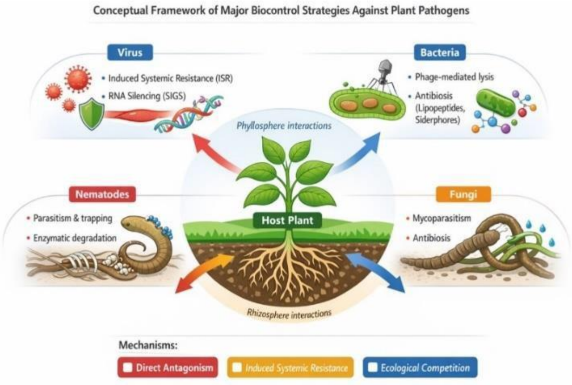

Figure 1. Conceptual framework of major biocontrol strategies against plant pathogens, illustrating direct antagonism, induced systemic resistance, and ecological competition across viral, bacterial, nematode, and fungal infections.

Table 1: Comparison of Biocontrol Mechanisms

Mechanism Type	Description	Speed of Action	Target Pathogens
Direct antagonism	Physical or chemical destruction of the pathogen.	Fast	Bacteria, fungi, nematodes
Induced systemic resistance (ISR)	Activation of plant defense pathways.	Moderate	Viruses, bacteria
Antibiosis	Production of antimicrobial compounds.	Fast	Bacteria, fungi
Parasitism/Mycoparasitism	Direct invasion and consumption of the pathogen.	Fast	Fungi, nematodes
Ecological competition	Competition for nutrients and ecological niches.	Slow to moderate	All pathogens

1.2 Antiviral Biocontrol Strategies and Induced Systemic Resistance

Viral infections cause severe cellular disruption in agricultural crops. Obligate intracellular parasites lack independent metabolic machinery. The direct neutralization of viral particles by microbial antagonists rarely occurs outside the host cell (Burton, 2023). Eradication of viral diseases has been dependent on induced systemic resistance pathways. Fungal and bacterial endophytes colonize plant tissues without causing disease. The deployment of endophytic fungi happens by colonizing root networks (Bard et al., 2024). Mycorrhizal fungi and specific strains of *Trichoderma* stimulate defense cascades in host plants (Pacheco-Trejo et al., 2022). The activation of plant immunity alters transcriptomic outputs. Salicylic acid accumulation happens rapidly following microbial colonization. Jasmonate pathways are dictated by continuous microbial signalling. Endophytes provide rapid immune priming against mosaic and leaf curl viruses (Farhana et al., 2025). The architecture of the defence network prevents viral replication and restricts movement through the plasmodesmata. *Bacillus velezensis* induces systemic resistance against specific viral pathogens. Cyclic lipopeptides produced by *Bacillus* strains trigger defense gene expression (Ruiz et al., 2024). The above modifications create a biochemical environment that is highly hostile to viral assembly. However, vector control is a complementary mechanism for viral suppression. Most plant viruses are transmitted by different insect vectors. Aphids and whitefly vectors are affected by entomopathogenic fungi, which can infect these vectors and eventually annihilate them (Francis et al., 2022). *Beauveria bassiana* and *Metarhizium anisopliae* are entomopathogenic fungi that can infect insect cuticles, while protease and chitinase are secreted by them to digest the insect tissues. Reducing the vector population directly decreases viral transmission rates. Gene silencing induced by spray is a new strategy for controlling viruses. Foliar application of double-stranded RNA facilitates trans-kingdom RNA interference (Chen et al., 2025). These molecules are taken up, which activates targeted destruction of viral messenger RNA. Dicer-like enzymes chop the introduced genetic material into small RNA fragments (Fukudome & Fukuhara, 2017). These fragments are inserted into an RNA-induced silencing complex, which allows the virus to find and destroy complementary copies of itself. This non-transgenic strategy is highly effective in inducing viral immunity. To mitigate the rapid degradation of naked double-stranded RNA in the environment, nanoparticle carriers must be developed.

1.3 Phage-Mediated and Bacterial Control of Phytopathogenic Bacteria

Infection by bacterial phytopathogens occurs through stomata and physical wounds in plant tissues. *Xanthomonas, Pseudomonas* and *Erwinia* species evoke devastating blights and wilts. By achieving antibiotic resistance, bacterial populations result in substantial management crises (Gupta et al., 2024). Bacteriophages are defined as the viruses that attack and destroy bacterial pathogens. Lytic phages are extremely efficient at digesting bacterial cell walls. The infectious cycle initiates when the bacteriophage tail fiber attaches to a specific bacterial surface receptor and viral genetic information moves into the host cytoplasm. The metabolic machinery of the bacterium duplicates to serve phage replication. This buildup of viral particles results in bacterial lysis. Phage biocontrol relieves plant immunity burden. Plants undergo an extreme oxidative stress response during infection with *Xanthomonas campestris.* Lytic phage treatment represses expression of bacterial virulence factors (Erdrich et al., 2025). This includes the downregulation of Type III secretion system during phage application. Transcriptional repression of flagellar biosynthesis genes is extreme. These genetic changes disable the bacterial infection machinery. Phage therapy also prevents the rapid generation of resistant bacterial mutants within the plant phyllosphere. Bacteriophages for field application need to adjust themselves towards environmental aggressiveness. The use of ultraviolet radiation denatures viral proteins and degrades nucleic acids. During peak daylight hours phage viability decreases significantly. Applications are generally conducted at nighttime to optimize the contact time with the bacterium. Formulations include ultraviolet protectants to extend survival (Gdanetz et al, 2024). Cocktail mixtures make use of multiple strains of phage for broad-spectrum coverage. Cocktail strategy stops target bacteria from creating simple mutations in their receptor. The commercialization of phage products is a culmination of years of extensive field trials and stabilization research (Choudhary et al., 2025). Bacterial antagonists also show strong control on phytopathogenic bacteria. Different species, such as *Bacillus* and *Pseudomonas*, can colonize root (rhizosphere) and leaf (phyllosphere). *Bacillus velezensis* produces strong anti-microbials that are secreted (Kenfaoui et al., 2024). Different cyclic lipopeptides have a membrane damaging mechanism against bacteria such as iturin, surfactin, and fengycin. Lipopeptides induce collapse of target membrane's physical architecture. The race for essential nutrients hastens pathogen starvation. The *Pseudomonas* species (P) produces siderophores, which chelate Fe (III) in soil. Bacterial pathogens cannot grow with limited iron and do not synthesize virulence factors. The efficacy of biocontrol hinges on the rapid establishment of antagonist biofilms on plant surfaces (Vinatzer et al., 2024).

1.4 Fungal and Bacterial Interventions Against Plant Parasitic Nematodes

Plant parasitic nematodes endanger root systems and compromise water absorption. Root-knot nematodes establish specialized feeding sites called giant cells. Cyst nematodes protect their eggs within rigid structures. Nutrient extraction occurs via stylet penetration into vascular tissues. Synthetic nematicides highly effect the non-target soil fauna when applied against nematodes. Biological control leverages predatory and parasitic microorganisms to reduce nematode populations. Nematophagous fungi utilize diverse trapping mechanisms. *Arthrobotrys oligospora* forms adhesive nets and constricting rings. The capture of juvenile nematodes initiates hyphal invasion. The digestion of nematode tissues happens by extensive enzymatic secretion. Endoparasitic fungi infect nematodes via adhesive spores. Facultative parasites target sedentary life stages. *Pochonia chlamydosporia* and *Purpureocillium lilacinum* parasitize nematode eggs. The digestion of the eggshell is achieved by specific chitinases and proteases. Lytic enzyme degradation exposes the developing embryo to fungal toxins. Bacterial antagonists disrupt nematode life cycles through multiple pathways. *Pasteuria penetrans* is an obligate parasite that act against the root-knot nematodes (Jagadeeswaran et al., 2024). Endospores of these bacteria stick to the cuticle of infective nematode juveniles. Once in the nematode pseudocoelom, spore germination propels the penetration tube. The internal organs are devoured by bacterial multiplication and reproduction is hindered. *Bacillus thuringiensis* produces crystalline proteins (Yamamoto & Powell, 2024). Cry proteins are also absorbed causing severe intestinal damage in nematodes. Multi-omics approaches identify the metabolites responsible for this toxicity (Ayaz et al., 2024). Nematodes respond to volatiles released by beneficial rhizobacteria. Root exudates are masked by repellent volatiles and host-seeking juveniles become confused. Nematicidal compounds induce direct paralysis. Resorcylic acid lactones are potent inhibitors of nematode motility (Gao et al., 2025). In addition, integrating fungal and bacterial strains into microbial consortia provides more effective pest management (Yadav et al., 2025). Consortia application targets multiple nematode life stages simultaneously. Synergistic interactions between *Trichoderma* species and *Bacillus* strains suppress gall formation. The above approaches typically do not address the needs of highly degraded soils without concurrent organic amendments. Sustainable management requires the continuous application of biocontrol agents to maintain suppressive soil profiles as shown in table 2 (Shakeel et al., 2023).

Table 2: Major Biocontrol Agents and Their Mechanisms

Pathogen Type	Major Biocontrol Agents	Mechanism of Action	Key Advantage
Virus	*Trichoderma*, *Bacillus*, endophytes	Induced systemic resistance (ISR), gene silencing	Enhances plant immunity
Bacteria	Bacteriophages, *Pseudomonas*, *Bacillus*	Lysis, antibiosis, siderophore production	Direct pathogen suppression

Pathogen Type	Major Biocontrol Agents	Mechanism of Action	Key Advantage
Nematodes	*Arthrobotrys*, *Pochonia*, *Pasteuria*, *Bacillus thuringiensis*	Trapping, parasitism, toxin production	Multi-stage lifecycle disruption
Fungi	*Trichoderma*, *Bacillus*, *Ceriporia*	Mycoparasitism, antibiosis, competition	Strong fungal suppression

1.5 Antagonistic Dynamics Against Phytopathogenic Fungi

Fungal phytopathogens cause massive agricultural losses through root rots, wilts and foliar blights. *Fusarium*, *Rhizoctonia*, *Sclerotinia* and *Botrytis* are persistent threats. Chemical fungicides disrupt fungal sterol biosynthesis but drive rapid evolution of resistance. Biological control relies on hyperparasites and antagonistic bacteria. *Trichoderma* species are ubiquitous soil fungi that parasitize pathogenic strains. Mycoparasitism is a highly coordinated attack sequence. *Trichoderma* hyphae detect chemical gradients emitted by the host fungus. Directional growth leads to physical contact. Coiling around the target hyphae happens immediately. Appressoria formation anchors the biocontrol agent to the pathogen. The digestion of the host cell wall is achieved by chitinases, beta-glucanases and proteases (Inglis & Kawchuk, 2002). Lytic enzymes breach the structural integrity of the target. Cytoplasmic extraction follows the penetration of the host mycelium. Antibiosis is a parallel mechanism for fungal suppression. *Trichoderma* strains synthesize potent secondary metabolites (Oyesola et al., 2024). Peptaibols form pores in the pathogen membrane. Gliotoxin and trichokonins disrupt internal metabolic processes. The volatile compound 6-pentyl-alpha-pyrone inhibits spore germination. Native *Trichoderma* isolates demonstrate high effectiveness against different soil-borne pathogens (Atlagić et al., 2025; Rauf et al., 2024). Bacterial agents secrete specific antifungal compounds. *Bacillus amyloliquefaciens* produces lipopeptides that degrade fungal membranes. Volatile emissions from *Bacillus* species halt mycelial expansion. *Ceriporia lacerata* is a white-rot fungus that functions as a biocontrol agent. The application of *Ceriporia lacerata* lyses pathogenic hyphae and triggers beta-glucanase production (Yin et al., 2023). Competition for space and nutrients restricts fungal pathogen establishment. Rapid root colonization by *Trichoderma* denies physical attachment sites to *Fusarium* species (Awal et al., 2024). Siderophore secretion deprives pathogenic fungi of essential iron. Biocontrol fungi also alter root architecture and enhance overall plant vigor (Rubayet & Hossain, 2024).

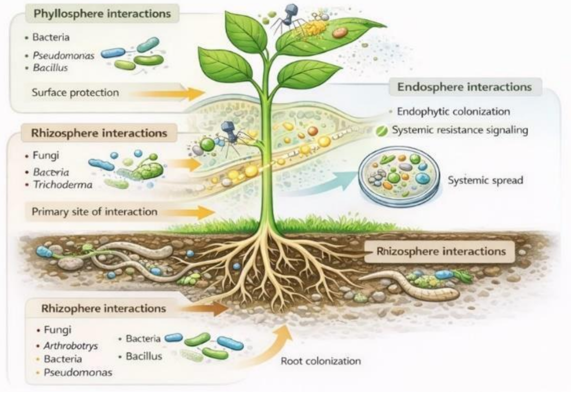

Figure 2. Spatial distribution of major biocontrol agents across plant-associated microenvironments, illustrating interactions within the rhizosphere, endosphere, and phyllosphere that contribute to effective plant disease suppression.

2 Integrated Perspective on Biocontrol Strategies

The important technical hurdle is the conversion of laboratory success to effectiveness in field conditions. Deployment of biocontrol agents is associated with strong abiotic stress. Overheat, soil acidity and lack of water threaten microbe's survival. The environmental viability of the biocontrol product relies on its formulation (Hegde & Vijaykumar 2024). Wettable powders, granules and liquid suspensions need specific stabilizing agents. In order to prolong the shelf-life, new encapsulation technologies need to be studied. Encapsulation shields sensitive microbial cells from UV radiation and desiccation.

Table 3: Field Application Challenges and Considerations

Factor	Impact on Biocontrol Agents	Example
Environmental stress	Reduces microbial survival.	Ultraviolet (UV) radiation affecting bacteriophages
Host specificity	Limits the broad-spectrum use of biocontrol agents.	Bacteriophages targeting specific bacterial species
Formulation stability	Affects shelf life and field performance.	Need for encapsulation technologies
Soil microbiome interaction	Native microorganisms may outcompete introduced biocontrol agents.	Reduced efficacy of microbial inoculants
Application timing	Influences the effectiveness of biocontrol treatments.	Evening application of bacteriophages to minimize UV exposure

Host specificity restricts the widespread use of some agents. Bacteriophages can only target particular strains of bacteria. Even the closest matching of the phage to the field pathogen is a hard criterion. Viral mutation disrupts surface receptors for phage attachment. Phage cocktails reduce this risk but make the manufacturing process more complex. Relatively the same applies to fungal antagonists which must be adapted to local soil microbiomes. Introduced commercial isolates are outcompeted by native strains. Identification of the indigenous microbial communities informs the selection of suitable Biocontrol strains. Regulatory frameworks often impede the rapid commercialization of biological products. Safety assessments must prove the absence of any harm of these to humans and non-target microorganisms. The registration process is expensive and time-consuming. Farmers exhibit reluctance to adopt biologicals due to perceived inconsistencies in performance. Chemical pesticides serve fast visual results. Biological control requires preventative application and longer incubation periods. The integration of biocontrol agents into existing agronomic practices requires extensive farmer education (Ayaz et al., 2023). Advances in computational intelligence facilitate the discovery of novel biocontrol mechanisms. Genomic sequencing identifies silent biosynthetic gene clusters. The activation of these clusters extracts new antimicrobial compounds. Spray-induced gene silencing bypasses the need for living microbes by utilizing synthesized nucleic acids. The above technological leaps address the stability issues of live organisms. Disease suppression remains dependent on the continuous refinement of these delivery architectures.

3 Conclusion

Major biocontrol agents offer a sustainable alternative to chemical pesticides in plant disease management. Microbial antagonists act through direct suppression, induced systemic resistance, and ecological competition. Fungal agents such as Trichoderma, bacterial genera including Bacillus and Pseudomonas, and bacteriophages collectively target fungal, bacterial, viral, and nematode pathogens through diverse biochemical and molecular mechanisms. Their effectiveness is influenced by environmental conditions and formulation stability. Direct mechanisms provide rapid control, whereas host-mediated responses ensure longer-term protection. The integration of microbial consortia and emerging approaches such as spray-induced gene silencing enhances overall efficacy.

Continued improvements in formulation and field application are essential for reliable large-scale use.

Author Contributions

Muhammad Asif Shabbir, Muhammad Usman Ghani, Sonum Bashir, Iram Bilqees, and Muhammad Hamza Saeed contributed to the conceptualization, literature search, review of microbial biocontrol agents and plant-pathogen interactions, synthesis and classification of biocontrol mechanisms, interpretation of the relevant scientific literature, organization of the manuscript, and preparation of the article. All authors contributed to writing—original draft and writing—review and editing. All authors read and approved the final version of the manuscript and agreed to be accountable for all aspects of the work.

Conflict of Interest

The authors declare that they have no financial, professional, commercial, institutional, or personal conflicts of interest that could have influenced the content or conclusions of this article.

Funding

This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

Data Availability

No new experimental or field dataset was generated or analysed for this study. All information supporting the review was obtained from the published scientific literature cited in the manuscript.

Informed Consent

Not applicable. The study did not involve human participants or the collection of personal information.

Use of Generative AI

The authors declare that no generative artificial intelligence tools were used to conduct the literature review, generate the scientific content, interpret the evidence, or formulate the conclusions presented in this article.

4 References

Agrawal, R. (2024). Emerging technologies for improvement of microbial strains using omic sciences and measuring methods for maximum product formation. In R. Agrawal (Ed.), *Textbook of industrial microbiology* (pp. 13–39). Springer. https://doi.org/10.1007/978-981-97-9582-6_2

Atlagić, K., Cvetić Antić, T., Lukičić, J., Kruščić, K., Živić, M., Unković, N., Pajić, T., Stevanović, K., & Todorović, N. V. (2025). Biocontrol Potential of Native Trichoderma Strains Toward Soil-Borne Phytopathogenic and Saprotrophic Fungi. *Journal of Fungi*, 11(7), 535. https://doi.org/10.3390/jof11070535

Awal, M. A., Abdullah, N. S., Prismantoro, D., Dwisandi, R. F., Safitri, R., Mohd-Yusuf, Y., Suhaimi, N. S. M., & Doni, F. (2024). Mechanisms of action and biocontrol potential of Trichoderma against Fusarium in horticultural crops. *Cogent Food & Agriculture*, 10(1), 2394685. https://doi.org/10.1080/23311932.2024.2394685

Ayaz, M., Ali, Q., Farzand, A., Khan, A. R., Zhao, H., & Gao, X. (2024). Biocontrol of plant parasitic nematodes by bacteria and fungi: a multi-omics approach for the exploration of novel nematicides in sustainable agriculture. *Frontiers in Microbiology*, 15, 1433716. https://doi.org/10.3389/fmicb.2024.1433716

Ayaz, M., Li, C. H., Ali, Q., Zhao, W., Chi, Y. K., Shafiq, M., Ali, F., Yu, X. Y., Yu, Q., Zhao, J. T., Yu, J. W., Qi, R. D., & Huang, W. K. (2023). Bacterial and Fungal Biocontrol Agents for Plant Disease Protection: Journey from Lab to Field, Current Status, Challenges, and Global Perspectives. *Molecules*, 28(18), 6735. https://doi.org/10.3390/molecules28186735

Bard, N. W., Cronk, Q. C., & Davies, T. J. (2024). Fungal endophytes can modulate plant invasion.

Biological Reviews, 99(5), 1652–1671. https://doi.org/10.1111/brv.13085

Burton, D. R. (2023). Antiviral neutralizing antibodies: From in vitro to in vivo activity. *Nature Reviews Immunology, 23*(11), 720–734. https://doi.org/10.1038/s41577-023-00858-w

Chen, C., Imran, M., Feng, X., Shen, X., & Sun, Z. (2025). Spray-induced gene silencing for crop protection: recent advances and emerging trends. *Frontiers in Plant Science*, 16, 1527944. https://doi.org/10.3389/fpls.2025.1527944

Choudhary, M., Bankole, I. A., McDuffee, S. T., Parajuli, A., Poudel, M., Balogh, B., Paret, M. L., & Jones, J. B. (2025). Bacteriophages as Agents for Plant Disease Control: Where Are We After a Century? *Viruses*, 17(8), 1033. https://doi.org/10.3390/v17081033

Das, S., Ray, M. K., Panday, D., & Mishra, P. K. (2023). Role of biotechnology in creating sustainable agriculture. *PLOS Sustainability and Transformation, 2*(7), e0000069. https://doi.org/10.1371/journal.pstr.0000069

Erdrich, S. H., Župunski, M., Schurr, U., Grossmann, G., Frunzke, J., & Arsova, B. (2025). Phage biocontrol reduces the burden on plant immunity through suppression of bacterial virulence. *bioRxiv*, 2025.04.26.650785. https://doi.org/10.1101/2025.04.26.650785

Farhana, A. P., Krishnapriya, P. J., Heera, G., Anu Rajan, S. S., Sherin, A. S., Saru Sara, S., & Arya, S. R. (2025). Endophytes for the management of plant viruses. *Journal of Plant Disease Sciences*, 20(2), 291–323.

Francis, F., Fingu-Mabola, J. C., & Ben Fekih, I. (2022). Direct and endophytic effects of fungal entomopathogens for sustainable aphid control: A review. *Agriculture, 12*(12), 2081. https://doi.org/10.3390/agriculture12122081

Fukudome, A., & Fukuhara, T. (2017). Plant dicer-like proteins: Double-stranded RNA-cleaving enzymes for small RNA biogenesis. *Journal of Plant Research, 130*(1), 33–44. https://doi.org/10.1007/s10265-016-0877-1

Gao, Y., Li, W., & Ruan, H. (2025). The chemical and biological properties of natural resorcylic acid lactones. *Natural Product Reports, 42*(8), 1387–1410. https://doi.org/10.1039/D5NP00033E

Gdanetz, K., Dobbins, M. R., Villani, S. M., Outwater, C. A., Slack, S. M., Nesbitt, D., Svircev,
A. M., Lauwers, E. M., Zeng, Q., Cox, K. D., & Sundin, G. W. (2024). Multisite Field Evaluation of Bacteriophages for Fire Blight Management: Incorporation of Ultraviolet Radiation Protectants and Impact on the Apple Flower Microbiome. *Plant Disease*, 114(5), 114–125.

Gupta, L., Chauhan, M., Kumar, A., & Chauhan, D. (2024). Management of bacterial diseases in plants. In D.Srivastava, R. K. Gaur, & A. K. Tiwari (Eds.), *Plant diseases and their management* (pp. 293–333). Apple Academic Press. https://doi.org/10.1201/9781032722856-10

Hegde, G. M., & Vijaykumar, K. N. (2024). Advances, Challenges and Perspectives in the Application of Novel Biocontrol Agents for Plant Disease Management. *Asia Pacific Biofertilizer and Biopesticide Information Platform, 1,* 1–15. https://doi.org/10.56669/HYZL2696

Inglis, G. D., & Kawchuk, L. M. (2002). Comparative degradation of oomycete, ascomycete, and basidiomycete cell walls by mycoparasitic and biocontrol fungi. *Canadian Journal of Microbiology*, 48(1), 60-70. https://doi.org/10.1139/w01-130

Jagadeeswaran, R., Singh, B., & Dubey, J. (2024). Isolation of *Pasteuria penetrans*, an obligate hyper-parasite infecting root-knot nematode (*Meloidogyne* spp.) from the rhizosphere of pulses in India. *Egyptian Journal of Biological Pest Control, 34*(1), 9. https://doi.org/10.1186/s41938-024-00775-7

Kenfaoui, J., Dutilloy, E., Benchlih, S., Lahlali, R., Ait-Barka, E., & Esmaeel, Q. (2024). Bacillus velezensis: a versatile ally in the battle against phytopathogens-insights and prospects. *Applied Microbiology and Biotechnology*, 108(1), 439. https://doi.org/10.1007/s00253-024-13255-7

Liu, Y., Xu, Z., Chen, L., Xun, W., Shu, X., Chen, Y., … Zhang, R. (2024). Root colonization by beneficial rhizobacteria. *FEMS Microbiology Reviews, 48*(1), fuad066. https://doi.org/10.1093/femsre/fuad066

Niu, B., Wang, W., Yuan, Z., Sederoff, R. R., Sederoff, H., Chiang, V. L., & Borriss, R. (2020). Microbial interactions within multiple-strain biological control agents impact soil-borne plant disease. *Frontiers in Microbiology, 11,* 585404. https://doi.org/10.3389/fmicb.2020.585404

Oyesola, O. L., Tonjock, R. K., Bello, A. O., Taiwo, O. S., & Obembe, O. O. (2024). Trichoderma: A Review of Its Mechanisms of Action in Plant Disease Control. *Preprints.org*, 2024051390.

Pacheco-Trejo, J., Aquino-Torres, E., Reyes-Santamaría, M. I., Islas-Pelcastre, M., Pérez-Ríos, S. R., Madariaga-Navarrete, A., & Saucedo-García, M. (2022). Plant defensive responses triggered by *Trichoderma* spp. as tools to face stressful conditions. *Horticulturae, 8*(12), 1181. https://doi.org/10.3390/horticulturae8121181

Palazzotto, E., & Weber, T. (2018). Omics and multi-omics approach to study the biosynthesis of secondary metabolites in microorganisms. *Current Opinion in Microbiology, 45*, 109–116. https://doi.org/10.1016/j.mib.2018.03.004

Rauf, A., Subhani, M. N., Siddique, M., Shahid, H., Chattha, M. B., Alrefaei, A. F., Hasan Naqvi, S. A., Ali, H., & Lucas, R. S. (2024). Cultivating a greener future: Exploiting Trichoderma-derived secondary metabolites for fusarium wilt management in peas. *Heliyon*, 10(1), e29031.

Rubayet, M. T., & Hossain, M. M. (2024). Bio-Exploration of Plant Growth-Promoting Fungus Trichoderma as a Potent Candidate for Plant Disease Management: An Overview. *OnLine Journal of Biological Sciences*, 25(1), 22-52. https://doi.org/10.3844/ojbsci.2025.22.52

Ruiz, V. V., Gándara-Ledezma, A., Villarreal-Delgado, M. F., Villa-Rodríguez, E. D., Parra-Cota, F. I., Santoyo, G., … de los Santos-Villalobos, S. (2024). Regulation, biosynthesis, and extraction of *Bacillus*-derived lipopeptides and its implications in biological control of phytopathogens. *Stresses, 4*(1), 107–132. https://doi.org/10.3390/stresses4010007

Shakeel, A., Khan, A. A., Bhat, A. H., & Sayed, S. (2023). Insights into Biocontrol through Antagonistic Organisms to Control Root-Knot Nematodes. *Pathogens*, 12(2), 238.

Stenberg, J. A., Sundh, I., Becher, P. G., Björkman, C., Dubey, M., Egan, P. A., … Viketoft, M. (2021). When is it biological control? A framework of definitions, mechanisms, and classifications. *Journal of Pest Science, 94*(3), 665–676. https://doi.org/10.1007/s10340-021-01354-7

Sundin, G. W., Villani, S. M., Zeng, Q., Hulin, M. T., Rabiey, M., & Cox, K. D. (2025). Maximizing the Biocontrol Potential of Bacteriophages: A Call for Critically-Needed Field Research. *Plant Disease*, 109(12), 2473-2475. https://doi.org/10.1094/PDIS-109-12-2473

Vinatzer, B. A., Bull, C. T., & Huerta Vazquez, A. I. (2024). Conference: ICPPB & Biocontrol 2024 Virginia Tech in Blacksburg, VA. *Plant Institute*, 1.

Yadav, S. P., Sharma, C., Pathak, P., Kanaujia, A., Saxena, M. J., & Kalra, A. (2025). Management of phyto-parasitic nematodes using bacteria and fungi and their consortia as biocontrol agents. *Environmental Science: Advances*, *4*(3), 335–354. https://doi.org/10.1039/D4VA00216D

Yamamoto, T., & Powell, G. K. (2024). *Bacillus thuringiensis* crystal proteins: Recent advances in understanding its insecticidal activity. In *Advanced engineered pesticides* (pp. 3–42). https://doi.org/10.1201/9781003573883-2

Yin, J., Bai, R., Yuan, L., & Huang, J. (2023). Application of Ceriporia lacerata HG2011 as biocontrol agent against multiple phytopathogenic fungi and Oomycetes. *Pesticide Biochemistry and Physiology*, *190*, Article e105316. https://doi.org/10.1016/j.pestbp.2022.105316